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Toward an Epistemology of Physics

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The aim of this work is twofold: to understand the intuitive sense of mechanism
that accounts for commonsense predictions, expectations, explanations, and judg-
ments of plausibility concerning mechanically causal situations and to understand
how those intuitive ideas contribute to and develop into school physics. To facili-
tate this, I provide a framework for describing and correlating characteristics of
weakly organized knowledge systems. The framework is aimed at answering, at
a coarse level of detail, a set of questions central to a full theory of knowledge:
What are the elements of knowledge; how do they arise; what level and kind of
systematicity exists; how does the system as a whole evolve; and what can be said
about the underlying cognitive mechanisms that are responsible for the normal oper-
ation of the system and its evolution?

The empirical base is a set of clinical interviews of undergraduate physics stu-
dents trying to solve a set of specially designed problems. Observations from this
core and from the existing literature are extended with informal data and synthe-
sized using the general framework.

Major claims are that the intuitive sense of mechanism involves many simple
elements whose origins are relatively unproblematic, as minimal abstractions of com-
mon events. The system as a whole is only weakly organized, and it is subject to
a number of constraints including a relative lack of depth in justificatory structure
and the inability to resolve conflicts on the basis of knowledge within the system.
Despite weak organization, the system exhibits some broadly characteristic traits,
a number of which are identified. They include a prominent causal schematization
in terms of agents, patients, and interventions ("causal syntax"); a tendency to fo-
cus on static characterizations of dynamic events, including the global form of trajec-
tories; and a relatively rich phenomenology of balancing and equilibrium.

The intuitive sense of mechanism contributes substantially to understanding school
physics. This development requires a denser knowledge organization, adding depth
and breadth that allow more confident application of fewer fundamental explanato-
ry elements.

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The later sections of the monograph have three goals: (a) to abstract and clarify the theoretical framework into a form suitable for application to knowledge systems other than the physical sense of mechanism; (b) to summarize and independently motivate major claims; and (c) by contrast, to highlight the implications of the basic claims of the monograph in comparison with other proposed frameworks for understanding commonsense physics knowledge.

INTRODUCTION

The Physical Sense of Mechanism

In dealing with the physical world, humans gradually acquire an elaborate *sense of mechanism*—a sense of how things work, what sorts of events are necessary, likely, possible, or impossible. When my older son was 6 years old, he was puzzled when the moon appeared to follow us in the car. He said that he thought it was an illusion, although he readily admitted he did not know how it worked. Thus, he must have had indirect reasons for believing the moon did not move in that way. He also evidently knew about illusions and the contrast of appearance and reality. He had enough feel for what an explanation would be that he knew he did not have one: Asserting that the moving moon was an illusion was not deemed sufficient. All in all, such a simple remark is full of implications concerning how much he knew about what things happen, what things do not happen, and how one explains it all. This monograph is about that naturally acquired sense of mechanism concerning the physical world and how it develops toward expert scientific understanding of physics. The ultimate goal for this work, which is approached here only very approximately, is a computationally explicit genetic epistemology that explains how experience feeds into knowledge like my son showed, which in turn, feeds later into learning school physics.

A sense of mechanism is the knowledge that provides us with the capability to:

1. Assess the likelihood of various events based on generalizations about what does and does not happen.
2. Make predictions and "postdictions." That is, one can trace entailments forward or backward in time, explaining what will happen on the basis of what is the case, and explaining what must have been the case in order for the present circumstances to exist.
3. Give causal descriptions and explanations. That is, one can look at a physical event and assign credit or blame for what happens to certain aspects of the circumstances and to general facts about the world.

Control of the physical world is one function for the sense of mechanism—being capable of taking actions so that they have felicitous consequences. But

there must be many such aspects of muscular control that are inarticulate. I am primarily interested in the pieces of our ability to control the world that can have impact on articulate reasoning and problem solving, pieces that constitute or feed into learning science.

An alternate, simple description of the sense of mechanism would be *causality*. Which events follow which others regularly, and why do they do so? I deliberately use the term *sense of mechanism* to emphasize that the picture I paint of human causality is dramatically different from many other characterizations. It involves diverse and diffuse judgments and impressions more than it consists of some small set of sharply defined and necessary principles.

I wish to chart the structure of this sense of mechanism as a knowledge system. What are the elements of the system and to what extent are they isolable? Are some of these the commonsense equivalent of physical laws? How are the elements organized? Do they cluster, form hierarchies, or settle into layers of importance? Is there a core notion of causality, even if it is not entirely localized or theory-like, or is this a profoundly distributed system? How does sense of mechanism develop, and, more important, because the motivation for this work is educational, how could it be made to develop?

To begin the exploration, consider an expert's understanding of the physical world. There are two parts of a physicist's explanation. The first, circumstantial, describes the conditions that, although they need not be the case, conspire to produce the result. It happens that one billiard ball strikes another. The second, explanatory part, is more central to our concerns. It is the physicist's sense of mechanism and involves those facts about the world that are true in more and more general circumstances as the physicist considers more and more universal and fundamental descriptions, ending with basic laws or principles that he or she holds always to be true. Balls bounce, but, more fundamental, energy and momentum are always conserved, and these determine the detailed outcome of the billiard collision. Although the most fundamental layer, here represented by energy and momentum conservation, is the most readily recognized as physics, not even physicists have time to reduce every complex event to basic principles. Instead, they accumulate a phenomenology of events, like bouncing. These events or phenomena, although not fundamental in the sense of containing laws, still have special status to the extent that they are known to happen without detailed justification at each occurrence. Light (i.e., illumination, shadows), the spectrum, radio waves, and even mechanical forces such as pushes and pulls by which means objects are moved around are all consequences of Maxwell's equations. Yet these phenomena are, in some degree, independently understood.

In the less fundamental, more "phenomenological" layers of understanding, the distinction between circumstances and explanatory principles becomes confused. This is because special circumstances warrant the encoding of particular phenomena for rapid explanation and prediction, independent of a deeper sense of mechanism that might exist. Some specialized phenomena may sometimes be

treated as self-explanatory. Everyone knows that a book can rest on a table without considering the compression of the electron clouds of the book and the table and without doing the calculation that shows, with ordinary densities of matter, it is possible but very unlikely that the book could fall through the table. Everyone knows a hot filament can be seen to glow without checking from first principles that tungsten in a near vacuum can produce visible radiation (i.e., that obtainable temperatures put the peak of the black body radiation curve in the region of human visual sensitivity to electromagnetic radiation).

The nature of the continuum from common events (which are simply known to happen in familiar circumstances) to fundamental laws (which are supposed to explain all events) is a crucial concern in this monograph. Two of my central claims relate to it. The first is that the naively developed sense of mechanism does not come close to the expert's in depth and systematicity. Instead, it is both less focused and less integrated. Although physics-naive people make important distinctions between superficial phenomenology and deeper mechanisms, these distinctions are very unlike those made by experts. For experts, phenomenology must uniformly be reducible, via an analysis of circumstances, to a few core theoretical ideas. This is not the case in the naive sense of mechanism. My second central claim is that learning physics can be viewed in significant degree as building this gradient between phenomenological and fundamental by reorganizing and prioritizing existing phenomenology. This is an epistemological claim that the development of scientific knowledge about the physical world is possible only through reorganized intuitive knowledge.

Intuitive Physics in Brief

Although there have been many attempts historically to understand the development of physical causality that relate in important ways to what is said here, one recent trend is notable. Especially during the last 15 years, a significant body of data has accumulated concerning intuitive physics, sometimes under the label of "preconceptions," "misconceptions," or "alternative conceptions" (Brown & Clement, 1987, 1989; Clement, 1982, 1983, 1987; Confrey, 1990; diSessa, 1982, 1983; Eylon & Linn, 1988; McCloskey, 1983a, 1983b; Minstrell, 1982; Roncato & Rumiati, 1986; Viennot, 1979; Vosniadou, 1989). Studies in the United States have focused largely on students in high school and early college and, at that level, tell a story of the failure of school physics to affect the fundamental beliefs of students about the workings of the physical world. When confronted with qualitative problems, most of which scarcely appear tricky or out of the range of basic understanding, students offer descriptions and solutions that are inconsistent with and often in direct contradiction to basic physics principles. *Qualitative* is an important qualification in that students may be capable of solving a problem posed in explicitly quantitative terms, yet they may think very differently when asked for a qualitative analysis of the same problem. These studies also

show that intuitive physics is quite robust—changing relatively little despite years of physics instruction. In fact, its robustness may be its most striking feature. Although the parameters of its systematicity are not well charted, it is not unusual to find that roughly 50% of students agree on the most common answer and that most of the remaining students choose from among relatively few other answers.

A simple and ancient example of intuitive physics, discussed in the dialogs of Galileo, is the expectation that a cannonball released from the top of a mast of a moving ship falls straight down, directly toward the center of the earth. Because the ship continues to move during the fall, one might reason that it moves "out from under" the cannonball, which then lands "behind" the foot of the mast. This is a misconception in that the cannonball actually falls straight down in the moving frame of the ship and mast. In doing so, it falls directly to the base of the mast (ignoring small effects of air friction and the rotation of the earth). Differently said, the cannonball starts its fall already possessing the forward motion of the ship, and, conserving that momentum, it thus keeps up with the ship's and mast's forward motion.

More subtly, one finds students' analyses that are based on correct literal descriptions of phenomena but that imply an incorrect understanding of the underlying mechanism. A novice sees that a coin tossed in the air stops at the peak of its trajectory because of balanced forces. A physicist sees only one force on the coin, the constant downward force of gravity. The upward motion of the coin after it leaves the hand perpetuates itself without external or internal forces. To many novices, satellites go in circular orbits because centrifugal force, which by itself would cause the satellite to fly away, is balanced by the pull of gravity, which by itself would cause the satellite to fall to earth. A physicist again sees only one force, gravity, and maintains that the satellite is falling (accelerating) toward the earth. Centrifugal force simply does not exist.

Intuitive physics as described earlier clearly exists, but fundamental questions abound concerning what one should make of it. One of the best known interpretations is that intuitive physics represents a coherent, even theoretical, view of the world. Michael McCloskey (McCloskey, 1983a, 1983b, 1984; McCloskey, Caramazza, & Green, 1980) is a notable proponent of this view. His ideas make an excellent point of reference, to which I refer several times. The educational implications of the view of intuitive physics as theoretical include that misconceptions can and should be confronted, overcome, and replaced by valid principles (e.g., McCloskey, 1983b). For this conclusion to be viable, misconceptions need to be relatively isolable and few in number, they need to be false or at least unproductive so that replacement is in order, and they need to be amenable to "attack" with data and argument. This monograph questions all of these assumptions. Instead, I approach intuitive physics as an expression of an underlying sense of mechanism that occasionally exhibits relatively uniform results but on the whole lacks important systematicities of theoretical science. As such, it does not need to be replaced so much as developed and refined.

Guide to the Monograph

The three central sections of this monograph—Elements, Development, and Systematicity—constitute a synthesized set of interpretations of a single empirical base. That base was obtained over 3 years, mostly from interviews of college freshmen while they took a course in mechanics at MIT. Each section has a different style of analysis. The section on elements consists of a relatively long list of descriptions of elements of the sense of mechanism, including descriptions of the contexts of their use. The section on development includes a number of case studies of the development of some concepts of Newtonian mechanics, showing how the naive sense of mechanism is involved and how it evolves. Because these case studies generally cover a broader time scale than the empirical base per se, they are necessarily more interpretive and integrating. They interpolate and extrapolate from patterns actually observed, toward important longer time-scale issues of conceptual development. The section on systematicity organizes the interpretations made to that point into arguments against hypotheses that compete with those developed here about the level and kind of systematicity one finds in the sense of mechanism.

The three central sections just described can stand on their own, especially for readers interested primarily in the empirical base. However, the section immediately following this one, Theory Sketch, develops a brief theoretical sketch to orient the reader toward the interpretations of following sections. The theory section prepares the ground for more detailed theoretical discussions to come later and also serves as a summary and overview of this work.

The section following theory concerns empirical method. It attends to how data were used to identify elements of the sense of mechanism. It may be skipped by readers interested mainly in the theoretical line or simply in results. That section should be most interesting to readers who want to know, "How do I know an element of intuitive knowledge when I see one?"

Following the three core sections, Cognitive Mechanism sketches some central issues concerning the computational genetic epistemology that constitutes the ultimate aim of this work. It deals with issues of modeling and modeling languages, explains and justifies assumptions made earlier about cognitive mechanism, and points the way toward future work by identifying open questions. It will be of most interest to artificial-intelligence-oriented readers.

The final section of this monograph offers an interpretive summary, in part by contrasting the broad approach to conceptual change in science developed here with some other recent work.

Appendix A augments the methodological comments in the text proper with two case studies for the existence and described character of certain elements. Appendix B gives a relatively complete listing of the intuitive knowledge elements discussed in this monograph and their properties. It may be useful as a review or to refresh readers' memories when necessary.

THEORY SKETCH

My program for studying humans' sense of physical mechanism centers on iden-
tifying and analyzing specific elements of knowledge. These analyses are intend-
ed to account for the "preconceptions" of students in problem solving and related
activities. On a larger scale, they are central to a genetic epistemology for com-
monsense knowledge and to the partial learning theory for school physics sketched
here. As I have done elsewhere (e.g., diSessa, 1988), I refer to the present view
of the sense of mechanism as "knowledge in pieces."

This view of physics understanding and physics learning is strongly knowledge
based. It assumes only a few very simple cognitive mechanisms, although the
resulting knowledge system is conjectured to be large and complex. Methodo-
logically, I believe it important to pursue at once a set of related issues that is
germane to theory building about any knowledge system:

1. *Elements:* Describe the size and character of the knowledge structures in-
   volved. Relevant but insufficiently precise categories are ideas, categories,
   concepts, models, and theories.
2. *Cognitive mechanism:* Provide an image of the operation of the intuitive
   knowledge system. The point is, in the first instance, to have some grounds
   for interpreting problem solving and reasoning that use intuitive knowledge.
   Beyond this, we want eventually to have a computationally explicit model
   that shows how development emerges from use.
3. *Development:* Understand the genesis and development of the system. We
   would like to understand how elements and system properties change. Pat-
   terns in those changes should, in turn, account for instructional difficul-
   ties, like the persistence of alternate conceptions, and should suggest
   instructional opportunities to enhance development.
4. *Systematicity:* Describe the level and kind of relatedness of the elements
   in the system. This includes descriptions of decompositions into subsystems
   that are both relatively integrated within themselves and also relatively in-
   dependent of other subsystems.

The central focus in addressing these issues is a hypothetical knowledge struc-
ture I call a *phenomenological primitive*, p-prim for short, having these proper-
ties (following the previous list):

1. *Elements:* P-prims are rather small knowledge structures, typically involving
configurations of only a few parts, that act largely by being recognized in a phys-
ical system or in the system's behavior or hypothesized behavior. In some partic-
ularly important cases, p-prims are themselves behavioral, or necessarily entail
behavior, which allows them to serve important roles in explaining physical
phenomena. P-prims of this sort may be self-explanatory — something happens

"because that's the way things are." In these cases, p-prims become the intuitive equivalent of physical laws; they may explain other phenomena, but they are not themselves explained within the knowledge system.

The name, *phenomenological primitive*, is meant to capture several of the most important characteristics of these objects. They are *phenomenological* in the sense that they often originate in nearly superficial interpretations of experienced reality. They are also phenomenological in the sense that, once established, p-prims constitute a rich vocabulary through which people remember and interpret their experience. They are ready schemata in terms of which one sees and explains the world. There are also two senses of primitiveness involved. P-prims are often self-explanatory and are used as if they needed no justification. But also, *primitive* is meant to imply that these objects are primitive elements of cognitive mechanism — nearly minimal memory elements, evoked as a whole, and they are perhaps as atomic and isolated a mental structure as one can find. This latter speculation is not essential to the more general image of intuitive knowledge presented here, but it helps specify a preliminary computational model.

2. *Cognitive mechanism:* P-prims act largely by being recognized. Recognition does not literally mean being seen. Rather, it means being cued to an active state on the basis of perceived configurations, which are themselves previously activated knowledge structures. One can view this recognition as occurring roughly in layers. At the top are relatively conscious ideas and concepts that involve and are cued by lower level elements, down to sensory schemata or other low-level but less directly data-driven aspects of internal state. In this very rough model, p-prims occupy midlevels. They belong neither to the lowest, possibly "hard-wired" and data-driven sensory elements, nor to the world of ideas, or named concepts and categories. Learning should provide that p-prims are activated in appropriate circumstances, and, in turn, they should help activate other elements according to the contexts they specify.

For describing the operation and systematicity of p-prims, we need a more refined model of cognitive mechanism than simply recognition. This refinement can be provided by a description of the local topology of the recognition network. The topology is based on successive activation — which elements cue which others. The way a particular p-prim's transition to an active state is affected by other previously activated elements is called *cuing priority*. High or low cuing priority indicates a stronger or weaker connection between structures that are antecedent in the cuing sequence and the recognized one. A high cuing priority means only a small additional contingent activation is needed over the described context to activate the element in question. The contingent activation is provided by other parts of the network, and the context should be described in terms of particular, relevant, and active elements. Suppression can be represented by negative cuing priority.

Reliability priority describes processing initiated by the activation of a p-prim that can more or less directly affect that element's state at future times. In other

words, it describes potential feedback that can reinforce or undo the initial acti-
vation. A high reliability (with respect to a specified context) means it is unlikely
a p-prim will be turned off by subsequent processing; it is an assertion of likely
reinforcement and unlikely suppression through all activation paths that return
to the element.

An example may be helpful. Suppose you tend to be tense and nervous in so-
cial situations. We could model this by having a tense-and-nervous element that
is cued by numerous indicators of social encounters, such as the perception of
a flock of individuals (see Figure 1). The tense-and-nervous element is related
with high cuing priority to flock-of-individuals-in-proximity. The activation of
tense-and-nervous, in turn, may have a high cuing priority in relation to panic-
and-flee. This does not mean you necessarily enact the consequences of panic-
and-flee whenever you are tense and nervous, but it means it will not take much
more to enact them. Tense-and-nervous specifies a context in which only a small
contingent cuing activation from other elements (e.g., these-are-threatening-
people) will activate panic-and-flee.

Suppose that when you might need soothing you think to look for your mother.
In this case, my-mommy-is-near? will have some cuing connection from tense-
and-nervous. My-mommy-is-near?, if activated, will initiate sensory sensitivity
or activities related to determining whether my-mommy-is-near! needs turning
on. If mommy-is-near! is turned on, it strongly suppresses tense-and-nervous.
In net, mommy-is-near? and mommy-is-near! are in the reliability loop from tense-
and-nervous; the activation of tense-and-nervous might result, via some inter-
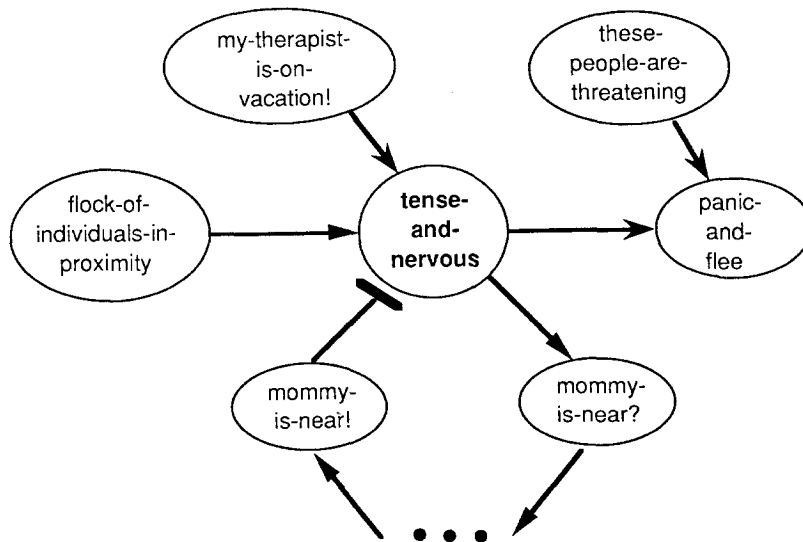

FIGURE 1   A structured priorities network.

mediaries, in turning tense-and-nervous off. Note that if you knew your mother was nearby, tense-and-nervous would already have been suppressed without the reliability loop. Alternatively, other reliability checks activated by tense-and-nervous, such as my-therapist-is-on-vacation!, could result in positive feedback, securely locking on tense-and-nervous. Tense-and-nervous will have a high reliability priority with respect to my-therapist-is-on-vacation! To summarize, the connections, weightings, and triggering levels in the network establish the details of a model. Cuing and reliability are qualitative descriptions of relations between elements in the model.

Of course, it is not good to press such a model too far with respect to the complex processing suggested in this example. However, the framework at least provides relatively unambiguous specification of possibilities for simpler systems.

Structured priorities refers to the pair, cuing and reliability. *Structured* means priorities are not global; they do not provide a general ranking. Instead, priorities are structured according to context, the state of "neighboring" knowledge elements. In circumstances where there is little chance of confusion or when I wish to make a general statement about both kinds of priorities in a fairly broad context, I will speak loosely of high or low priority p-prims without specifying reliability or cuing.[1]

3. *Development:* As mentioned before, p-prims often originate as minimal abstractions of common phenomena. In this monograph, I mostly assume that origins are relatively unproblematic and focus more on the "life history" of p-prims, especially how they might become embedded in more physics-sophisticated thinking. The development from naive to expert physical intuition is hypothesized to occur in the following ways. First, the rather large but relatively unstructured collection of p-prims present in naive individuals gets tuned toward use in instructed physics. *Unstructured* means cuing and reliability are only established in small neighborhoods within the network. Priority is local, and there may be no central and dominate elements. There may even be no sense-of-mechanism-based way to decide which of two p-prims actually should apply in a case of conflict. During "tuning toward expertise," the priority of some p-prims becomes greatly enhanced or reduced, and contexts of activation may migrate, expand, or contract, depending on the elements' new roles in the developing physics knowledge system.

Undoubtedly some entirely new p-prims are generated as the learner's descriptive apparatus changes to focus on different features and configurations in the

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[1]*Structured priorities* has little value in describing elements connected by long chains of thought. In the extreme case of several hours or even days of thought, even if the thought sequence is coherent in some sense, factors such as whether or not you managed to find the appropriate literature reference, interruptions by other tasks, along with the intrinsic instability of human thinking patterns, make cuing and reliability priorities dubious as intrinsic measures of relations in the knowledge system. They "average over" too many contingencies. However, intuitive thought operates primarily, I believe, over short intervals of coherence. Long time-scale coherence, presumably a product of persistent and/or easily reactivated elements (e.g., problem-solving strategies or goal, plan, and interest patterns), will not concern us in great detail. This is clarified in the section on cognitive mechanism.

physical world. But, a more drastic revision in the intuitive knowledge system is in the change in function of p-prims. They can no longer be self-explanatory but must defer to much more complex knowledge structures, such as physics laws, for justification. P-prims come to serve weaker roles, as heuristic cues to more formal knowledge structures, or they serve as analyses that do their work only in contexts that are much more particular than the range of application of the general or universal laws of physics. I call this reuse and integration of intuitive knowledge structures into the functional encoding of expertise *distributed encoding*. This name is intended to imply that the encoding of, for example, a physical law may be spread over many intuitive contributors that each play some small role in "knowing the law." Whereas in some cases knowledge may be packaged in explicit bundles such as propositions and formulae, invoking such bundles and unpacking their meaning in contexts of application may require a large number of specialized structures, which may be p-prims.

Accompanying this change in the function of p-prims from relatively isolated, self-explanatory entities to pieces of a larger system is a substantial structural change in the priority network. The depth, breadth, and integration of the expert's priority network marks a major change from intuitive physics.

4. *Systematicity:* Systematicity is difficult to approach for three reasons. First, no initial assumptions about systematicity are built into the theory. Second, the empirical methods used so far are better crafted to identifying elements rather than systematicities. Finally, work so far suggests that the set of physical p-prims is, in fact, rather large and loosely coupled. Nonetheless, because of its probable importance, I begin with the following a priori list of kinds of systematicity, to which I later attach appropriate examples.

A. *Mutual use:* The mere use of p-prims in dynamic sequence, or simply in relatively standard clusters, provides a kind of systematicity that can account for sets of p-prims all being raised or lowered in priority simultaneously.

B. *Common attributes*[2] *(common "base vocabulary"):* If some p-prims all involve the use of a common base vocabulary of other prims, they clearly enter into a particular relationship with each other. A specific set of attributes might provide for a kind of utility package that is frequently used and determines overall characteristics of the system, such as the salience of whole classes of phenomena.

C. *Top-down coherence:* Symbolic and verbal propositions are prominent in instruction. It is possible to view these as being learned prior to the broader coordinations in intuitive knowledge that are eventually required. This is like the way learning slogans may precede a deeper commitment to a political ideology. Learning by starting "at the top" in this way is similar

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[2]I use the term *attribute* in a very general sense as a feature of a situation, without necessarily implying strict attachment to objects, a family of attribute values, or other systematicities.

to Freudian views that take a single memorable event to organize a panoply of reactions and strategies.

The subtleties and reliability of top-down coherence generation as a developmental principle are important to understand. Most schooling seems to count heavily on explicit and literally rememberable elements. My working assumption is that this only works well within subsystems that already involve a sufficiently rich and reliable network. As a minimal specification, I would like the theory sketch developed here to be capable of expressing the difficulties in top-down development.

D. *Mutual plausibility*: The results of particular episodes of situation-specific reasoning can accumulate a kind of integration. Important elements reinforce each other or generate new elements via specific episodes of reasoning.[3] *Phenomenological syllogisms* are a class of mutual plausibilities: One may simultaneously note that "x means (implies) y, and y means z," and, therefore, encode that "x means z." For example, heavy things generally move more slowly, and if something moves more slowly, it generally takes more time to complete an act. So one may "conclude" and separately encode that heavy things take more time.

In the previous example, both premises make presumptions. Heavier things move more slowly only if the force used to propel them is the same as that propelling the lighter object. The conclusion also, therefore, makes these presumptions. The accidental failure or systematic inability to encode presumptions and prerequisites should be expected to typify low-reliability subsystems. That is, an expectation or deduction may be valid only by virtue of situation specifics that might not be encoded. Indeed, it seems empirically true that many misconceptions come simply from using an element outside its range of legitimate applicability.

The term *syllogism* suggests predicate logic, but logic is intended only as a familiar example of reasoning processes. Weaker and less conscious reasoning patterns must be involved if mutual plausibility is to account for systematicities of lower priority elements. Describing these processes, then, is central to the goal of understanding this type of systematicity. I make no presumption that these are complex, generic processes that work across a range of circumstances, say, analogical processes. Instead, they might best be described in terms of configurations of knowledge elements that lead to specific changed relations as a result of a particular pattern of use.

E. *Completeness:* A set of lower priority p-prims should be expected to be linked to some contexts in order to fill out explanations for real-world phenomenology not covered by more fundamental intuitive expectations. This class includes "excuses" for why p-prims do not work in certain

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[3]This is really a developmental principle rather than a systematicity per se. However, the resulting systematicity might be most parsimoniously described by the processes that create it.

circumstances or why unpredicted phenomena actually occur. Friction and magic may be invoked to explain otherwise inexplicable phenomena.

F. *Abstraction:* In the denser parts of the intuitive knowledge network, several phenomena may be related by having a common abstraction. If there is a core to intuitive physics, it may lie in a broad or universal abstraction common to diverse phenomenology. In general, common abstractions should have their own cuing networks, which may be expected to behave something like the disjunction of the cuing patterns of the specialized elements.

METHOD

The primary empirical base for this monograph is a series of interviews conducted over a 3-year period with students taking elementary physics at MIT. Each of the approximately 20 students was interviewed for roughly 1 hr each week during the course of first-term physics (mechanics). The sessions were audio recorded. Students were selected on the basis of (a) doing well in physics in high school (and almost all subsequently did well in their course at MIT) and (b) being reasonably competent in thinking aloud as judged in a preliminary interview. To this base, I have added the experience of informally interviewing a significantly greater number of subjects, from high school level to adult nonscientists. This seems appropriate because the nature of the enterprise is to uncover plausible structures and mechanisms, not to prove the existence of any particular one or to accumulate reliable statistics.

Data Analysis Overview

This monograph is theoretical. Its aim is to develop a framework for understanding the origins and development of commonsense knowledge about the physical world, particularly as it influences the learning of school physics. Nonetheless, data play three important roles. First, they provide the basis for abstracting theoretical ideas and a testing ground on which to refine them. The role of empirical work in the development of theory is much less discussed and standardized compared with its use in testing predictions or developing facts within well-established frameworks. But the important suggestive and refining roles of data in theory construction are undeniable. Second, data ground theory and instantiate it in preparation for further theoretical and empirical work. The principles that identify instances of theoretical objects are frequently nontrivial and need articulation and exemplification. That the notions developed here come with substantial empirical elaboration is, I believe, to the credit of the theory. Third, the particular empirical results developed here should, if the theory sketch is correct, have value in the application of the theory, for example, in instruction. If particular intuitive conceptions play important roles in the development of physics understanding, it warrants our effort to uncover and describe them.

The formal data collection phase of this work consisted of open-ended clinical interviews concerning an evolving set of problematic situations. I believe the data themselves are relatively unproblematic. They are similar to that which has been produced in many intuitive physics studies in the past 15 years. Indeed, I draw directly on other people's data to build some of the arguments here. I have added detail to my own observations roughly to the extent that I believe them to be surprising and to the extent that they are not documented elsewhere. Fundamentally, however, this is not a data-impoverished enterprise; what cleverness there is lies in the synthetic analysis.

Interpretation of the data is not as straightforward as its collection for two main reasons. The first is that the data initially served primarily for theory building. The second reason is that the theory sketch that emerged entails a number of constraints and difficulties in interpreting data that are not easily overcome. In particular, no uniform and packageable technique exists that, for example, identifies p-prims, and I do not think one should be expected. The case for each must be relatively extensive, involving diverse forms of argument.

Difficulties notwithstanding, I discuss interpretation techniques in order to put other researchers in a reasonable position to evaluate the techniques' adequacy and to help some who might choose to pursue similar analyses. I do this first by explaining some of the in-principle limitations that emerge from the theory. Then, I provide a list of heuristic principles on the basis of which cases for the existence and proposed character of individual elements may be made. Identifying elements and their characteristics is the core of the contribution that data make here. Extrapolation to system properties and development are made on the basis of elements, with comparatively little direct empirical input to these other issues. Finally, I also provide case study arguments about the existence and character of particular p-prims that can be made on the basis of my list of heuristic principles. These case studies appear in Appendix A. Readers will find them more comprehensible after the examples used in the appendix are presented in the text proper.

Difficulties in Empirical Investigation of P-Prims

Micro-events.   P-prims are, in general, rather small and particular knowledge elements among a large collection. Their application may be fleeting, and a particular element may seldom apply. Even less often will a p-prim, in isolation, direct the flow of problem solving, except locally. More likely, p-prims will be used in clusters or in combination with other kinds of reasoning.

Nonbehavioral.   Problem strategies, goals, and plans organize substantial action patterns in ways that are, comparatively speaking, transparent. Means–ends analysis determines patterns of search for operators, and it determines conditions of satisfaction. P-prims entail no such general patterns. Their content is not

specifiable in advance, for example, by abstract task analysis, and reasoning that follows up a p-prim activation will likely depend delicately on the problem situation and the subject's mental state beyond the activation of that single p-prim.

A p-prim that accounts for a subject's satisfaction with a part of his or her problem-solving state is unlikely to be commented on; in its firmest application, a p-prim will be treated as self-evident. A p-prim that accounts for an unease and motivates continued consideration still does not determine, of itself, much about how improved understanding is sought.

Inarticulate. P-prims are not strongly related to dictionary lexicon. Much less do they have explicit propositional form. I presume that conscious access to their application is very limited, mostly localized in satisfaction or dissatisfaction with a current state of understanding. Subjects may make predictions on the basis of a p-prim, but the prediction is not the p-prim.

Unfamiliar vocabulary. Rather than relating to linguistically sanctioned attributes, p-prims are likely to have been abstracted, for example, in terms of body sensations and internal sensorimotor terms. Not only does this contribute to subjects' inarticulateness, but it also means that, as theorists, we have a much tougher job finding adequate descriptions.

Ultimately, we must describe these mental objects in terms defined by the rest of the knowledge network that cues and follows up on a p-prim's activation. Otherwise, we will fail to discriminate the contexts in which a p-prim will actually be used from less relevant external characteristics of the problem context or less relevant characteristics of the particular use of the p-prim. This puts a heavy burden on completeness and on the precision of the theory of operation of p-prim networks. Interfaces to language and other reasoning capabilities may eventually need to be described.

Bootstrapping problem. Fundamentally, it is an individual's extended experience with the physical world that determines what particular p-prims exist. These are not specified in advance by the theory. So validation through establishing systematicities among elements and continuities in development depends on getting the elements right, not just their generic properties. There are few strong "dataless" predictions to be made.

A sociological argument. The diversity of empirical claims relating to intuitive physics in the existing literature is impressive. There is no agreement on terms of description, much less on particular elements. Intuitive physics is described as a theory, a systematic but alternative framework, or a series of isolated misconceptions. Intuitive explanations may even be treated as noise on the central problem of building expertise and, as such, ignored. See Smith, diSessa, and Roschelle (in press) with regard to these different treatments. The

diversity of views on intuitive conceptions calibrates the job before us. My judgment is that, before any firm empirical agreement can be fashioned (or simultaneous with it), we need an ontological agreement on the form of knowledge that common sense and intuition represent.

All of this motivates theory building as a response. It is only in this way that the foundation for cumulative empirical work can be laid and that a breadth of observations can be coordinated to draw sharp and firm conclusions. Like the discovery of electrons, I do not think concepts such as p-prims will be confirmed by fine methods that "observe" them. Rather, confirmation will evolve if the developing theory finds broad application and success.

In summary, the sense of mechanism is, by hypothesis, rich, diverse, delicate, inarticulate, and (in many ways) rather unsystematic. It probably contains "meaningless" elements, by ordinary standards of meaning. Unreliable and sparse knowledge systems (terms that are developed more systematically later) are remote enough from everyday vocabulary and commonsense epistemological terms that critical experiments and refined observational techniques are, by themselves, extremely unlikely to do the job that needs to be done.

Heuristic Principles for Identifying P-Prims

Despite the difficulties enumerated, I believe there are opportunities to build relatively firm empirically based accounts of p-prims. Again, the core task is to bring data and arguments of various sorts to bear on the nature of individual p-prims. I use data in the verbal protocols to build a case for each p-prim. Subjects' spontaneously proposed predictions and explanations are critical data. Evidence concerning satisfaction with a particular description of a situation and the predictive implications of those descriptions (e.g., confidence or, alternatively, ambivalence or search for alternatives) is also particularly important in establishing priorities. Many times I describe data as generalities about predictions and explanations. These are comparable to typical epidemiological results of misconceptions studies that report correct and incorrect answers and sometimes also report suggestive explanations produced by subjects. Population frequencies, however, are not relevant to the arguments made here. Sometimes I use particular critical instances or citations from protocols to make more particular points.

The cases that emerge concerning individual p-prims need criteria for judgment, which are provided by the principles that follow. If a case is strong by many or most of the criteria, the proposed p-prim should be considered validated. If it is weak, the case may be improved by reformulating it in view of its particular weaknesses, proposing alternative interpretations, and evaluating those.

I will not belabor the ways in which these principles reinforce each other and follow from the theory sketch. To help make connections with what follows, however, I anticipate some results in the context of the principle that gave rise to those results. Most of the principles are two-edged. They both judge proposed

p-prim descriptions and propose strategies to uncover other p-prims or better descriptions.

Principle of obviousness.   The familiarity and unproblematic nature of some physical events needs explanation. In the present context, this usually means they need a p-prim to attach to them. In general, p-prims establish abstract classes of unproblematic happenings. This is the opposite of misconceptions research strategy, which never analyzes "correct" intuitions. The principle of obviousness gains explanatory power in conjunction with the principle of invariance (to follow); having understood p-prims underlying common events, we may be able to understand subjects' reactions to uncommon events using those same p-prims.

Principle of impenetrability.   P-prims are relatively primitive in an explanatory sense. This is the primary sense of *primitive* in *p-prim*. If people are satisfied making an explanation by asserting a description, this likely indicates a p-prim. In contrast, we must recognize that people can sometimes form complex explanations, for example, of devices using mental models in a more or less articulate way. These explanations may hint at many p-prims along the way but are unlikely to display p-prims directly in the presented explanation. The principle of impenetrability is limited by the fact that p-prims may frequently be only relatively primitive. That is, some reliability loop may lead to finding other explanations — other p-prims, combinations of p-prims, or more macro-explanatory systems.

Principle of diversity.   I believe there are many p-prims. So, heuristically, it makes sense to retain a skeptical stance toward unification. Attend to nuance. The principle of diversity is limited in that taking each instance of felt-to-be-explanatory analysis to entail a different p-prim undermines the very function of p-prims. Again, see the principle of invariance that follows.

Principle of coverage.   The breadth of common experience must be covered by p-prims. Misconceptions approaches generally fare badly by this criterion. It is easy to find situations that have nothing to do with misconceptions listed in the literature, in which people have no trouble predicting or explaining. The principle of coverage especially critiques reductionist programs that see physical intuition to reside in small sets of principles that cover only a schooled class of problems, such as trajectory problems. In contrast, phenomenographic analyses (Marton, 1981) are more consonant with the principle of coverage.

The principle of coverage several times led me to discover new classes of p-prims. For example, constraint p-prims (p. 133 and following) emerged in consideration of obvious situations, such as why a book rests comfortably on a table. Subjects also gave accounts of other situations, such as why a ball follows a particular constrained path, that appeared not to involve already-cataloged p-prims (or listed misconceptions). Similarly, problems such as an orbit around a square

planet (p. 165) initiated consideration of figural primitives as a class—those that result from attending to overall spatial form, for example, of trajectories.

Principle of strong vocabulary.   P-prims probably cluster in areas of strong descriptive (representational) capability. Indeed, they may be classified by such vocabulary. For example, figural primitives (p. 165 and following) contrast with interactive ones: p-prims of observation versus p-prims of participation. The following two principles suggest that thinking about the origins of p-prims can help identify them.

Principle of unproblematic genesis.   Generally, there should exist common events in which a p-prim might archetypically be used and from which it may plausibly have been abstracted. This involves both the "vocabulary" available for abstracting the p-prim and the availability of common events that may be governed by the p-prim. Functionality (discussed later)—that invoking a p-prim is more than simply feasible; it is also likely useful—is important with respect to genesis. The principle of unproblematic genesis is limited by the fact that p-prims might be abstracted in one class of situations and migrate to others.

Principle of the body.[4]   This is a specialized principle of strong vocabulary (as just discussed) and continuity (discussed soon). P-prims are likely to be

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[4]This heuristic is too close to a program of studying meaning advanced by Mark Johnson (1987) not to remark on the similarities and differences. Johnson is centrally concerned with how meaning emerges and extends from bodily experiences in the same way I believe experiences—prominently, but not exclusively, bodily experiences—form the basis of naive causality and, eventually, of the expert causal sense as well. Three of the central chapters in Johnson's book deal with issues of force, issues of balance, and spatial organization and constraint, roughly parallel with the subsections of the Elements section that describe different classes of basic causal p-prims. I do not pursue a detailed comparison here. There are, however, three central differences between our points of view. First, Johnson is interested much more in "horizontal" issues, that is, how meaning extends across multiple domains. I am primarily interested in the details of meaning within a selected domain (i.e., mechanical causality). In addition, a fundamental dimension for me is "vertical." The pursuit of deep explanations and the relations of shallow to deeper explanations are critical. Johnson deals with descriptive phenomena—how one describes events; I deal, more centrally, with explanatory ones—why things happen. Second, Johnson is not very concerned with what is here most central, change. How are some conceptual changes blocked or impeded, and how are some open and awaiting either particular moves of instructors or particular problem-solving or explaining experiences? In particular, I attend to what happens to naive causal schematizations when they are changed and incorporated into expert scientific understanding. Third, Johnson has a vested interest in denying the existence of abstract (or simply "logical and rational") schemata. Instead, he concentrates on dynamic flexibility and metaphorical extension. These are processes that he claims explain broad use. In contrast, my view is that p-prims may apply broadly (and may be the root of metaphorical or analogical transfer), in part because of their highly schematic nature. I am less interested in accounting for the full nuance of meaning and descriptive capability. I am more interested in the details of specifically explanatory schemata. I am not directly concerned with how words collect and combine senses or p-prims, or with how the felt-to-be-explanatory core of certain domains, like mechanical causality, is similar to and different from the cores for other domains, such as law or reason.

abstracted in internally evident terms, especially early in development. Thus, agency, (muscle) tension, and so on are likely to be represented in important base vocabulary for p-prims. The following two principles suggest that considering how p-prims are used can help identify them.

Principle of functionality.   This principle emerges from the presumption that the sense of mechanism, intuitive causality, evolves to serve individuals in dealing effectively with the physical world. P-prims that are "wrong" (by school standards) are very likely to be better understood if they are described in terms that make evident contexts of useful application. Naturally, such application should conform with the principle of ready availability (discussed next) and may benefit from use of the principle of strong vocabulary.

Principle of ready availability.   One should be able to understand how a proposed p-prim applies to any of its situations of use on the basis of relatively ready intuitive representations of those situations. This depends critically on vocabulary, as discussed before, but also entails analysis of particular situations in those terms.

The next two principles have to do specifically with how the time-sequenced use of different explanations—in an interview, across months of instruction, or years of development—can be brought to bear for identifying p-prims.

Principle of continuity.   A fundamental constructivist principle is that new knowledge arises from old. Similarly, p-prims evolve from earlier knowledge so that earlier knowledge provides good hints for later. Understanding the genetic path of a p-prim can help explain aspects of its character that are not otherwise evident. Thus, data on children's conceptual development are especially useful. See also the principle of scavenging data.

Principle of dynamic.   The evolution of subjects' explorations in an interview can give very important information about p-prims. It is not only the first or final reactions that are relevant. First answers must make use of the most ready vocabulary, especially if they are firm. P-prims of generally high priority may be evoked ("things that usually work" are almost always a good guess to start with), then retracted on closer consideration of the situation particulars. Later descriptions are indicative of reliability in the context more than they are indicative of direct and simple cuing. Paths taken by subjects between initial and final stances may indicate which features of the situation, gradually uncovered, lead to the cuing or reliability judgments involving particular p-prims. In addition, many system properties are implicated in such explorations. For example, alternative explanations that are considered help the researcher determine the aspects of situations attended to; they may show richness or sparseness of the set of p-prims that apply to a context; and they may show reliability considerations in

subjects' "competitive argumentation." In general, I found first answers almost never exhausted the ways people could think about the situations proposed. The dynamic was frequently extensive and informative. The following methodological principles are very general. However, especially the first two have particularly apt application to uncovering p-prims.

Principle of invariance.   This is a general principle that, if one gets a description right, the p-prim (or any theoretical construct) will apply in all implicated contexts. So if a p-prim appears to be used in situations in which it is not evidently applicable for us as theorists, some redescription of the p-prim may be in order. Similarly, if a p-prim is not observed to be used in a context in which it should be, given its current description, problems in the p-prim description are indicated. The principle of invariance is particularly apt and strong for the present theory because of the importance and difficulty of getting the basic description of p-prims correct. Strong evidence is provided when one can invent situations in which the predicted application of a p-prim leads to surprising behavior (e.g., predicting "misconceptions"). See the principle of discrepancy, discussed shortly.

Principle of diverse evidence.   This is related to, but more general than, the principle of invariance. Different problems in which a p-prim is used triangulate on its properties. This principle is sometimes difficult to apply to p-prims because the diversity of the knowledge system makes it difficult to craft new situations that cleanly implicate a target p-prim.

Principle of redescription.   In sparse knowledge systems, it is important and difficult to get the descriptive frame right. Commonsense vocabulary and intuitively ready characterizations seldom suffice. Thus, tuning and competitive argumentation concerning multiple descriptions of a p-prim can optimize coherence with other principles.

Principle of scavenging data.   The human sense of physical mechanism is hypothesized to apply to almost all familiar and unfamiliar physical contexts. Although they might not be ideal for analysis, the predictions and explanations made by people for almost any situation are relevant to the theory. There is no need for highly refined and idiosyncratic experimental setups. Thus, data from large numbers of reported experiments, if reinterpreted, can contribute to the analysis of p-prims. For example, data from many of Piaget's books, before reinterpretation into his theoretical framework, can provide valuable help. Also, many misconceptions and alternative conceptions studies have been useful, such as those of McCloskey (1983a, 1983b), Roncato and Rumiati (1986), Viennot (1979), and Clement (1982, 1987). Again, this is not a data-impoverished enterprise, and use of others' data highlights the importance of the theoretical frame.

Principle of discrepancy.   Evidently when people give nonphysics explanations or show nonphysics expectations, there is a good opportunity to uncover explanatory roots in p-prims. This is basically *the* methodological principle defining misconceptions work. However, the principle of discrepancy does not override the principles of obviousness, unproblematic genesis, and functionality; p-prims must cover ordinary cases, must be plausibly abstracted from available experience, and must be useful to individuals.

The principle of content over form.   P-prims are content-based analyses. This view of human causality implicitly denies that it lies in some small set of universal forms, in analogies, or in the application of mappings judged by purely structural criteria (Gentner, 1983). Thus, p-prims cannot be removed from an analysis in favor of general processes such as analogical reasoning. This perhaps contentious principle anticipates a longer discussion in the Interpretive Summary section that compares this work with others'.

ELEMENTS

The Basic Force and Motion Cluster

The range of phenomena covered by the intuitive sense of mechanism is not obviously that of any scientific theory, for example, Newtonian physics. Nonetheless, it seems that intuitive knowledge is relatively rich in the vicinity of Newton's laws. This richness may well account for the robustness that shows up in students' difficulties in changing their intuitive physics to accord with textbook physics. The first subsection that follows deals with what seems to be the core of this richness. The p-prims involved are adequate to account for many well-known misconceptions concerning the dynamics of objects in trajectories, as I describe especially in the Interpretive Summary. This first cluster prominently features intuitive attributes having to do with an individual's personal and kinesthetic sense of agency.

The second subsection that follows deals with situations that are handled, by and large, without invoking agency. Instead, constraints posed by geometric configuration of objects have direct causal implications. This turns out to be the root of an instructional problem explored in the Development section. In sketch, students invoke a strong agentive causality in learning physics, but that causality must be modified in two important ways: (a) It must be extended to cover phenomena that are seen initially as nonagentive, and (b) the agent–patient relation must be symmetrized to effectively encode Newton's third law.

The third and fourth subsections that follow deal with balance and equilibrium. These involve a still more abstract and mathematical cluster of p-prims that concern the causal implications of symmetry and asymmetry. As does the sub-

section on constraints, these two subsections concern the implications of the naive sense of mechanism in many situations that are not handled in the misconceptions literature.

In this and following sections, I use italics to denote p-prims. I systematically note, parenthetically, observations that relate to the various types of systematicity listed at the end of the Theory section. It is convenient also to extend some remarks here briefly to related points about development. More extensive comments on systematicity and development are reserved for their own sections, which follow this one.

Force and Agency Elements

Ohm's p-prim.   I begin with a prominent and richly connected element that I call *Ohm's p-prim*. It comprises the following subentities: an **agent** that is the locus of an **impetus** that acts against a **resistance** to produce some sort of **result**. The major function of this element is to provide for activation (Systematicity A, mutual use) of a set of qualitative relationships among differentials in the effort of the agent (amount of impetus), the resistance, and the result: More effort implies more result; more resistance implies less result; and so on. The assumption is that activation of *Ohm's p-prim* attached to particular circumstance allows one to use these qualitative proportionalities as needed for prediction and explanation.

Ohm's p-prim can be abstracted from any number of physical experiences, such as pushing objects. It serves the fundamental functions of (a) allowing one to modulate appropriately one's effort and (b) explaining why that modulation is needed and effective. One pushes harder to move heavy objects, which "resist" motion more. It is plausible that this p-prim evolved out of and extends the usefulness of completely inarticulate capabilities to respond appropriately to tasks requiring different amounts of exertion. Thus, *Ohm's p-prim* may be a common abstraction over a broad range of already competent sensorimotor schemata. How much knowledge appears in compiled form and is only later abstracted into felt-to-be explanatory schemata is an important and open question.

Ohm's p-prim also seems to interpret intellectual and interpersonal relations, such as trying harder and influencing, in addition to directly physical situations. In these latter cases, as in cases in which *Ohm's p-prim* is invoked to serve explanatory purposes, purely sensorimotor schemata are inadequate to account for familiar human competences.

A situation fabricated to elicit *Ohm's p-prim* clearly is the case of a vacuum cleaner that is switched on, and then its intake nozzle is covered. Subjects are asked whether the pitch of the motor goes up or down, and why. In the vacuum cleaner, the motor is a model impetus; indeed, agency in the weak form of an initiator of motion is undoubtedly a coordinate attribute, that is, an attribute connected with a high cuing priority to motors. (Coordinate attributes are a particular subclass of Systematicity A, mutual use.) Covering the nozzle is an interference

(imposed resistance), which leads some subjects to predict a reduced result (corresponding to slower speed and lower pitch); the motor should slow down and emit a lower pitch.[5] An alternate interpretation of the situation begins with the same basic interpretation, but it adds a seemingly anthropomorphic feedback loop, that an increased resistance provokes the motor to work harder to compensate.[6] In this case, higher pitch is interpreted as representing the greater effort. *Working harder* is likely an independently encoded p-prim that people may recognize directly in the increase in pitch resulting from the blocking of the hose. Then *Ohm's p-prim* and the anthropomorphic tendency to work harder when resistance is increased justify the use of *working harder*. Some subjects use *working harder* to justify their prediction that the vacuum cleaner emits a higher pitch, and some use it to justify increased pitch in retrospect, when told that the blocked vacuum cleaner emits a higher pitch.

What is actually happening is the opposite of both interpretations. Putting one's hand over the nozzle causes the mechanism by which air is pumped, using energy from the motor, to stop working. (Much less air strikes the blades, but instead the air near the blades turns with them.) With *less* work to do, the motor speeds up. Thus, this particular interference actually decreases resistance. Readers should be aware that this explanation amounts to little more than yet another application of *Ohm's p-prim*, although this one has the property that it can be refined straightforwardly into a legitimate physics explanation.

From a physicist's point of view, the intuitive attribution of resistance to covering the nozzle has no justification; a specific mechanism is needed connecting that act with any force felt by the motor. Intuitively, however, covering the nozzle is sufficiently resistance-like to evoke *Ohm's p-prim* with that resistance modulating the result of the impetus of the motor. No more specific reliability loop appears to be needed.

Agency and related notions such as **patient** and **effort** seem to comprise a fundamental set of attributes at the genetic roots of intuitive physics (Systematicity B, common attributes). Anthropomorphic and animistic phenomena provide explanation for many things for many naive physicists, not just children. Working harder, for example, is seen in the vacuum cleaner by some adults as well as children. Although agentive phenomena seem collectively to fade in priority with developing expertise, still the genetic influence of these ideas is powerful.

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[5]This interpretation probably forces us to see the impetus as residing in the motor, but not to coincide with its motion: Motion is a *realized* impetus. The alternative is seeing impetus directly in the motor's motion. I will not try to settle the question of which way *Ohm's p-prim* applies. Indeed, it may be that the recognition of *Ohm's p-prim* does not imply that the subject has selected an unambiguous interpretation. A p-prim may be cued without firm binding of its "slots." Not discriminating close interpretations and inability to localize attributes such as agency are typical of the kinds of limitations I posit for intuitive physics. See Appendix A for further discussion.

[6]In this case, the linking of impetus directly to motion of the motor seems more plausible than linking it to the hidden cause of that motion.

Agency orients thinking about the most fundamental ideas of physics long into university instruction. Particular elements built directly on agentive phenomena, such as *Ohm's p-prim*, find their way into the working vocabulary, if not into the fundamental beliefs of expert physicists. Further comments on agency are found in diSessa (1983), and I return to the topic later in this monograph, particularly in the section on development.

Resistance.   *Spontaneous resistance* to forces and influences is a phenomenon separable from the imposed resistance in the vacuum cleaner. The distinction is in the locus of agency. *Spontaneous resistance* resides in the patient of an action, in the mass that is pushed or pulled, not in an external agent that imposes an interference. *Spontaneous resistance* sometimes provides the reason for the returned pressure felt when a force is exerted on an object (sometimes called "reaction force"). For instance, it explains why a string gets taut when used to pull an object: The object resists motion. Lighter objects, of course, exert less resistance and thus allow greater result (faster motion). In this schematization, two impetuses, a thrust and a resistance, interact competitively to determine motion. In a Newtonian schematization, force is modulated by an entity that does not have the same agentive status—an inert mass.

Plausibly, *resistance*'s roots are in personal experiences of reacting against an external agent. If this is the case, however, a fairly early refinement over a blatantly anthropomorphic agency, reacting to counter a force, is indicated in some situations; children will often vehemently deny that the wall is pushing back when they push on it, admitting only that it is resisting. Adults almost certainly have both interpretations available: People may resist (actively); objects can resist (passively). The difference is that further expectations about the internal state of the resistor (e.g., its level of effort and that it may cause motion) follow from active resistance but not from passive resistance. Surprisingly, some adults may occasionally see very active resistance in inanimate objects; an object resisting the tug of a string may leap backward if the string is cut, as may happen to a team in a tug of war if the rope breaks. The active–passive distinction in a patient seems to be marked in lexical items such as "constrain" (passive) versus "restrain" (active).

Unlike *resistance*, many phenomena seem not to have active interpretations associated with them. *Blocking* (what a heavy brick does to a hand striking it) and *bouncing* impute no agency, but are kinematic, as it were, describing phenomena visually and geometrically. That is to say, these latter phenomena may be abstracted from situations of observation rather than participation, and one can maintain that an object blocks or causes bouncing without any sense of effort or strain in the object. More on bouncing appears in diSessa (1983). I turn in earnest to this class of kinematic p-prims in the next subsection.

I believe successful resistance, what a sturdy wall offers to a push, is encoded separately from the unsuccessful variety that a ball typically exerts in reaction

to a tug on a string. The argument for this conclusion is based, in part, on the general importance of distinguishing an agent's winning from losing in situations of conflict, such as when the tendency toward rest of an object at rest conflicts with an imposed tendency toward motion. Later I discuss schemata such as *overcoming*, whose existence reinforces the idea of such distinctions. More directly, Talmy (1988) described a large cluster of apparently important language-based schemata that center on success–nonsuccess judgments. The implication of strongly encoding the distinction between success and nonsuccess situations is that people should be in very little danger of confusing the two classes, say, in recalling an event.[7]

Force as a mover.   Pushing an object from rest causes it to move in the direction of the push. The p-prim abstracted from that behavior, at that level of detail, I call *force as a mover*. To a physicist, the at-rest condition is an important precondition to the alignment of push and resulting motion. However, it appears this is not true of naive individuals. This leads to various nonphysical expectations, exemplified in the extreme by the universally counterintuitive nature of gyroscopes; it is perplexing that gyroscopes do not go in the direction you push them.[8] See also Clement (1982) and Viennot (1979) for misconceptions involving this primitive. A perspicuous setting in which *force as a mover* strongly asserts itself is when students are given control of a computer-implemented Newtonian object, a dynaturtle (diSessa, 1982), whose movement they attempt to control by applying pushes to it. The turtle is Newtonian in the sense that it obeys Newton's laws, traveling in a straight line with uniform speed when not pushed and obeying Newton's second law when pushes are applied. The almost universal expectation of elementary school students and of many undergraduates and naive adults is that the turtle should always move precisely in the direction of the last push. Instead, pushes actually add to the existing motion to produce what might be described by a p-prim, *deflection* (see Figure 2).

It helps to say what is not attended to in *force as a mover*. The process of acquiring speed is irrelevant to the *force as mover* sketch, which prescribes only directed intervention and result. One sees this reflected in protocols that describe a tossed coin, where students agonize over the details of change of speed in the air but accept the toss itself as primitive (see diSessa, 1988).

Expert physicists use *force as a mover* as a useful shortcut in simple situations. It would be bizarre to suggest that physicists need to access formal means

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[7]I did not obtain convincing protocol data to support the separate encoding of successful and unsuccessful versions of resistance as opposed, for example, to two separate attributions—one of resistance and one of success–nonsuccess. In the same way, active and passive versions of resistance might be combinations of independent attributions. Better data and argument are needed to settle the issue.

[8]It is more accurate to say a gyroscope does not turn in the direction you twist it. See *force as a spinner*, discussed shortly.
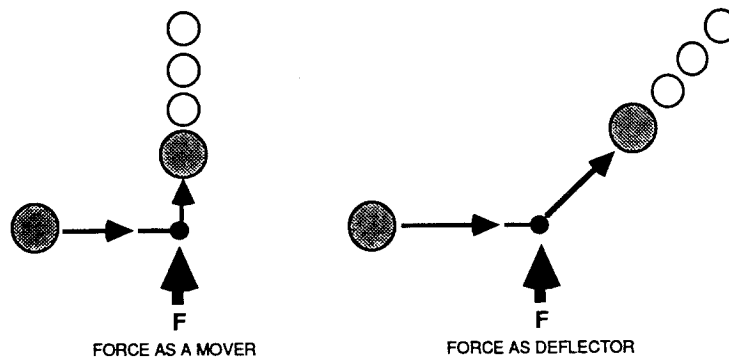
FIGURE 2   Alternative models of a shove's effect on a moving body.

to predict that an object, when pushed from rest, moves in the direction of the push. The difference between novice and expert use is that the expert priority system "knows" much better when to and when not to use that intuition.

Ohm's p-prim applies to the relations between the agent's effort and its result in situations where *force as a mover* applies. More push means more resulting motion (greater speed or more distance). Here, the resistance slot in *Ohm's p-prim* is occupied by the *spontaneous resistance* remarked on earlier and is usually taken, effectively, to be proportional to the weight of the object.

Force as a spinner.   Young children often know that pushing an object off-center causes it to spin. This phenomenon is, in many respects, the rotational version of *force as a mover*. The cuing priority of *force as a spinner* is greatly heightened in cases of circular symmetry or by other suggestions that the issue is one of circular motion. As is true with most p-prims, context determines whether this or competing p-prims are applied, not articulable applicability conditions or general methods of conflict resolution. In the case of the yo-yo shown in Figure 3, most subjects will simply see that the issue is one of spinning, although there is nothing particularly circular about a pull to the right. They will predict that the yo-yo will spin counterclockwise and, hence, that it will roll off to the left. A few will admit that, because the object is being pulled to the right, it might move to the right—an apparently simple application of *force as a mover*, which
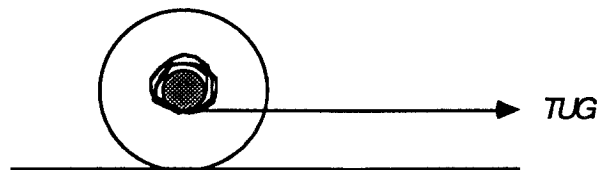
FIGURE 3   *Force as a spinner* predicts the yo-yo spins counterclockwise and rolls to the left. It actually rolls to the right.

provides a correct prediction in this instance. Almost no one who senses both possibilities has any way to decide which applies. Again, p-prims are relatively primitive; there are, in general, no methods or more reliable knowledge elements to decide conflicts.

Continuous push.   A p-prim related to *force as a mover* is *continuous push*, abstracted from, say, continuously pushing a cup across a table. The important features are a caused motion and a persistent intention (i.e., force) that causes it. The engine in an automobile cruising along is interpreted as the cause of motion in this way. (If there is no directionality attributed to the push of the engine, this situation probably reduces to *Ohm's p-prim.*) In a Newtonian view, neither the hand pushing the cup nor the engine is an ongoing cause for the motion. (The hand and engine are supplying energy but not motion in any direct way. The effect of forces is, at best, acceleration, not velocity.) Motion perpetuating itself with no intervention is the physical notion of momentum, and, in fact, Newton's laws require that there be no net force on an object if it is traveling at a uniform velocity. Again, *Ohm's p-prim* interprets the relationship between push and resulting motion in a *continuous push*.

Several important points about p-prims can be illustrated in the comparison of *force as a mover* and *continuous push*. They are both linked with high cuing priority to *Ohm's p-prim*. Beyond similar connectedness in the knowledge system, these p-prims are obviously very similar in internal structure: (a) They involve the same physical configurations of agency, intention or effort, and patient, and (b) the mental representation of the intention and the result may be made in the same geometric vocabulary. These similarities may be represented in shared abstractions of, in the first case, realized interventive intention and, in the second, a particular geometric directedness, the direction of intention and result. Possibly, the two p-prims even have a single common abstraction (Systematicity F, abstraction), a scenario of directed intention and its realization. Richer areas of intuitive physics can be expected to be redundant in this way.

The distinction between *force as a mover* and *continuous force* is one of pattern of effort. *Force as a mover*, having been abstracted from throwing or boosting situations, involves a burst of effort, then relaxation typical of a shove or throw. (The term **push** is somewhat ambiguous with respect to pattern of impetus; **shove** is not so much so. **Strike** indicates a very brief [violent] shove.) *Continuous push*, obviously, involves relatively constant amplitude. What is implicated generally is a vocabulary of time-dependent amplitudes such as those that athletes must be particularly adept at recognizing and reproducing to tune their efforts. Although personal effort is the most obvious place from which these patterns may be abstracted, they or related patterns must play an important role in interpreting speech (prosody), in dramatic tension in plays and stories, and, even more, in music. Consider an orchestra conductor expressing patterns of volume through muscular tension and physical actions such as punching or gentle waves, actions

that characteristically involve certain patterns of amplitude. It is more than that these acts demonstrate the pattern but that, as they become conventionalized, the pattern expressed is reliably cued as a coordinate attribute of the acts.

Rapid change of intensity, especially with high peaks, is a pattern that one might call *violence*. Aristotle took this to be a fundamental distinguishing attribute in his physics, separating violent or forced actions from natural ones. An object thrown (*force as a mover*) is very likely to be seen as having been imparted a force that will carry it along on its own. An object carried along (*continuous force*) is in a passive relationship to its motion, receiving it on an ongoing basis from its carrier. McCloskey (1983a) documented that carried and thrown objects are perceived differently. In the Interpretive Summary, I return to place this phenomenon more carefully in the present frame.

It goes without saying that patterns of amplitude play a minimal explanatory role in pure Newtonian mechanics; thus, a development is required for expertise that results in common interpretations of naively disparate situations. Any moving object must come to be perceived as having momentum, whether or not it moves as a result of violence.

Violence cues *strength* (the potential for great impetus) with high priority. Strength is an attribute that seems to play an important role in early thinking about the physical world. It also evidently has an interesting spontaneous developmental history in view of the fact that adults have a much more articulated notion of strength than children. For example, we find in Piaget that children sometimes appeal to weight to explain both the sinking of dense objects and the floating of big ones like ships. In the latter case, I infer an intermediary: Big things are strong (strong is a coordinate attribute to big), and strong things may do as they wish in conflict situations, as when gravity "wants" them to sink. In another situation, consider the response of my younger son at age 6 in reacting to a query about why a magnet can attract metal through paper: "I guess the magnet is stronger than the paper." (In relation to such explanations, see also the discussion of simple conflict schemata in the discussion of *dynamic balance*, which follows, and later on in the discussion of *overcoming*.)

To hint at some of the development that must take place in changing strength from a global attribute that explains much about what happens in any situation of conflict to a much more restricted one, consider my other son's spontaneous comment (also at approximately 6 years of age): "I figured out why machines are stronger than people. It's because machines are metal, and people are plastic." Indeed, strength is often not a primitive explanation for overcoming or other conflict resolutions in the adult sense of mechanism. Instead, conflict resolution may depend on particular aspects of the conflicting situation (e.g., geometric aspects such as leverage or positioning) or on intrinsic characteristics of the actors (e.g., the strength of the materials of which they are composed as opposed to their agentive strength or power). Corroboration of the importance of *strength* and generally simple resolutions of conflict such as overcoming is offered by linguistic structure (Talmy, 1988).

Dying away/warming up.   Everyone recognizes the phenomenon that earthly motion essentially always dies away. Although it can be explained with notions such as friction and dissipation, *dying away* is often taken intuitively as a primitive. This p-prim is essentially the stipulation that a certain pattern of amplitude (gradual diminuendo) is natural for a particular class of amplitudes (actions by inanimate objects that are not subject to continuous influence). Novice adults often treat *dying away* as a relative primitive. That is, they will often be satisfied with an explanation that does not have any particular cause for the dying away. But if their attention is drawn specifically to the issue of dying away, they may seek causes such as the interference of gravity or friction. This responsiveness to the need for deeper explanation exhibits a gradient in their sense of mechanism (toward more reliable descriptions), albeit not a steep or reliable one.

The situation of bringing an object up to speed, like a car accelerating, seems to be the occasion for abstracting a *warming up* primitive—that it takes some time for any result quantity to reach its final value when a change in impetus takes place. Put more succinctly, change takes time. The *warming up* to speed in a toss is precisely the phase accepted as unproblematic in a toss. Although weaker than *motion dies away, warming up* is sometimes applied in inappropriate contexts such as the change of acceleration given a change in force on an object. Some students believe the acceleration that a force causes in an object, especially if it is very rapid, continues for a time after the force ceases. To a physicist, change of force is instantly realized in a change of acceleration.

Constraint Phenomena

For a physicist, *bouncing* (a moving object impinges on a fixed one and rebounds), *blocking* (an object's tendency toward motion is thwarted by another object in its path), and similar constraint phenomena such as *supporting* (blocking, where gravity is supplying the thwarted downward impetus) or *guiding*[9] (such as a tube does to a ball moving inside) must be reduced to the action of forces. They cannot be appealed to as primitive explanations. Naively, these phenomena are known to happen in their respective circumstances and need no explanation at all, let alone an explanation in terms of a force-like interaction. When these expectations are questioned, naive adults appeal to justifications that sound more logical (essentially *reductio ad absurdum*) than mechanistic: "It would be absurd for the ball to penetrate the wall of the tube." Within the naive sense of mechanism, impenetrability can be taken to be a mechanical explanation, but it is not primitive in a physicist's world view.

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[9]The use of standard lexical terms to describe p-prims may invite the misinterpretation that p-prims are the conventional meanings of these terms. In general, p-prims are a good deal more specific than word meanings, possibly closer to individual senses of words. Readers should treat p-prim names simply as mnemonic labels for particular abstract scenarios rather than taking natural language meanings too seriously.

Clamping (holding fixed) shows plainly the need for complex reasoning in order to reduce many common phenomena to a physicist's level of fundamental explanation. Within the naive sense of mechanism, the idea that an object sandwiched between two opposing forces is held stably in place is primitive. For a physicist, the existence of two opposing forces does not ensure lack of motion. Zero net force, in fact, ensures that any existing motion will continue. Even if the clamped object happens to start out at rest, the naively assumed stability of the situation requires further mechanism for a physicist. That is, if a small force is applied to the clamped object, it remains at rest only in virtue of the clamping object's developing a new net force to cancel the applied perturbation. To explain how it is that those new forces arise requires an attribution of increased deformation to part of the clamping object.

Given the complexity of the reduction to force-like terms and the unification of a diverse set of phenomena that reduction requires, it should not be at all surprising that undermining the perceived primitivity of p-prims such as *clamping, guiding,* and *blocking* is difficult and takes time. Clement (1987) and Minstrell (1982), for example, documented the misconceptions manifestation of this systematic difficulty. In diSessa (1983), I noted that the reduction uniformly involves the development of a high priority for the phenomenon of springiness, which replaces naive rigidity near the peak of reliability in the physicist's sense of mechanism. Springiness[10] (deformation with consequent development of restoring force) plays the crucial role of generating the forces that explain all mechanical constraint phenomena. Yet even springiness is a nonprimitive element for a physicist: It has a reduction to higher priority notions. I briefly describe the development of springiness here in anticipation of a fuller treatment of central difficulties in learning Newtonian mechanics (see the Agency in Action and Reaction subsection of Development) in which springiness has a particular role.

The inherent springiness of all matter is almost never directly discussed in textbooks. This is likely due, in part, to the fact that it is largely unnecessary for problem solving. Instead, students can (and often do) settle for magical new primitives like normal forces, which are the reaction of supporting objects to the pressure of supported objects on them. A second reason that springiness is not deliberately discussed is that it does not belong to the core notions of Newtonian mechanics. Even though it is central to overcoming key difficulties in converting the naive sense of mechanism to the expert's, it is considered pedagogically uninteresting.

Despite the fact that it is seldom taught, most of my freshmen did develop the springy point of view. This suggests that expert intuitions might develop for reasons of increasing coherence of the knowledge system (Systematicity D, mutual

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[10]There is probably a basic p-prim at the root of the concept of springiness. I discuss this later as the *spring scale* primitive. It is fairly easy, however, to discuss springiness with students. Thus, it is likely springiness also belongs to the category of more elaborated and conscious concepts.

plausibility) even though such intuitions may not be instructed or even have any direct instrumental role in problem solving. Consider that normal forces, which are explicitly instructed, may be explained and reduced to more core Newtonian concepts via springiness. Normal forces are simply a conventional name for the springy force that develops on a surface when an object is pushed against it. Students may see the redundancy of the concept of normal force subtly in instructors' explanations, or they may discover the reduction techniques and thus understand the unifying and simplifying properties of a springy point of view on their own. Similarly, clamping and guiding become examples of springiness's implications, lending a broader coherence to the system. Development via mutual plausibility goes beyond the view that competence at solving problems establishes the sole goal and means for developing expertise. The force of a coherent point of view, although not as strong as we might like, should not be ignored.

However it develops, the reasoning that reduces constraint phenomena to more central elements of physics has a strong stabilizing effect in increasing the priority of the more central notions and reducing that of the less central ones. Furthermore, it allows reliable checks on the application of the midlevel knowledge elements, like normal forces, when necessary. Thus, even if it has no direct role in routine problem solving (if one uses normal forces properly, there is no need to reduce them to more fundamental ideas), learning the reduction via springiness may be vital for the perceived coherence, stability, and reliability of the knowledge system.

Balance and Equilibrium

This section sketches an apparently rich and important class of p-prims having to do with balance, equilibrium, imbalance, and overcoming. Again and again, one hears novices explaining situations by things being "in balance" or a system "returning to equilibrium."

Dynamic balance.   *Dynamic balancing* is likely abstracted from situations in which two opposing forces "try" to achieve mutually exclusive results but happen to cancel each other out. A paradigmatic case is two people pushing against each other with equal force, accomplishing nothing. *Canceling* itself is an important naive p-prim (see diSessa, 1982). *Canceling* is likely a common abstraction for many cases of joint, although not necessarily simultaneous, application of "equal and opposite" tendencies. For a situation involving *dynamic balancing, canceling* justifies lack of result.

Dynamic balancing entails agents in interaction and conflict as important elements in the cuing priority. Recall that the case of a person pushing on a wall is not, in the naive sense, an instance of *dynamic balancing*. For the pushed-upon wall, there is only one agent, the person, and there is no motion simply because the wall resists the push on it.

One frequent use of *dynamic balancing* at novice stages of physics problem solving occurs in explaining circular motion. It is said that force pulling toward the center of the circle—gravity in the case of an orbit or string tension in the case of a rock on a string—"balances out" the centrifugal force, which pulls the rock or satellite outward.[11] Centrifugal force is sometimes justified as the "resistance" to the tug of gravity.

In view of the acceptance of balancing forces as an explanation of circular motion, apparently circular motion is taken to be a relative primitive. Novices who declare "centrifugal balances centripetal" do not ask further what else causes the circular motion, as opposed to straight-line motion, which would be the actual result of balanced forces, or as opposed to no motion at all. The relative primitiveness of circular motion is not hard to understand. The world offers many examples of circular motion where no evident agency is needed to maintain the motion (e.g., parts of a spinning wheel). If it were not the case that physics training increases the salience of centripetal forces (causing worry about the lack of motion toward the center), one could just start out with the end stance in the previous argument: Circular motion sometimes just happens. Note further that *clamping* might increase confidence that the pair of forces, inward gravitational and outward centrifugal, "lock" the object in orbit. Some subjects verbalize "locking in."

Symmetry, such as having an obvious center, encourages novices to think about circular motion problems so as to view circular motion as primitive. Many novices who propose *dynamic balancing* to explain circular motion have great difficulties explaining less natural elliptical orbits, especially if they know or if it is pointed out to them that the center of attraction is not at the center of the ellipse. Note here that visual patterns, as opposed to reasoning about mechanical or dynamic causality, play a role in judgments of plausibility. Such a role for visual patterns is a case in which the naive sense of mechanism attends to substantially different attributes than a Newtonian sense of mechanism. In contrast, whereas $F = ma$

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[11]The balancing view of circular motion seems more common after the early stages of physics instruction. A more naive understanding involves a force pushing "around," tangent to the circle (White, 1981). I suspect there are coordinated changes (Systematicity D, mutual plausibility) that account for this developmental pattern. Instruction names and sanctions the force toward the center in circular motion situations. Thereafter, the need for centrifugal force to avoid the simple *force as mover* prediction (that the object should just move toward the center) is stronger. When centrifugal force is questioned, students sometimes explain that, without it, the orbiting object would simply move toward the center. The evolution of the concept of centrifugal force should make an interesting case study, because this and other observations suggest it is, at least in part, an unintended artifact of instruction. Although centrifugal force is not a Newtonian concept and, indeed, is explicitly denied in most contemporary textbooks, the intuitive lesson students learn on their own is that it is necessary to make sense of circular motion. Centrifugal force seems to be a very robust concept. Students are frequently adamant about its existence, and popular presentations of science (e.g., in the press) use the concept extensively.

and *force as a mover* are technically at odds, they share in many circumstances a basically mechanical causal focus on contact intervention. I continue the discussion of visual patterns in the Systematicity section.

Gravitational orbits and ball-on-a-string situations are sometimes seen differently from what is a physics-identical motion, a ball in a circular tube. In the latter, the *guiding* primitive and lack of any overt force toward the center make the countering centrifugal force also unnecessary, and it may be denied in these circumstances by students who affirm it in other situations.

Abstract balance. Consider the following problem: A monkey hangs on a rope looped over a pulley with a weight of the same mass as the monkey hooked to the opposite end of the rope. Initially, the monkey and weight are balanced, stationary, and at equal height. If the monkey starts to climb the rope, what happens to the weight?

The correct answer is that the weight rises exactly parallel with the monkey, at exactly the same speed. The interesting point is that students who get the answer correct often appeal spuriously to conservation of energy to justify the equal reaction of the weight. In fact, conservation of energy in no way justifies the spatially balanced solution to the problem. Equal weights can balance at unequal heights. My interpretation of this novice explanation involves a p-prim, *abstract balancing*, which matches off amounts in a pair and attaches a balancing imperative to the two. *Abstract balancing* is an assertion of required correspondence, a weak form of identity. The imperative nature of *abstract balancing* contrasts with *dynamic balancing*: Abstractly balancing things should or must balance; *dynamic balancing* is balancing by accident or by conspiracy. *Abstract balancing* is a partial, but appropriate, interpretation of algebraic equality.

Abstract balancing is perhaps the central scheme in "worth," as when one asserts so many eggs are worth so many dollars. It may be abstracted from many situations of similar correspondence and serves its role in asserting a required correspondence, probably without any prejudice as to the mode of establishing or enforcing the correspondence (e.g., trading eggs and dollars or direct, universal correspondences such as one finds in mathematical or physical laws). Piagetian conservation— number or amount as a property necessarily preserved through time and physical manipulation of sets—probably involves this primitive. Similarly, conservation of energy should appropriate *abstract balancing* as a distributed encoding, leading to a generally high priority use of *abstract balancing* in physical analyses. So, in the monkey problem, seeing an initially balanced situation, students use the imperative nature of *abstract balancing* to justify a prediction of maintaining symmetry (balance). They announce conservation of energy as the underlying principle because it is an overtly sanctioned version of *abstract balancing*.

Conservation of energy is misapplied in the case of the monkey and weight for a fundamental reason. Conservation only applies to the same thing at two

different times, not related things in two different places. Novices who use conservation of energy as a justification in the case of the monkey evidently have not linked the "transformation-through-time" perspective adequately to the use of energy. They happily appeal to conservation when only their intuitive perception of *abstract balancing* actually applies. It is precisely this partial learning of the notion of conservation of energy that suggests we must take a knowledge structure such as *abstract balancing* seriously. If complex notions are gradually assembled out of more primitive elements, different developmental states should be characterized by partial assembly. That, in turn, should reveal the pieces of the whole.

An idiosyncratic example of an inappropriate importation of balancing into understanding physics involved a student who constantly puzzled me by drawing force vectors on free-body diagrams in the opposite direction from real forces. The reason for this behavior became apparent when she openly declared that the meaning of $F = ma$ for her was that "nature required everything to be in balance," and the ma was the thing that balanced (apparently in the sense of *dynamic balancing*—canceling out—but with the imperative attribute of *abstract balancing*) any force. Thus, for any force, she frequently identified the balancing ma force as necessarily existing. This example is valuable in showing how, contrary to the misconceptions point of view of widely held systematic difficulties, the present view allows us to understand individual, although sometimes personally pervasive, constructions as attempts to universalize combinations of common primitives into a more systematic sense of mechanism.

Imbalance and Re-Equilibration

Balance is one side of a coin, and imbalance is the other. Imbalance, in intuitive physics, has two manifestations. First, in cases of accidental balancing (*dynamic balance*), there are specific related happenings when the balance dissolves. In the case of *abstract balance*, the imperative nature of the balance can be interpreted as a tendency rather than a strict principle of equality. The balance may be perturbed by an external intervention, although it is not dissolved by it. Then, new p-prims describe both the interaction of the perturbation with the balancing tendency and what happens when the perturbation is withdrawn.

Dynamic imbalance.   *Dynamic balancing* alerts (Systematicity A, mutual use) a primitive I call *overcoming*, which is what happens when one force is greater than the other and, perhaps gradually at first, "gets its way." This way of describing *overcoming* is meant to suggest what I take to be the anthropomorphic roots of the abstraction. *Overcoming* is a rather primitive scenario for the interaction of forces or influences in that it prescribes that one of the influences wins over the others, and the winner's "intended result" is achieved. This works rather well for forces that are directly opposed, but it fails to capture nuances such as either

combining or compromising among forces that are not directly opposed. Categorical predictions of *overcoming*, when one or another influence gets its way, seem particularly widespread. This may be surprising because a likely domain of application is social interaction, where complex negotiations can result from conflict. But, nonetheless, simple *overcoming* seems to dominate early explanations and predictions. See, for example, the late appearance of compromise predictions with a dynaturtle (diSessa, 1982), and also note that Aristotle's physics never provided any principle for combining influences such as nonaligned forces.

Consider another example of conflict and categorical overcoming. A frequent prediction about the trajectory of an object thrown horizontally over a cliff is that the horizontal impetus lasts for a while (gradually *dying away*), then gravity "takes over," leading to a near right angle turn. It is important to add that this kind of simplification of interactions is only relatively strong, not strictly adhered to. In many cases, subjects prompted to inspect the right angles they have drawn immediately patch them by smoothing the corners. Most novices sense that sharp turns are very atypical in situations of continuous physical motion, although they may need to be prompted to cue this reaction.

An exemplar of *continuous force*, say, an object being pushed at a constant speed across a table, is frequently interpreted at a refined level as the push of the hand overcoming the resistance of the friction of the table. As compelling as this is, a Newtonian interpretation has no imbalance. The force of the hand is exactly equal to the resistance of friction, and an initially supplied motion (momentum) is left to perpetuate itself. Because it is so familiar and involves central intuitive schematizations, coming to understand this simple situation is surprisingly difficult, as I elaborate later in the Development section.

The following example of *overcoming* highlights a function for intuitive knowledge in physics novices that I believe is very common. Intuitive schemata can provide a top-level analysis that serves as a plan that is elaborated in rather straightforward fashion into a complete problem solution. Consider a mass resting on top of a spring. How far must you push the mass down in order to have the mass jump off the spring when you release it? A novice sees simple opposition between the force of gravity and the force of the spring pushing upward. Gravity wants to hold the mass down, and the force of the spring is trying to toss the mass into the air. If the spring is pushing any amount more than the (dynamic) balancing point, it will assume the role of the stronger, overcome gravity, and toss the mass into the air. (This analysis is nearly an exact quotation from some novice protocols.) At this point the solution is planned in terms of *balancing* and *overcoming* schemata, and all that needs to be done is to express the dynamic balancing point algebraically, which novices do by equating the force exerted by the spring (kx, where k is the spring constant and x is the displacement from equilibrium) with the force of gravity (mg, where m is the mass and g is gravitational acceleration). To a physicist, this equation merely specifies the amount of compression needed to have the spring support the mass. Compression

a bit more than this specified value will result in the mass bouncing up and down upon release but will not have it tossed into the air.

Abstract imbalance.   Elements connected with high cuing priority (mutual use) to *abstract balancing* are generally very different from ones connected to *dynamic balancing.* "Out of balance" can mean some perturbing force is interfering, but the abstract balancing tendency can still be in effect. Consider a pan balance that is sustaining a temporary downward push from a finger on one side. The pan is said to be out of balance, but the tendency to balance is still in effect.[12] After all, one may feel the pressure of the pan "trying to return to equilibrium." More generally, in cases of abstract balance, one typically gets displacement from equilibrium by an amount in proportion to the perturbing force rather than *overcoming.* Displacement from equilibrium proportional to the perturbation is a p-prim I call *generalized springiness,* which applies outside of genuinely spring-like situations. In contrast to the intuitive schematization of imbalance modulated by *generalized springiness,* a physicist would informally describe the out-of-balance balance scale as a new balance. More formally, it is described by opposing forces that happen to be equal.

Push a tall block or package of cereal standing on a table toward the side, and it tilts more until it falls. Because naive physicists assimilate the push and subsequent tilt to *generalized springiness,* I suspect many would be surprised to discover that, in this case, the greater the tilt, the *less* hard you are pushing!

Suppose one takes a pair of equal weights and hooks them to the ends of a rope that runs through a pulley. The weights are initially balanced at equal heights, as in the previous example with the monkey and weight. If one adds another weight to one side, novices frequently predict that the now heavier side will move downward a distance proportional to the weight added. In actuality, that added weight will cause the rope and weights to accelerate, allowing the heavier weight to fall until the lighter weight hits the pulley. (That is to say, dynamic imbalance and *overcoming* would be a better interpretation of this situation.) Roncato and Rumiati (1986) explained the naive prediction by asserting an intuitive theory of balancing of potential energy. Indeed, if the heavier weight goes down a distance in proportion to the perturbing weight, the potential energy on one side might balance the potential energy on the other. But according to the present interpretation, balancing potential energy is a spurious and misleading interpretation of what novices are doing. They are, instead, using *generalized springiness* to determine the extent of disequilibrium rather than determining the position of a new equilibrium by matching energies.[13] Besides connecting this situation to a broader range

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[12]It is plausible that *abstract balancing,* rather than being ambiguous about whether the balance is always exact (as in conservation), really comprises a number of distinct p-prims, some of which involve strict equality, others of which involve only a tendency.

[13]Balancing potential energy has another untoward property. If we denote the smaller weight by m, the other weight by $M = m + i$, the height of the m side by h, and the difference in heights

of phenomena through *abstract balancing* and *generalized springiness*, the present interpretation avoids attributing misconceived "theories" involving instructed concepts to students who may have no intuitive feel for or any real conceptual grasp of potential energy.

The fact that *abstract balancing* can be interpreted as a tendency rather than a strict balancing means it can be temporarily violated without the constant exertion of a perturbing force. Without the perturbing force, however, things return to equilibrium, and *equilibration* is the operational primitive. In contrast, as noted before, physicists know stable equilibria must be the result of a relatively complex mechanism; any return to equilibrium has a deeper cause.

Equilibration may have presentations that are very different from a pan balance. An absence or sparseness of material next to an abundance leads, primitively, to flow and *re-equilibration*. The space left by a scoop taken out of a body of sand or water is refilled. *Equilibration* here can serve as a replacement for more mechanistic explanations, for instance, that there are forces that cause the return to equilibrium. See the discussion of sucking that follows.

In some cases, the return to equilibrium of a disequilibrated situation is specified in more detailed primitives than generic *equilibration*. Two patterns of motion are taken as typical of the return to equilibrium. One is a bobbing movement of diminishing amplitude, such as the oscillation of a balance scale or the sloshing of a disturbed pan of water. The other is a nonoscillating movement, a steadily slowing movement toward stop at equilibrium, such as a car (with working shock absorbers) pushed down and then released.

Interestingly, damped bobbing and the simpler slowing return to equilibrium often appear with very different priority in naive subjects compared with more expert ones. One of my MIT interview subjects, responding to the question of how far a mass must be pushed down on a spring in order to have the spring toss the mass in the air, took the problem as indicating a simple return to equilibrium. She assumed the latter pattern (no oscillation) as the way of things and refused to do the problem as stated. A physicist can scarcely look at a spring without thinking *oscillation*. This student not only denied oscillation but also maintained that the brick could never be thrown off the spring at all. It would just be pushed gradually back up to equilibrium. In other situations as well, she never spontaneously suggested oscillation as a possible motion with springs. What is particularly striking is that this student declared that throwing the brick down might give it enough "energy to rebound" off the spring. Evidently, thinking of throwing the brick down evoked a set of p-prims different from that evoked by push and release. Throwing the brick down (violence?) caused her to see the situation as a *bounce*. The stopped state half way through a bounce, which physicists would

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for the new "equilibrium" by d, then equalizing potential energy implies the following: $mgh = (m + i)g(h - d)$. So $ih = Md$. This equation shows that the displacement, d, depends on the height, h, at which the apparatus is placed. If you do the experiment on top of a hill, you get a result that differs from doing it at the base. I doubt even naive physicists would find this congenial.

see as identical to the state of an object compressed by hand and about to be released, is not salient in her abstraction of bouncing.[14] Instead of the stopped state half way through the bounce, apparently she saw something continuously happening that a physicist does not see going on (or does not see as explanatory), namely, *bouncing*. That makes the situation different for her from just releasing the brick from rest.

Fundamentally, the physicist sees the world in terms that do not admit that being engaged in a process such as bouncing is in any deep explanatory way part of "what is going on" in a system. The rich vocabulary of circumstance-specific processes of intuitive physics, which often explains situations in which they occur, defers in the physicist explanations to universal descriptions of change based on state involving only things such as geometry (reflecting, e.g., state of deformation) and straight-line velocities. The emergence of deference of common phenomena to a sparser set of explanatory terms is an important and general pattern that I continue to elaborate later.

DEVELOPMENT

I have sketched plausible contexts for the abstraction of p-prims and commented on some issues of development to the degree these have been immediately useful in understanding the nature of the p-prims listed so far. However, larger developmental issues need to be addressed. These issues have mostly to do with reorganization. New p-prims are undoubtedly generated to accommodate natural conceptual development and physics instruction, but this seems relatively unproblematic. What is more interesting is the restructuring of the system of existing elements. Following the theory sketch, I describe these changes as shifting priorities, which may gradually relocate a knowledge element within the knowledge system.

An insightful way of looking at the shifting priorities of knowledge elements is to describe the shifts in terms of the changing functions that elements have. For example, some p-prims might serve transient roles, primarily to cue the use of others, whereas some are more fundamental in that they are broadly applicable and treated as explanatory. Learning physics, I conjecture, requires systematic modification from the naive state in the following ways. One starts with a very shallow explanatory system: many p-prims serving as essentially primitive explanations for various phenomena. Gradually, p-prims cluster and become organized as distributed encodings. Recall that *distributed encoding* refers to the reuse of intuitive knowledge elements as parts of expertise, such as aspects of

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[14]Recent data involving children indicate that a stopped state not only is not salient in a situation of reversal but also may be rejected as implausible when suggested (diSessa, Hammer, Sherin, & Kolpakowski, 1991).

more sanctioned physical ideas, special cases, and approximate versions of laws and principles. The human encoding of Newton's laws of motion must be assumed to be very complex compared with simple knowledge elements such as p-prims. Notions of agency get built into the concept of force. P-prims such as *force as a mover* operate as special cases for a physicist (pushing from rest). Springiness of matter becomes more salient than rigidity, and it mediates the reduction of constraint phenomena such as blocking to more central Newtonian concepts such as force. In addition, balancing ideas become refined to play an important but partial role in encoding laws such as conservation of energy. Overall, p-prims become an essential part of what makes $\mathbf{F} = \mathbf{ma}$ work in a physicist's head.

The fundamental change in structure is that, instead of a very broad and shallow explanatory system, whatever p-prims are still used must defer to or become part of the complex but few subsystems that are the encoding of the physical laws themselves. Instead of a slew of p-prims, only physical laws are explanatorily primitive at the highest levels of reliability.[15]

In this section, I provide more, and more elaborate, examples of p-prims taking on several important roles in expertise. Aside from serving as part of the encoding of the laws per se, p-prims may serve as "legitimized phenomenology," where, like springiness, a phenomenon is known independently to happen yet can itself be explained and connected to the highest reliability elements in virtue of circumstantial particulars.[16] Other roles include cuing more reliable analyses (e.g., sensations of *abstract balancing* cuing conservation) and providing planning knowledge (more successful versions of the kind of thing demonstrated by the use of the *overcoming* schema as a sketch of a solution to the compressed spring problem discussed at the end of the previous section).

I consider the learning-developmental histories of three physics conceptualizations. First, as a brief introduction, I look at sucking, its relation to p-prims and their explanatory status. Second, I consider an extended example of the developing relationship between a cluster of p-prims and an element of textbook physics: the simple harmonic oscillator. Finally, I take a look at a particular pedagogical problem, learning Newton's third law, which entails a more refined look at the development of the crucial phenomenology of agency. These case studies of conceptual development extend the list of p-prims in the preceding section a bit, but, more important, they provide (a) comments on how clusters of elements interact in particular lines of conceptual development, (b) discussion of some important general roles p-prims may play in development, and (c) some apparently

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[15]Laws are, of course, not primitive in other than an explanatory sense. They have empirical support in the form of evidence. They have logical support in terms of definitions of terms, but they do not have explanatory support from more fundamental principles.

[16]I assume it is not harmful to propose that legitimized phenomenology can always be reduced, explanatorily, to "official" principles. This likely catches the general flavor of priority relations in any case, but it would be interesting if independent world assumptions got built into theories by virtue of the phenomenology that accompanies expertise.

general developmental patterns and at least a general chronology for some particular developments.

Sucking

Many of the patterns of development that I believe are important and typical can be illustrated in the simple example of sucking, as in sucking water through a straw. Initially the overt agent, the person sucking on the straw, is viewed (via an early form of sucking p-prim) as the direct cause of the liquid's motion. At an intermediate stage, a more elaborate causal chain is envisaged: Sucking removes or otherwise rarefies air; then the partial vacuum pulls the liquid. Sucking is no longer the direct explanatory analysis of what happens when you suck on a straw, but the motion of the liquid is explained by a general fact that everyone knows: Vacuums draw gas and other substances into them. This is the level of pop physics.

Later in development, at the level of a physicist's informal description, an invisible, inanimate agent (i.e., air pressure pushing down on the liquid in the glass) becomes the direct cause of motion; it pushes the water up the straw. This happens when the balance of pressures (pressure on the water in the glass balances pressure on the top of the liquid inside the straw) is broken by the overt agent—the person sucking. It is notable that, at this stage, in contrast to earlier stages, a vacuum or partial vacuum can in principle never pull (suck) at all. Sucking is entirely gone as an explanatory primitive. In a bit more detail, the new analysis is: The person changes the geometry of the situation, for example, by increasing the volume inside his or her mouth in which a fixed amount of air exists. This results in decreased pressure on the liquid on the straw-and-mouth side of the system. A decreased pressure on the inside of the straw and an undiminished atmospheric pressure on the other side cause the water to move.

Actually experts know they must further explain the propagation of differences in pressure in the air and in the liquid so that each moving element of substance experiences the force needed to move it. This is a level of detail that is usually ignored, because it is known to be a legitimized piece of phenomenology. In most instances, one can simply treat objects, even things like chunks of liquid, as rigid objects, ignoring the internal deformations that are necessary to produce local forces that move individual pieces of the chunk. Indeed, even this explanation omits details in that it employs a version of *force as mover*—unbalanced forces cause motion. Instead, unbalanced forces develop accelerations, the legitimate Newtonian quantity that responds to force.[17] Furthermore, unless prompted, a physicist would almost certainly use some version of *guiding* or "channeling" implicitly to avoid having to explain exactly how the water knows to follow "the

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[17]I suspect it would be a doable but not a trivial challenge for most physicists to explain correctly why there is no apparent acceleration, given a difference in pressures.

obvious" path into and up the straw. It would take solving field equations with boundary conditions to say exactly how water flows from various places in the glass into and up the straw. Although such subtle, usually suppressed considerations give rise to observable phenomena (e.g., propagation delays) and give rise to questions that would be impossible immediately to answer (e.g., how the flow toward the straw "inlet" in the glass proceeds), no physicist would say he or she does not understand how sucking on a straw causes the water to move, even if he or she has never done a detailed analysis. Instead, one can remain at an intuitive but legitimized level of analysis in giving explanations, because one knows roughly how the story of propagating pressure differences, viscous friction, and so on, works out so that those explanations are respectable.

To summarize, learning physics involves reducing the explanatory priority of many p-prims, such as sucking, that prescribe direct connections between a class of actions and resulting motions. Instead, the Newtonian explanations of motion are channeled into a single, complex notion (i.e., force), which requires elaborate situation-specific reasoning to explain familiar phenomena. Despite acknowledging, if pressed, the need to rely only on basic principles, physicists still use ideas such as *force as a mover*, rigid object assumptions, and guiding or channeling to provide high-level descriptions that avoid many complexities in reducing a phenomenon to basic causal relations. The fundamental reorganizational phenomenon exhibited here is that p-prims become subordinated to more core concepts and principles, yet some selected ones are preserved as legitimized phenomenology, so that everyday phenomena do not escape explanation that is judged Newtonian without carrying out all the situation-specific reasoning necessary actually to establish an explicitly Newtonian explanation.

Bells: Toward Expert Intuition

This example deals with intuitive knowledge elements that eventually play an important role in a large and complex piece of expert knowledge. The expert knowledge is much like what Kuhn called "exemplars" (Kuhn, 1977, p. 298), "concrete problem solutions, accepted by the group [in this case, physicists] as, in a quite usual sense, paradigmatic." Collecting and systematically attaching p-prims as distributed encodings for physical principles is a structural and knowledge-based view of the process that Kuhn identified as central to learning a discipline, the process by which students learn to see the exemplar outside its initial context while problem solving. P-prims interpolate between the world's diverse and familiar presentations and the highly schematized abstractions of sanctioned physics.

The particular exemplar at issue here is called the *simple harmonic oscillator*, a standard problem worked out at great length in every relatively complete college-level treatment of mechanics. The simple harmonic oscillator is considered by physicists to be fundamental to a large class of phenomena. Before considering

it in detail, let us first look at the intuitive knowledge that genetically predates that notion.

One of the Montessori educational materials is a set of musical bells with varying pitches but all of the same size and shape. How do these apparently identical bells, made of the same material, manage to have different pitches?[18] I have posed this question to a large number of people at various levels of physics sophistication in addition to the students in my formal interviewing sample. Most correctly conclude the bells must vary in thickness. But the question remains as to whether the thicker bells are lower in pitch or higher.

Almost uniformly, people answer that the thicker bells must be lower in pitch. Interestingly, this is true even of those people who do not know that pitch is related to frequency of vibration. Some make analogies to various musical examples of the principle: xylophones, chimes, or organ pipes, where the bigger the piece, the lower the pitch. But even those who do not spontaneously mention examples — indeed, they may have difficulty producing an example when requested — know that bigger things have lower pitch. A few subjects, presumably the more physically sophisticated ones, produce the chain of implications as follows: Thicker means heavier, which implies slower (lower pitch). But most seem unable to go beyond *"bigger implies lower pitch"* as a primitive phenomenon.

The second phenomenon in this chain, that *"heavier implies slower,"* is a reinforcing or justifying primitive that could be abstracted from shaking or pushing objects of differing mass. Note that here, as with *force as a mover*, there is a precondition that is not abstracted into the p-prim. In this case, the precondition is equal force applied to the differing objects. Omitted preconditions, whether because of systematic inability to encode them or because they seem (or actually are, in most circumstances) irrelevant, is an important developmental phenomenon. Further examples of omitted preconditions are discussed later and also in Appendix B, in the section on children's p-prims.

Note that *slow* in *heavier implies slower* is an attribute that applies to slowly moving objects (speed) and also to slowly vibrating ones (frequency). This is typical of differentiations that do not seem to be useful for intuitive conceptualization but become more and more important in physics instruction. Lack of such differentiation lays the cognitive ground for conflict. It is possible that an object vibrates faster but moves more slowly. Some studies exist that show the lack of differentiation and potential conflict that may arise between versions of slow and fast in the case of angular speed (frequency of revolution) versus linear speed (see Levin & Simons, 1986).

A note on abstraction.   It is worth a moment to consider the genesis of the *bigger implies lower pitch* p-prim. In particular, one might question its phenomenological roots. Is this simply an abstraction of a phenomenon, a straightforward

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[18]This problem was first presented to me by Jeanne Bamberger.

schematization of an event as I characterized the generic abstraction process for p-prims? It seems more likely to arise from a comparison of two perceptions (comparing a low-sounding object to a smaller, higher sounding one), thus abstracting the p-prim might imply reasoning beyond simply describing. The abstraction process might involve a reflective event, perhaps a conscious search for reasons that the quality of two events differs.

One can make two moves at this point. The first is to accede to the heuristic nature of the sketch I made in the preliminary theory sketch of the abstraction process as a "minimal and unproblematic abstraction." Sometimes it might happen in different, possibly more complex, ways. For example, the abstraction of a p-prim might be the residue of a fairly complex process of reasoning, akin to Piagetian reflective abstraction (e.g., Piaget, 1967/1971a), say, comparing two situations and identifying an apparently causal difference that explains other differences. More than not being ruled out a priori, it makes good sense that the abstraction process should be complex in certain instances. Indeed, I have said nothing about the process that selects particular parts of an event for abstraction into a p-prim. There must be mechanisms at work in this selection that extend and refine an individual's current sense of mechanism, for example, determining what aspects of the event are most useful to incorporate into causal descriptions. Expanding the inquiry concerning mechanisms involved in generating p-prims changes little that I say here, because most of what I report is independent of the abstraction process.

Without denying that the genesis of p-prims might be complex, it is possible to make a more conservative move in this particular case. We can depend on the fact that relative features such as bigger and lower seem to have primitive precursors as absolute rather than as relative attributes in children's conceptual development (e.g., Piaget, 1970/1972, p. 30). In situations where the absolute forms of the attributes are salient, a single abstraction of an event is all that is needed. For example, "(Big) Daddy's voice is low." Juxtaposition of big and small objects might serve, via generic processes, to enhance the salience of absolute big and small attributes by contrast, thus promoting the incorporation of these into the abstraction.

Considering absolute attributes as precursors for relative ones suggests that the intellectual development that enables one to deal with relative quantities involves schemes that patch together reasoning involving absolute attributes into functionally relative reasoning. Absolute associations could be extended to relative ones by a generic capability to think relatively, when necessary, or by concept-specific changes that have the same effect. This would parallel the way I propose naive p-prims are patched together to produce behavior that avoids the pitfalls of the naive primitives through an augmented system of priorities.

However it is that qualitative correlations such as the expectation of lower pitch for bigger objects come to exist, adults seem to have many items of the form "the more x, the more y" in their sense of mechanism, as the list that is

developed later attests (stiffer implies less motion, heavier means slower, shorter distance means less time). Qualitative proportionalities have been incorporated into several researchers' models of qualitative reasoning (e.g., Forbus, 1984; Roschelle, 1991).

A very small proportion of interviewees explain the thickness–pitch correlation by remarking that thicker must mean stiffer, which in turn must mean faster (higher pitch). The latter part of this phenomenological syllogism might be drawn from the experience of muscle tension causing or being needed to cause rapid shaking. Indeed, stiffer might really appear as "more tense" in the p-prim, abstracted directly from muscle tension. Another possibility is abstracting from a musical situation, say, tighter strings on a guitar making a higher pitch. Some subjects indicate a third and slightly more complex process of genesis in another syllogism: Stiffer things do not move very much (in more technical language, small amplitude vibration is associated with stiffer things), and because that is true, they can accomplish their motion in less time, again implying a higher frequency. The *less distance means faster* primitive is typical of primitives with omitted preconditions that seem to be behind children's puzzling responses to time, rate, and distance problems posed by Piaget (1946/1971b). For example, some children seem to believe that going faster entails more time (even in cases of constant distance traveled), which possibly results from a phenomenological syllogism—faster is associated with farther, but farther means longer time—that can be constructed only with omitted preconditions.

It appears certain that most people have *bigger (or heavier) implies lower pitch* as both a more salient and a more reliable p-prim than *stiffer implies higher pitch*. The latter seems to occur mainly as a "virtual concept," the conclusion of an on-line phenomenological syllogism.

There is potentially a good deal of mutual plausibility work going on in these phenomenological syllogisms: Based on a given vocabulary, situation-specific reasoning derives or rederives another element that might then be separately remembered. In these cases, it seems likely that deriving a previously stored phenomenon should increase the priority of the elements of the derivation, especially if the derivation is by novel means. (Again, *derivation* must be taken advisably.) By the same token, drawing an unlikely conclusion is as likely to undermine the reasoning or presuppositions as it is to change the belief system directly in a dramatic way (i.e., encoding the unlikely conclusion).

Let us turn to expert thought and to the exemplar of the simple harmonic oscillator. The underlying model consists of a perfect spring attached to a rigid support on one side and to a particle on the other. The derived behavior includes the fact that the frequency of oscillation of such a device is proportional to the square root of k/m, where k is the spring constant characterizing the stiffness of the spring, and m is the mass of the particle. My claim is that experts, when they need this information qualitatively, use intuitions of precisely this form—*heavier implies slower* and *stiffer implies faster*—but that their confident use is

generally restricted to the specific context of a simple harmonic oscillator. That is, experts attach intuitions of the same kind as (and maybe even identical to) those that novices have to more specific contexts. The expert's confidence in the use of the intuitions is linked to having an elaborate knowledge system that can validate the simple harmonic oscillator context in any particular case, and it is linked to being able to justify the qualitative results with high-reliability notions via a more careful derivation if necessary.

We can model an expert analysis of the bell problem crudely as follows. Sound and frequency issues, and possibly other recognized configurations such as struck objects, cue vibration as a problem context. Vibration cues simple harmonic oscillator knowledge, because that is the expert's fundamental model of vibratory behavior. The expert reasons that "the thicker bell will be more massive, so it will tend to vibrate more slowly; but the extra thickness will make it stiffer; hence, vibration will tend to speed up." Of course, this reasoning might consist minimally of only three mental events, the recognition of the two qualitative correlations in the perceived situation, and the recognition of a conflict between their suggested conclusions. Thereafter, the expert must reason with greater precision to resolve the conflicting tendencies. It turns out that stiffness wins the competition because stiffness increases as the square of thickness, whereas mass only increases linearly. That is why the thicker bells have a higher pitch.[19]

The expert may need to check that the situation is truly like a simple harmonic oscillator via reliability loops. But the fundamental point is that he or she may confidently use essentially the same intuitions that naive people have, but restricted to a specific class of situations that can both be elaborately specified and that allow justification of the intuition if necessary.

In refining this model, it seems as likely that an expert might make the qualitative reasonings based on recognition of vibration alone, without any mediating cuing of the simple harmonic oscillator notion, except in post hoc justification of his or her intuitions. Indeed, we should question the very meaning of "cuing the harmonic oscillator." An exemplar is much too large a knowledge structure to be activated in any context-free sense, the way I suppose p-prims are. More likely, some subparts of "harmonic oscillator" may be cued, such as a subvocalization of its name or possibly activation of an appropriate germ of the particle-on-spring model. Other parts of the exemplar would be activated according to need and circumstance.

It is worth emphasizing that adding a complex justification context such as an exemplar to the knowledge system does not mean that it is always invoked. Indeed, for the purpose of rapidly pursuing possibilities rather than laboriously

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[19]A slightly different expert analysis might observe that the wavelength of the fundamental mode of the bell remains roughly invariant as the bell is made thicker. Because wavelength determines frequency via speed of motion (speed divided by frequency is wavelength), the question of pitch reduces to what happens to the speed of sound in the bell. That, in turn, reduces to the same ratio of mass to stiffness considered in the text.

pursuing necessities, one can expect experts to develop the ability to judge heuristically the applicability of the intuitive components of the exemplar according to features of the context. To cite an extreme case mentioned previously, no experts would hesitate to use *force as a mover* in a situation of pushing from rest, and they would not, under most conditions, need to resort to a law or principle to justify that prediction. In this case, something similar to a naive at-rest attribute could do the trick of judging applicability. In other cases, new p-prims might be specifically developed for the purpose of making such judgments. These p-prims would be legitimate parts of an expert's sense of mechanism, although they might be quite specific. I am suggesting here that it is implausible that experts would avoid using surface features in encoding dispositions for problem solving. See Chi, Feltovich, and Glaser (1981), Roschelle and Greeno (1987), and Smith et al. (in press) with regard to the plausibility of experts using surface features as part of their expertise.

In addition to adding a complex justification context to the basic intuitions, it is clear that a general shift in priorities has occurred, particularly in the case of *stiffer implies faster* compared with *heavier (bigger) implies slower*. The former notion is at best marginally recognizable to naive people. The curriculum of naive physics seems to teach *heavier implies slower* much better than *stiffer implies higher pitch*. Understanding why this is so makes a good case study, which I briefly pursue, of the circumstances that explain relative priorities of various p-prims.

A principal contribution to the fact that *heavier implies slower* is more salient than *stiffer implies higher pitch* is that the intuitive attribute *heavier* is more salient than *stiffer* (Systematicity B, common vocabulary). As noted in diSessa (1983), stiffness seems not to be well elaborated in naive senses of mechanism, tending to be perceived in categories such as (absolutely) rigid or squishy, like clay.[20] More particular, the relative stiffness of objects that make musical sounds, such as Montessori bells, is completely imperceptible to naive subjects. Certainly we have better access to sensing variations in mass through kinesthetics. We have even better access to patterns that are spatially describable, such as "more motion," because of our highly developed visual capabilities. This would lead to an increased priority for spatially describable p-prims, even if the motion involved is too small to be directly perceived. Indeed, *stiffer implies higher pitch* is likely to be derived indirectly from the spatial intermediary of *stiffer implies less motion*.

To add to the differential between *heavier implies slower* and *stiffer implies higher*, it seems an indisputable fact that it is more important (and also, thankfully, easier) for people to control motion through modulating force and reacting to mass than to control pitch by modulating stiffness. Functionality and instrumental access select one p-prim as more important than the other. All in all, it should

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[20]The intuitive phenomenology related to material properties—rigidity, squishiness, brittleness, and so on—would seem to make a rich and interesting study.

be no surprise that *heavier (or bigger) implies slower* has naively much higher priority than *stiffer implies faster*.

To summarize, the simple harmonic oscillator shows several developmental changes in the sense of mechanism that are instigated by learning physics. Some naively recognizable phenomena (*heavier implies slower*) become appropriated as distributed encodings of physically sanctioned ideas. In complementary manner, an exemplar such as the simple harmonic oscillator may serve intuitive ideas as a complex justification context. New p-prims or p-prims with greatly increased priority, such as *stiffer implies faster*, also come to play important roles. These may be of naively low priority for reasons such as their involving low-priority attributes (stiffness) or simply because they are not important in everyday life. I noted that many p-prims involve particular qualitative proportionalities among intuitive attributes: More x begets more y.

The discussion touched on several general developmental phenomena. Many early p-prims contain omitted preconditions compared with more expert schemes. Some differentiation (e.g., slow speed vs. slow frequency) is also implicated in development. I also noted examples of a fairly general mechanism of coherence generation, phenomenological syllogisms, in which two p-prims that are roughly of the form "Attribute A implies Attribute B" and "Attribute B implies Attribute C" may lead to the encoding of a p-prim—"Attribute A implies Attribute C." Finally, I discussed reasons to believe that, sometimes at least, the genesis of p-prims might be more complex than a simple abstract schematization of a phenomenon.

Agency in Action and Reaction

Agency is a crucial attribute in the development of many aspects of cognition. It is likely that developing some sense of personal agency is one of the first important learning tasks for babies. Piaget and his collaborators focused much effort on this topic and on the subsequent equally important learning task of discovering how and when we come to attribute agency to aspects of the world outside our selves. Various forms of overextension may be seen as anthropomorphic or animistic mistakes. On the other hand, these extensions of agency to the world are also insights about how, in some way, agency is a good model for many physical regularities. I offer here a few comments on some of the ways agency appears to contribute to and to develop as part of the physical sense of mechanism. This section follows up on the introduction of many p-prims in the Elements section that used agency as part of their encoding. It explains some of the broader developmental issues surrounding agency.

I have argued (diSessa, 1980) that a particular form of agentive causality common in intuitive physics comes to dominate early encounters with school physics. Schematically, the basic *causal syntax* includes an *agent* (an initiator or an impetus-containing object), a particular directed and legitimized *kind of action*

on a *patient,* which is an object in whose behavior the effect of the agent's action is at issue. "I [animate agent] hit [legitimized interaction] the ball [patient whose resultant behavior is at issue], and it moved [the result of the causal interaction]." "John pushed the rock (and it therefore moved because of the push or did not 'for other reasons')."[21]

The causal syntax is a primary interpretive framework for $F = ma$. Some agent is responsible for exerting a force, which has the effect of accelerating a mass. Newtonian mechanics need not be interpreted in this way. In fact, this interpretation is effectively a pedagogical decision to provide an overarching framework for interpreting Newtonian mechanics in terms of ideas provided by the naive sense of mechanism (diSessa, 1980). There are other ways to make that transition, other choices of intuitive frames to import into a Newtonian mechanics, that provide an initial intuitive accessibility. All of these frames, of course, need refinement; none of them can properly be identified as aspects of Newtonian mechanics that we know before schooling.

One of the implications of legitimizing causal syntax is that agent and patient continue to be strongly differentiated in early learning of Newtonian mechanics. The effect of a force on the patient is far more salient (because it is the focus of the syntax) than return effects on the agent of the interaction. Indeed, the effects on the agent of the interaction are interpreted as another independent action, this time with the initial agent as the patient.[22] Thus, an unavoidable symmetry of Newtonian mechanics, Newton's third law, is expressed not directly, but by adding a mandatory but inversely directed asymmetrical relationship: "For every action, there is an equal and opposite reaction."

This patch—asserting a mandatory reaction—represents a relatively good pedagogical move, but it entails a host of related difficulties. These all stem from the fact that top-down coherence (Systematicity C) takes a long time to achieve. Students first learn "action and reaction" largely as a slogan. The many coordinations needed to effectively encode the third law only gradually fall into place.

The first difficulty is with paths cuing reaction and with the persistence (appropriate reliability) of that cuing. Students take a long time before they come to apply the reaction patch instinctively. Reactions do not become salient and are not felt to be necessary merely by virtue of the fact that the book and instructor say they exist. Actions continue to be seen as directed, and it takes constant prompting by instructors to consider the reaction.

"Actions and reactions" may be interpreted naively in terms of *violence,* either as a cue or as a justification for the reaction of the patient. If violence becomes

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[21]See Talmy (1988) for another schematization of this set of relations in a surprising context (i.e., grammatical structure). In Talmy's force dynamics, the agent or locus of control is entitled *antagonist;* the patient, defined by the locus of interest in terms of effect, is called the *agonist.*

[22]One can see the depth of the problem in that even our natural vocabulary seems to pick directed actions as the basic unit, with mutual actions described as pairs or clusters of *inter-actions.*

part of the cuing of reactions, then when gradual effects are at issue, there might seem to be no need for reaction. The gravitational pull of the earth causing the falling of a ball might not seem to occasion need for a reaction from the earth. More likely, a reaction might seem necessary if the falling ball crashed into the earth (although here, the action is likely to be interpreted as the blow the ball effects on the earth). In contrast, if violence becomes part of the justification for reaction, the earth, as big as it is, would seem unlikely to respond to an everyday object that happens to be pulled by the earth. Here, part of the difficulty is also that reaction is intuitively measured overtly, by evident effect, and, indeed, the earth will never show much effect in reaction to everyday objects falling near it.

The second difficulty entailed by using causal syntax and the action–reaction formulation is that recalling the action–reaction slogan, or even believing it must govern all interactions, is still some distance from being able to identify the reaction properly. Other inversely directed actions are mistaken for the proper reaction. For example, if I push on another person, his or her instinctive push back may incorrectly be interpreted as the reaction; or if I push on a cup, moving it across the table, the friction force of the table pushing back on the cup may be considered the reaction. A reaction, in naive terms, is only "oppositely directed" and "somehow causally related to the action," which are insufficient criteria to distinguish the real reaction force from others.

In a physicist's parlance, the expression "the force of A on B" selects a convenient *asymmetrical point of view on what is fundamentally a symmetrical relation.* If the complementary asymmetric view (the force of B on A) is not immediately available with appropriate identities (the magnitude of the force is the same in both cases and the physical locations of the two forces are identical), the knowledge system will have ineffectively encoded the fundamental symmetry.

The third difficulty is that the notion of agency must be broadened to see many reactions as plausible. (This is a specialization of the first difficulty, with cuing and reliability, to the role of agency.) The fourth difficulty is that competing naive schematizations of events must be undermined to preserve the plausibility of action and reaction across a diversity of situations. I illustrate these both with examples.

Consider the transition to understanding Newton's third law in the case of a cup supported by a table. A physicist sees that a table pushes up on a cup so that it does not move (i.e., fall down). To a novice, this reaction of the table to the cup is not plausible in view of an evident lack of agency in the table (the third difficulty). The table is not a likely animator; it exhibits no sense of strain. Furthermore, not moving is not a prototypical result of a push, and it seems entirely implausible that under any circumstances (say, gravity were instantaneously turned off) a table could cause the cup to fly up into the air. Besides, this situation is already covered by an "adequate" naive schematization (the fourth difficulty): The table is simply *blocking* the fall of the cup; no further explanation is necessary.

We see clearly in this example that distributed but coordinated changes in the sense of mechanism are necessary to encode Newtonian third law symmetry. Many coordinate–attribute ties must be individually broken, or a way must be found to effectively weaken them all simultaneously. Among these are expectation of strain in agents and, at least in some circumstances, the "it will cause motion if opposing forces are diminished" expectation (*overcoming*) for force-like interventions.

A dramatic example of a number of the just-listed difficulties, centering on agency, occurred in my interviews when a subject refused to admit that a metal cabinet could be said to pull a magnet to it, even to the point of denying she could feel the pull on her hand when I handed her the magnet and had her bring it near the cabinet. She said she was just feeling the magnet pull the cabinet. Presumably, she did this because she knows that magnetism resides in the magnet; hence, it must be viewed as the initiator of magnetic interaction. This is remarkably like children who refuse to believe a wall can under any circumstances push back on a person, even if they see a protuberance from the wall deforming a piece of clay held in the hand. Clement (1987) also cited the fact that novice physicists refuse force-providing status to passive objects even when the effects of the force are evident (e.g., you break your hand in hitting the wall).

Even if agency is attributed to a salient patient and competing p-prims are undermined in some situations, other p-prims in other situations can still interfere; the fourth difficulty is a broad one. This is a canonical effect of a broadly distributed sense of mechanism, and it further complicates the encoding of principles like the third law. The schemata of *balancing* and *overcoming* declare that the cause of motion is typically an imbalance—things move under a push because they do not resist enough, because the return force is not equal to the applied force. To watch a cup being pushed across a table and not see the hand overcoming the resistance of the cup or the friction marks quite an advance toward expertise. Because the balancing asserted in "equal and opposite" may be confused with *dynamic balance*, novices may wonder out loud how anything can possibly move if every force is balanced with an opposite one.[23]

The fifth problem with symmetry by patching together two asymmetries has to do with the long-term viability of the fundamental conceptual commitment represented in adopting causal syntax and the action–reaction schematization. These conceptualizations play into naive expectations that are, over the long term,

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[23]Some of the difficulties here have become more or less officially recognized by the physics teaching community (of course, not described in these terms) and are indirectly referenced in physics texts. The horse-and-cart paradox—that if the horse and cart are exerting equal and opposite effects on each other, nothing should move—is used to counter students' impressions that action and reaction may constitute a *dynamic balance*. The elephant paradox—that two elephants pulling on opposite sides of a rope do not effect more tension in the rope than one elephant pulling on a rope attached to a tree—is an occasion for attempts to get students to see a nonagent, the tree, as equivalent to an agent, another elephant in the tree's place.

undermined by the rest of the Newtonian sense of mechanism. It seems that a reaction might follow an action, but the distinction between initiator (agent) and patient lies entirely outside the core Newtonian frame and must gradually come to be perceived in that way. Initially, comfortable excuses (Systematicity E, completeness) that tend to preserve the intuitive categorization of action and reaction must fade. For example, students may say, "One can tell the action from the reaction according to who acts first." Or, as described earlier, they may have notions about what should be considered a natural agent (e.g., animate things). These or refined and extended versions must all lose credence as one puts together newly learned pieces such as that action and reaction are always simultaneous[24] or that situations that appear entirely inanimate must be interpreted by the same notion of force.

Although the third law is an inextricable part of the Newtonian notion of force, it appears to need special treatment to become even remotely intuitively accessible (via paired asymmetries). Given the systematic shallowness exhibited by unsophisticated senses of mechanism, it should not be surprising that the third law, even if it is effectively used, may develop its own independent explanatory power and not find its proper relationship in the developing knowledge network. This is a sixth difficulty. Like many p-prims before it, students will often be satisfied with the third law as a primitive explanation for motion. Why does a rocket move? Students say, "because of action and reaction." Many students will resist finding the force on the rocket that makes it move, because they interpret action and reaction as its own causal primitive. The force on the rocket is in reality easy to identify: It is that of the hot gasses that push against the forward wall but not against the (absent) back wall of the rocket's engine.

One of the general developments that aids novices in seeing the world in less directed, less agent-initiated terms is to shift toward seeing geometry as playing a causative role. This extends another commonsense form of causality—that situations are sometimes taken to be the initiators of events. One can say, "That Joe was in such a bind caused him to rethink his attitude." Studying physics encourages students to see, "That the cup and table are in a state of mutual compression implies that there is a force on each of them." Springiness, as in this example, is part of this broader move. Consider also coming to see a change in mouth geometry as the instigating event in sucking. More generally, gravity and electrical attraction are effects of the proximity of objects, and, indeed, all Newtonian forces are functions only of the spatial arrangement of objects. If geometry is taken as causal, neither of the interacting objects in an action–reaction pair needs to be seen as the instigating agent. Within the naive sense of mechanism, the use of geometry and configurations as causal initiators is lower in priority than causal syntax in mechanical situations. Moving toward

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[24]An aspect of causal syntax I have neglected is the presumption of time sequencing between cause and effect, whereas, in Newtonian mechanics, there can be no time lag.

causative geometry is a needed step toward compatibility with the Newtonian world view.

Related work.   Brown and Clement (see Brown, 1990; Brown & Clement, 1987, 1989) studied the difficulties students have in coming to see a reaction force. Their empirical work shows many student explanations for why they do not believe the table can provide a force. These explanations align with the interpretations provided here (e.g., Brown, 1990), although these researchers do not suggest the underlying reasons for these explanations. Minstrell (1982) also provided a long list of student reactions to third law situations that can be compared almost point for point with the list of p-prims and developmental difficulties cataloged here. In addition, Brown and Clement's work on pedagogical interventions (following on earlier work by Minstrell) shows how the model of objects as springy can effectively attack many but not all of the difficulties described here.[25] Springiness (see discussion in the Elements section, p. 134 and following) provides a model of blocking that is more compatible with Newtonian mechanics than the naive blocking p-prim. Springiness explains how a table may be seen more naturally as agentive. In contrast to the present framework, Clement and Brown explained the effectiveness of their interventions only in terms of the generally positive effects of analogies and of the root springiness intuition in particular. They did not report the positive influence of p-prims such as resistance (e.g., to a shove) in providing intuitive access to the third law. They did not interpret the effects of springiness in terms of its competition with other p-prims such as blocking or in the context of the central issue of agency, as sketched here.

To summarize, imparting intuitive accessibility to Newton's laws by building in a fundamental reliance on causal syntax has profound effects on subsequent learning. Even to state the third law requires patching in an intuitively arbitrary assertion of symmetry. A relatively global change such as the shift toward seeing geometry as causative is helpful. However, a host of other patches and refinements is necessary (a) to extend the circumstances in which the third law will automatically and justifiably be seen to apply (expanding cuing and reliability paths), (b) to encode aspects of the law that are implicit in its statement (e.g., required simultaneity of action and reaction) and to provide for smooth reasoning in problem solving using the law (e.g., appropriate shift of attention to retrieve the reaction force), (c) to refine agency so that its own cuing and reliability help

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[25]For example, they do not identify difficulties that may be provided by alternate schematizations such as violence, *dynamic balancing, overcoming,* and so on. These researchers consider neither the long-term effects of undermining naive assumptions of causal syntax and causal sequence nor other difficulties such as the third law incorrectly assuming its own primitive explanatory force. They also consider, by and large, only one way of overcoming the broad set of difficulties listed here— using "bridging analogies." I have been deliberately noncommittal about intervention procedures. See, in this regard, diSessa (1980), which suggests a global alternative to importing causal syntax into Newtonian mechanics.

make many reaction forces salient and plausible, (d) to make peace with competing p-prims (*blocking, dynamic balance*, and *overcoming*) that provide competing analyses, (e) to come to grips with the fact that there is really no Newtonian distinction between action and reaction, and (f) to keep the law from assuming its own independent status as a causal primitive rather than contributing as a proper extension of $\mathbf{F} = \mathbf{ma}$.

SYSTEMATICITY

I have already made a number of observations about systematicity. For example, I have considered: central elements (*Ohm's p-prim, force as a mover*) and less central elements (*wobbling, warming up*);[26] important attributes (agency) that may give rise to central causal schematizations (causal syntax); classes of recognizable patterns (amplitude patterns like violence and damped bobbing); and even a few mechanisms for producing limited systematicity, such as phenomenological syllogisms and slogans (equal and opposite reaction). In this section, I consider a pair of more global systematicities in detail. The central question is whether these systematicities can be localized, say, as relatively modular subsystems or as being due to the extended and integrated influence of a few elements. I argue that, in some restricted cases, there is evidence for modularity. Yet overall, the quality of knowledge systems such as the sense of mechanism makes it unlikely that broad and deep systematicities can be localized. The question has important pedagogical implications with respect to our expectations that narrow, focused interventions can achieve strong results. It is also important in deciding how simple an account of the development of knowledge we can expect to give.

The first systematicity is a *static predisposition* that seems to skew descriptions and explanations of dynamic events toward interpretations involving static phenomena. I present an extended set of examples of this predisposition, because it seems to capture, in some degree, many misconceptions that have been cataloged. My analysis of this systematicity is made by proposing an attractive way of localizing it to a basic categorical structure, namely, an ontology of change and cause. However, careful consideration suggests that this systematicity is, instead, the result of cumulative but relatively isolated effects.

The second systematicity involves a class of primitives that are also static in nature. These have to do with spatial/visual patterns presented by dynamic events. *Figural primitives* appear to be of a rather different descriptive class from many of the dynamic p-prims already considered. Because they may also be perceived as a class by students, and, further, because they relate all in the same way to

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[26]Strictly speaking, lists of central and less central elements (high- and low-priority elements) may explain systematicities in data but do not constitute, per se, relational systematicities among elements in the system, as listed in the Theory Sketch section.

a Newtonian sense of mechanism (they are essentially irrelevant), figural primitives may behave largely as a group in the evolving sense of mechanism. Thus, in contrast to the static predisposition, my analysis suggests figural primitives may constitute a module with significant unit properties, albeit of limited impact in the net transformation from a naive to a Newtonian sense of mechanism.

The Static Predisposition

Railroad car in space.   Consider a railroad car moving with a huge velocity on a track past a planet as in Figure 4A. Of course, gravity from the planet attracts the car and things in it. Suppose there is a mass on a spring inside the car, and the mass is constrained from the side so that it can only move up and down. What will a trace of the motion of the mass look like as the car rushes past the planet?

The most frequently given answer shows a compression of the spring that is symmetrical about a point of maximum compression nearest the planet (see Figure 4B). This solution seems to derive from a *spring scale* primitive—that squishy or springy structures compress according to the force or weight put on them.[27] This much can be read very directly from some protocols (see the example that follows). The *spring scale* primitive is probably learned with some version of weight, bigness or massiveness being the controlling attribute of the compressing object, but the transfer to a force interpretation in the course of physics instruction appears to be unproblematic. If asked for a justification for their initial responses to this problem, students often use Hooke's law, that the force exerted by a spring is proportional to compression; because gravitational force varies symmetrically on either side of the planet, symmetrical compression is predicted. That is to say, there is a garden-path route using instructed concepts that justifies the incorrect intuition. The bug in this justification is that the force of gravity is not the same as the force exerted by the spring. If it were, there would be no motion. Thus subjects seem to be assuming a dynamic equilibrium between gravity and the spring force.

The correct answer is shown in Figure 4C. The spring reaches maximum compression after the car is past the planet, and in fact it oscillates up and down. An important observation to which we return shortly is that the incorrect answer is actually correct in the static limit, when the car is moving arbitrarily slowly past the planet.

The incorrect answer shows remarkable robustness. Students literally discuss the problem for hours without coming to see the oscillation entailed. None of the students interviewed on this problem as part of the formal study even mentioned oscillation as a possibility during the initial ½ hr with the problem. One

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[27]This does not necessarily entail seeing the springy object as an agent pushing back, as is required of more sophisticated versions of springiness.
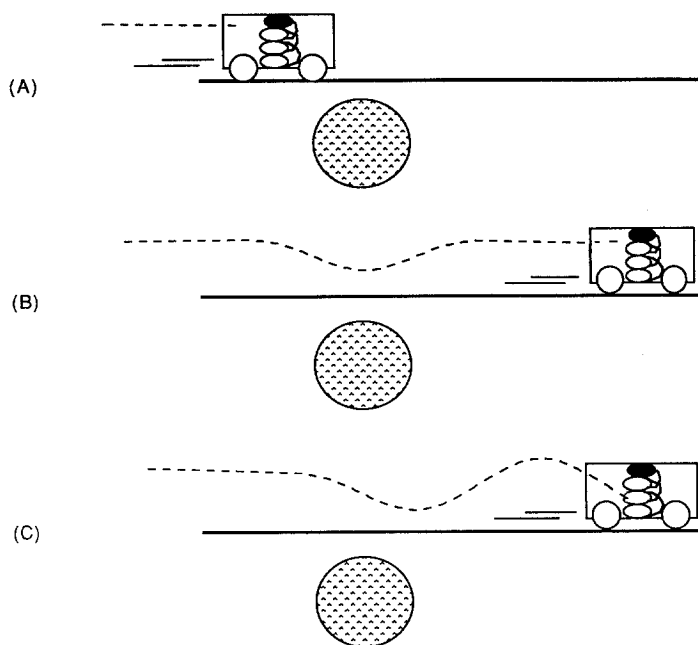
FIGURE 4   A boxcar in space whizzing past a planet.

might have expected oscillation to be attached to springs as a default behavioral attribute, much the same as impetus or intention ("wanting" some result) is attached to electric motors. This would cause oscillation to occur at least as a weak hypothesis about the behavior of the spring, even if it were delayed in consideration or rejected eventually in favor of the spring scale. But it appears that oscillation is much less strongly attached to springs by novices than by experts. This empirical fact is consistent with the proposal made in diSessa (1983) that the effective novice version of the fundamental behavior of springs is more like squishiness (large hysteresis) than springiness, so oscillation would be systematically underrepresented in answers. Recall the student who thought about the brick that was pressed down on a spring and then released in terms of a gradual return to equilibrium—the damped shock absorber image. In an attempt to help her think about the problem dynamically, I literally built an analogous system, a weight hung from a rubber band. She refused to believe the system would oscillate if pulled away from equilibrium but, instead, maintained it would just return smoothly to equilibrium.

During the course of discussing the railroad car in space, I uniformly tried various techniques for cuing a perspective different from the static spring scale image. Following are some sample probes and typical responses, the latter in italics and parentheses:

Imagine the car is going faster still. Would that make a difference? Can you motion in the air how the mass will move? (*Very fast hand motions up and down are typically produced.*) What is responsible for the mass moving upward much more quickly in that case? Isn't it the spring? Is the spring getting stronger? (*Yes, the spring is what pushes the mass up. No, it's not getting stronger. The mass just moves upward faster because the car is moving past the planet faster.*)

Note how the primitiveness of the *spring scale*, that it "just happens," is here replacing a physical analysis in terms of force and acceleration, the only legitimate principle of (change of) motion. Although admitting that it must be the force of the spring that causes return to rest length, that pronouncement of cause is not systematically maintained: Instead of observing that the spring force would have to change in order to produce quicker return to rest length and then considering the possible cause of that change (there is none!), the student maintains the nonphysics analysis by returning to the spring scale image. This kind of fluidity of causal linkages seems typical of intuitive analyses. Again, novices use primitive phenomena in place of analyses based on higher reliability notions. Their sense of mechanism does not require the use of the more restricted set of qualitative primitives used by experts, even when apparently attempting to check a proposed solution thoroughly. Schemes such as spring scale are cached as likely solutions at a level of confidence indistinguishable from physically justified explanations.

Imagine you, yourself, are the mass on the spring. What do you feel as far as the force of gravity is concerned? Eventually I convince students, if they do not see it for themselves, that when the speed of the car is very high, gravity acts just like a hammer blow to the mass, a downward force that comes and goes very quickly. (*Students still maintain the symmetrical solution, that after the force of the hammer blow is gone, no matter how quickly, the mass must have returned to an uncompressed state.*)

Note how in this context students simply do not perceive the force of gravity as supplying an impetus, which must then die out or be countered by the force of the spring. Intuitive physics is context fluid (with respect to the way physicists define contexts), and, in this case, *spring scale* dominates and suppresses more dynamic reasoning.

Describe to me the motion of the mass if there were no spring at all present. (*The mass continues moving down until it hits the floor, possibly long after the car has passed the planet*). Now, what if one inserted a very, very weak spring? (*Reversion to symmetrical prediction.*) Isn't that discontinuous behavior puzzling? (*Sometimes it is perceived as puzzling, but typically not enough to overcome confidence in the symmetrical solution.*)

A quotation from a protocol of a student who had, during about 45 min, been brought along this path of questioning should bring home the point. What makes this protocol particularly striking is that the subject, D, was an excellent physics student. He showed no trace of inappropriate *force as a mover* analyses and, as far as I could tell, reasoned flawlessly about the basic effects of force on objects. He did not have any trouble with reaction forces. To indicate his level of sophistication, when posed the question about what would happen if there were no spring, he observed that the mass would then be in orbit and travel on a hyperbolic path (exactly right). When queried about what would happen with a very weak spring, he reverted to the symmetrical prediction but was troubled without being prompted. How could this minor change of inserting a very weak spring cause such a big change in the resulting path? After spending about 5 min worrying about this, D said (Ellipses denote pauses; parenthetical remarks have been added to clarify context.):

You know, I've been explaining it to myself as basically the compression of the spring is a measure of the force, and so . . . almost . . . basically like having a bathroom scale with the mass sitting on it. You would weigh the most (most gravitational force) at the closest approach (to the planet) . . . and I think that is an accurate way of looking at it. But, um, I don't know. I really can't explain why basically a small change—having a spring and adding a little bit of tightness to it[28] would move that point (the point of most downward motion) so far (from infinity, to near the planet).

D straightforwardly and consciously examined his reasoning, even to the point of describing the primitive analysis (bathroom scale) in essentially the same terms I do. Yet he did not retreat from that into an analysis in terms of forces and velocities, which I have no doubt he could have done if directly pressed, an analysis which would have derived oscillation. Instead, he judged the p-prim sufficiently reliable to stand on its own, on a par with basic physical law. D ended the 1-hr interview concluding that he still believed the symmetric solution and thought, somehow, the discontinuity problem could be solved. A p-prim here simply replaced, by virtue of context (the spring problem), his knowledge about the details of force and motion, knowledge that was intact and working in other problems. The fact that even this relatively sophisticated novice could be satisfied with an analysis on the basis of a relatively noncentral p-prim such as the *spring scale* rather than moving to more physically central analyses is a strong indicator of the continued shallowness of novice explanation. It also indicates the difficulty of building the deep explanatory network of experts, deep in the sense that experts can always be more careful, retreating at need to sanctioned and richly encoded notions such as physical quantities and laws.

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[28]We had been talking about the case of no spring as having an infinitely loose spring and then increasing its "tightness" just a little bit. D had no difficulties thinking about infinity and limits.

It is worth unpacking the notion of a physicist "being more careful." The point is not that novices do not write down equations to derive oscillatory behavior; experts do not do that either in problems such as these. The point is that an expert's qualitative analysis can be improved by using intermediate priority phenomena (distributed encodings), as well as by resorting to the highest levels of the knowledge system, say, expressed in analytic versions of physical laws. Consider the following two examples of phenomena having to do with momentum that help experts deal with dynamic situations better than novices.

First, momentum may be perceived phenomenologically in the tendency of an object to keep moving in the face of resisting forces. That "braking scenario" may sound trivial, yet it is precisely what the novice mentioned before does not see in the downward motion of the weight in the boxcar. The spring is supplying a braking force to the downward motion supplied by an impulse of gravity. More cases of ignoring momentum in this phenomenological sense will be introduced later.

The second commonsense phenomenon that turns out to be more common sense for physicists than novices involves the case of a moving object compressing some other elastic, spring-like object. In such circumstances, momentum may be perceived as being "used up" or, better, "poured into" the compression, which leads to a rebound. "Momentum poured into compression" is a midpriority analysis in expert thought that is the replacement for naive bouncing.[29]

Braking and momentum poured into compression are more important to physicists than to those with a naive sense of mechanism. On the other hand, although they are not quite naive phenomena, these scenarios also cannot be mistaken for conservation of momentum or energy in any formal sense.

Other examples.   I believe there is an important systematicity reflected in the fact that the intuitive response to the railroad car problem is the static limit of the correct response. Let me mention some other examples of situations in which phenomenology abstracted from static situations is applied uncritically to dynamic situations. Figure 5 depicts an extremely compelling image of tides on the earth as caused by the moon. Water simply sloshes over in the direction it is being pulled by gravity, as if the moon and earth were nailed in place. In fact, the earth is falling toward the moon due to gravitational attraction. This causes two tidal bulges, one on the side of the earth facing the moon and one on the other side.[30] This situation is complicated by the fact that, even if one thought

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[29]Readers may protest that it is really energy rather than momentum that is "poured into" the compression of the spring. This is a proper refinement of the intuition; however, at the level of a recognition that would cue different behavioral assumptions in problems, I do not believe the distinctions among motion, momentum, and energy are encoded.

[30]Because the earth experiences a stronger pull than the bits of water farthest from the moon and less strong than the bits closest to the moon, it falls at an intermediate rate. (Imagine three cars of decreasing power lined up at a stoplight. On the light turning green, the cars spread apart just as the "inner tide" gets ahead in falling toward the moon, and the "outer tide" lags.)
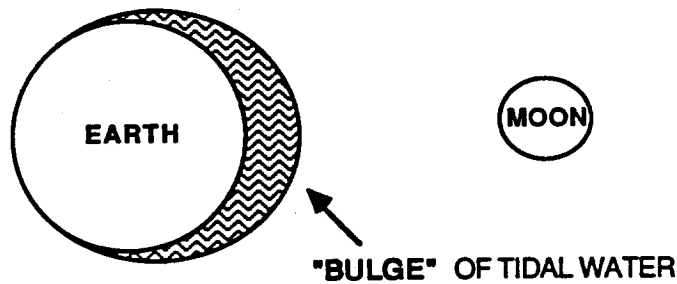
"BULGE" OF TIDAL WATER

FIGURE 5   An image of tides: The moon's gravity pulls Earth's water toward it.

of the situation dynamically, the motion of the earth is usually ignored in comparison with the larger motion of the moon. "Very big things just do not move," might be a verbal expression of this heuristically useful phenomenological assumption. Tides would be easier to understand if there were water on the moon, the *outer* lunar existing because of the centrifugal force from the moon's orbiting.

A well-known tricky situation for novices and even unwary experts involves a weight falling while attached to a string as in Figure 6. The temptation is simply to assign tension to the string as if it were holding the mass at rest. In reality, because there is acceleration, the tension in the string is less than the static situation. A static problem solution is here applied uncritically to a dynamic situation, which suggests that the knowledge system either does not easily recognize dynamic situations or does not know that they are essentially different from static ones.

The *force as a mover* primitive, which shows itself so prominently in dynaturtle problems and in nearly everyone's judgment that the behavior of gyroscopes is counterintuitive, is a prime case of a phenomenon that is (a) abstracted from
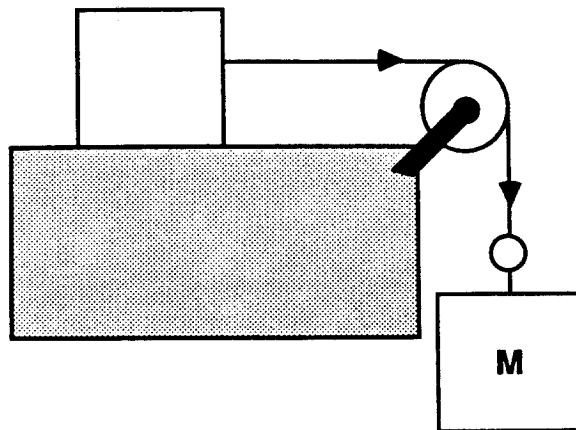

FIGURE 6   What is the tension in the string holding up M?

static situations (pushing on objects at rest) and (b) applied indiscriminately to dynamic situations.

Force as a mover or a closely related phenomenon appears in a problem first studied by Viennot (1979) and later by McCloskey: What happens if the supporting string of a pendulum is cut at various stages of its back and forth oscillation? (see Figure 7A). Figure 7B shows the prediction of *force as a mover*: Gravity pulls the pendulum straight down, *independent of existing momentum*. Because gravity is generally not thought of as a violent push or shove, I believe it is a separate primitive phenomenon doing the work in this case: *Released objects fall (straight) down*. The difference between this and *force as a mover* is that the former does not concern itself with agency but merely asserts as a default assumption that things fall down. Undoubtedly, however, subjects would appeal to *force as a mover* as justification if the shallower primitive were questioned. *Released objects fall* shows precisely the same omitted precondition as *force as a mover*: It is semistatic in that it ignores initial velocity. So even if *released objects fall* and *force as a mover* are separately encoded phenomena, the two notions nicely parallel and reinforce one another.

A surprisingly frequent error is to pronounce that the acceleration of a body at the peak of a toss is zero (Reif, 1987). In actuality, the acceleration of a body during a toss is always a constant downward quantity. This error fits the pattern of focusing on static aspects of a situation (a point of rest), ignoring the dynamic context (the point of rest is of infinitesimal duration and occurs within a process of constant acceleration).

Finally, I mention a class of interview problems from my study that I have not yet discussed. These have to do with weighing in a broad range of circumstances, in particular, weighing objects in downward moving or downward accelerating elevators. What is the reading of a scale supporting an object in an elevator going down? The most primitive responses are topological: If the object is on the scale, the scale should show the object's weight. Obviously, only a superficial mechanism is evident in such an explanation. Although those who proposed such predictions often realized that the elevator and attached scale could "run away" from the object, and that as soon as contact was broken, the scale could no longer read the weight of the object, the dynamics of the situation ap-
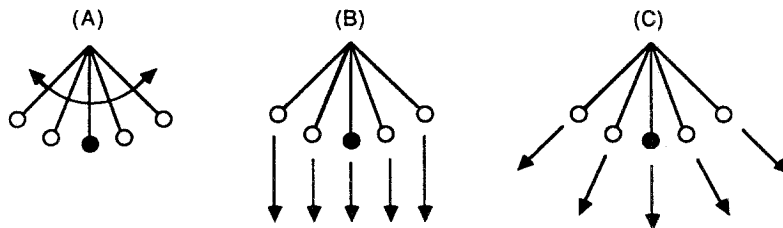

FIGURE 7   (A) The string is cut on a pendulum at various stages of its swing. What happens? (B) The pendulum falls down. (C) The pendulum falls "away."

peared irrelevant to them up to the "break-away" point. Their reasoning was essentially static: "If the object is on the scale, the scale measures its weight; if it is not on the scale, the weight is not measured." Before examining the roots of the static predisposition, we turn to a simpler but related issue.

Figural Primitives

The second class of systematicity appears in the use of figural patterns, judging plausibility of motions on the basis of the form or overall visual pattern of a trajectory. One example is the acceptance of circular motion as a primitive in situations in which obvious circular symmetry exists. It also seems plausible that the left–right symmetry of the railroad-car-in-space problem directly encourages the symmetrical prediction of the static spring scale phenomenon rather than the evidently asymmetrical dynamics.

Emphasis on figural patterns rather than on the mechanism or dynamic pattern generally plays a role in the static predisposition. I propose, however, that that role is separable from the semistatic phenomenology described earlier. I propose that figural patterns constitute a relatively primitive and modular piece of the developing sense of mechanism.

Although children often use judgments on the order of "it looks right" to make decisions about what happens in physical situations (Piaget & Inhelder, 1966/1971), physics students seem to lose confidence in the explanatory power of figural patterns sooner than with core and evidently behavioral statically oriented phenomena such as *force as a mover*. Thus, McCloskey found Figure 7C as a response to the pendulum problem, whereas none of my presumably more sophisticated MIT subjects gave such a response. I have found, however, even sophisticated adults, such as nonscience graduate students at MIT, who think that an orbit around a cubical planet should be notably square (Figure 8) and that elliptical orbits can only exist if the shape of the attracting body is nonspherical. So the

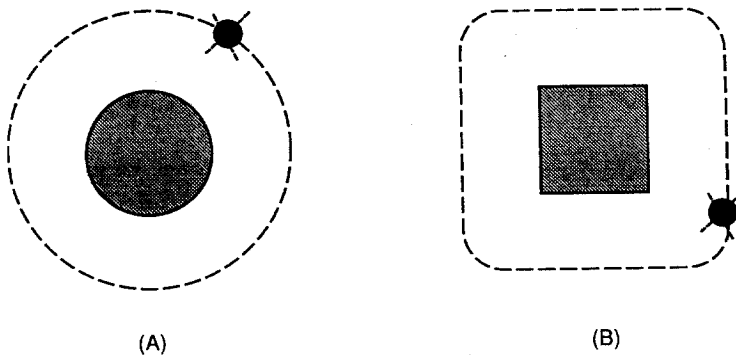

(A)   (B)

FIGURE 8   A prediction that an orbit around a square planet should be figurally similar.

downgrading of figural patterns in the sense of mechanism might specifically have to do with instruction.

It is worth commenting on an important possible exception to the modular reduction in priority of figural primitives. *Abstract balancing* seems to have much in common with figural primitives; it is cued, at least under some conditions, by spatial symmetry, and it is more a mathematical constraint than a mechanism. Yet, if it belongs to the class, it must become separated from other figural primitives, because experts have a rather specific need for it in the more mathematical side of their reasoning. Further, symmetry considerations eventually become linked to deep notions of mechanism in physics, so some aspects of figural reasoning might well be encouraged and survive.

There are reasons not to be too concerned with the apparent exception *abstract balancing* provides and with the potential link figural primitives might have with symmetry. *Abstract balancing* is abstract and may be relatively easily separated from genuinely spatial figures if the connection is ever strong. Indeed, as pointed out earlier in the monkey problem (p. 137), one thing students learn is not to interpret *abstract balancing* as relating directly to spatial symmetry. In introductory mechanics, one uses the primitive mostly in the context of algebra (e.g., expressing conservation of energy). Learning that one may use *abstract balancing* in such a narrow context should be relatively unproblematic. Symmetry considerations, which might reinforce figural considerations more widely, are usually barely touched in elementary mechanics. It is more prominent in advanced mechanics (Hamiltonian and Lagrangian methods) and in field theories such as electricity and magnetism.

How do we understand figural patterns to constitute a module in terms of the basic assumptions about the sense of mechanism expressed in the Theory Sketch section, particularly the assumption of fragmentary learning, mostly p-prim by p-prim? First, all figural primitives relate to Newtonian mechanics in essentially the same way. They are irrelevant. Thus, learning will not force students to treat them individually. Second, it does not seem unreasonable to assume that figures might be naively perceived as a class of recognitions. Thus, students could be adding a prominent meta-p-prim that deals with a common abstraction of the many figural primitives: "Figures are not relevant to how mechanical systems really work." Naturally, one would not expect to see a monolithic change in the status of figural p-prims in any case; some figures may lag or lead development. But a class abstraction could go a long way toward creating a module of phenomenology.

Ackermann (Ackermann-Valladao, 1981) has done some careful studies of the development of the notion of horizontality in children. These studies show some aspects of the early use of figural primitives and their demise in thinking about physical situations. The particular question she considers is how the level of water appears in a jug if the jug is tilted or even inverted. The youngest children always use the canonical, static image of water in a jug and draw the water

level near the base of the jug, parallel to it. Near-transition children can be provoked to change their answers by reminding them of phenomena such as the fact that "water falls down" or of images such as drinking from an inverted bottle, in which water must move to the mouth in order to be drunk. These children sometimes revert to the jug-frame image when encouraged to draw again, suggesting that the act of drawing, functioning something like a modality, encourages static imaging and suppresses more dynamic insights.

More generally, Ackermann traces the genesis of absolute-frame horizontality to gestural and dynamic imagery and sees the suppression of the mode of thinking associated with drawing, sometimes even self-conscious suppression, as important to the eventual understanding of horizontality. An analysis parallel to that suggested before is that children have or develop a family-resemblance sense that detects "drawing instincts" as a particular class of thinking, thus allowing the systematic reduction in their priority in the case of physics-like questions.

Church and Goldin-Meadow (1986) uncovered striking phenomena concerning such modalities. They show that children who give evidence in gestures of knowledge that differs from their verbal explanations are often near transition to a new stage of understanding. Such children are substantially more receptive to instruction than children who give no signs of having divergent conceptualizations in their gestures. However, these authors make little of the difference in modality, other than providing evidence of knowledge presaging transition. For example, they make no observations relevant to children's awareness of "different ways of knowing." For my purposes, unfortunately, it is less relevant that there are modes in knowledge than that knowers perceive such modes.[31]

These considerations are speculative. The data even undermine the modular contention somewhat in that, if children come to perceive gestural or dynamic primitives to be more relevant to situations such as the horizontality of water than figural ones, that clearly does not spread broadly to the use of figures like circular patterns in orbits. (At least it does not spread until the more systematic intervention of physics instruction.) Nonetheless, the sensitivity to modes of understanding would represent a possibly high-leverage development of meta-knowledge. Generally, phenomenology of phenomenology—abstractions that help define classes of phenomena and their applicability to classes of circumstances—may contribute some of the broadest and deepest modularities of naive physics.[32]

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[31]The existence of modes—significant chunks of mutual use systematicity—constitutes an opportunity for modular reduction of priorities through mechanisms other than meta-conceptualizations. This is not pursued here.

[32]Empirical pursuit of these questions should include investigating the robustness of, say, the figural answers to the pendulum problem, in response to interventions like Ackermann's: If students are asked the pendulum problem, say, in the context of dynamic simulation rather than in McCloskey's paper-and-pencil style, answers may change. In this context, see Kaiser, Proffitt, and Anderson (1985).

Explaining the Static Predisposition

The tentative descriptions of figural primitives as a module leaves the broader question of the origin and meaning of the static predisposition largely untouched. I make my proposal using an abbreviated "competitive argumentation," building on the examples presented so far and a few related ones, to draw the issues as sharply as possible. The competition is less fair than it might be, because I could not locate any substantial published defenses of the competing positions by the criteria I propose. However, I believe these competitors are interesting proposals that will serve to heighten by contrast some of the points I would make about my own proposal in any case.

Ontological explanations.   I begin with two proposals that are ontological in the sense that they propose that either physics-naive people simply do not have motion as a basic category of thought, or they have it placed in a fundamentally wrong category with respect to its causal nature. Learning must happen by acquisition of a new ontology or a major shift of a category from one ontology to another. A specific version of the former, which has been offered in the case of young children (Henriques, 1984),[33] is that reasoning about motion must be done as a sequence of static configurations and that no properties intrinsic to motion other than those evident in discrete change can be considered. This amounts to always thinking about motion as "snapshots" in time sequence, with reasoning done by comparing those snapshots. Such an argument might conclude that infinitesimal durations of rest are inconceivable inasmuch as a single snapshot shows absolutely nothing about motion, and the pair of snapshots that shows an object at rest also shows an interval of time over which the object is not moving. This reasoning could produce the novice bug of not seeing acceleration at the peak of a toss but seeing instead an at-rest condition of some extended duration. One could argue that the common answer to the railroad-car-in-space problem involved reasoning simply on the basis of a sequence of static images of the mass and the spring in gravities that are stronger at first, then less strong.

The second ontological explanation of the static predisposition is that motion is conceived early on as belonging to the category of "an effect" and that, universally, effects need a cause. This conception is a direct abstraction of the *continuous force* p-prim, effort engaged in the production of motion, although it elevates the level of abstraction and universalizes the relationship. In contrast, according

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[33]Others who hint at ontological explanations of development include Hayes (1979a) and Larkin (1983). The former suggested that the Piagetian development of conservation may reflect a change in ontology for liquids. The latter characterized novices' physical knowledge as strongly constrained by time-sequenced causality (cf. with evidence presented here for the use of figural primitives, which involves limited sequentiality, at best), whereas experts rely only on time-independent inferencing. Chi (1992) has recently offered an ontological account of difficulties in learning that contrasts strongly with the view presented here.

to Newtonian physics, motion is a state of the system and needs no intervention to perpetuate. Only changes in state need causes (forces).[34] Learning physics means motion must no longer be conceived of as an effect.

Because it is not specific about causes of motion, this second ontological explanation may be further specified by any number of kinds of causal relationships, although presumably the principle loses explanatory power and empirical plausibility as a sense of mechanism if it strays far from mechanical (forceful) interventions as the type of cause. "The object's whim" as a cause can explain arbitrary motion too easily.

A counterproposal.   Rather than proposing a competitor for these immediately, I will let it emerge from criticism of them. Three classes of criticisms are presented next as follows: theoretical inadequacy, empirical inadequacy, and subsumption into a better articulated competitor ("knowledge in pieces"). In the course of argumentation, I note three basic differences from the case of figural primitives. First, these ontological proposals are so broad and deep, covering the whole of the sense of physical mechanism, that a monolithic treatment, say, as a single modality, is extremely unlikely. Second, unlike figures, it does not appear plausible that any single meta-conceptualization can be responsible for a categorical unity. Third, the development of an expert sense of mechanism cannot treat all naive p-prims that might adhere to the naive ontology uniformly. Some of them are essentially correct and, unlike figural primitives, are needed at relatively high levels of reliability priority. Hence, learning will be more distributed, distinguishing the useful p-prims gradually from the less useful ones.

1. *Theoretical inadequacy.* The program I set forth in the second section of this monograph provides a set of questions to ask of any proposed description of a knowledge system. The target of these questions here is the encoding of ontological static predispositions. To take steps beyond a commonsense epistemology, one has the obligation to begin making more precise descriptions of proposed mental structures like ontologies.

A refinement of the commonsense description of these ontological proposals might be attempted along a number of lines, say, as specific rules or propositions, or as a propositional system. The latter has not, to my knowledge, been attempted. Rather than pursue these (in my view unlikely) possibilities, I briefly investigate refinement along the lines of the p-prims theory sketch. The major difficulty here lies in describing the integration of a diverse set of p-prims, the presumed origin of the naive sense of mechanism, into a monolithic ontology.

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[34]Philosophers, notably St. Thomas Aquinas, have considered the universality of the proposition that motion needs a cause in proofs of the existence of God: "There must exist an unmoved mover." Similarly, the claim that even existence needs a constant cause leads to the same conclusion. I do not take these arguments to have great intuitive force, despite their intuitive roots.

Any proposal that requires very broad or universal application of categorizations (change, cause), as ontologies do, is suspect on grounds of genesis and development. The processes that decide whether something necessarily must be interpreted as a change must be elaborate to be reliable. One needs to accumulate significant stores of knowledge specific to the many special contexts of application in order to classify reliably. Beyond classification, the spread of confident use of a p-prim such as *motion needs a cause* requires more than seeing the term in the situation. It requires seeing the entailments of the p-prim as basic and explanatory of all those circumstances that initially would be covered by more specific p-prims. Consider the arguments made about Newton's third law. P-prims are simple to generate but very difficult to elevate to universal status. Similar criticisms apply to any proposed universal method of viewing phenomena. For example, the ability to formulate and confidently apply a reduction, such as seeing all change as sequential snapshots, must be complex. These criticisms are played out empirically with reference to particular problems of universalizing across contexts next.

This line of argumentation is subject to a substantial challenge in that *motion needs a cause* may be a meta p-prim, an abstraction common to many unproductively causal p-prims. Causal syntax is a similar common abstraction. However, the story of causal syntax regarding development to expert thinking is not nearly so simple as that of figural primitives. In the first instance, causal syntax is in some ways productive. It is certainly encouraged at early stages of learning $\mathbf{F} = \mathbf{ma}$, and it is even correct if change is interpreted uniformly in the Newtonian way (i.e., as acceleration). More generally, one simply cannot treat all p-prims adhering to causal syntax uniformly in looking toward expert understanding. Although many primitives that obey causal syntax (e.g., *sucking* and perhaps even *continuous force*) must be reduced in priority, others (*force as a mover*) are certainly used by physicists. Moreover, even in the cases in which causal syntax succeeds, deep and complex refinements are necessary, as indicated in the discussion of action and reaction in the Development section.

It may generally be easier to dismiss a module from the naive sense of mechanism than to integrate it properly with Newtonian mechanics. Although one cannot rule out a priori that there exists a naively perceptible category other than causal syntax that unifies *motion needs a cause* in such a way as systematically to undermine exactly those primitives that need undermining and to advance those that need advancing, such a prospect is dubious given the case study of the causal syntax as a precedent.

2. *Empirical inadequacy.* On the basis of the empirical work already discussed, I can be very specific about some deficits of these ontological explanations. These will be the complement of the arguments just made. Not only is it unlikely that *motion needs a cause* is a disapproved module in the expert sense of mechanism, but also the idea is hardly a universally approved module in the naive sense of mechanism.

It seems clear that physics-naive people have dynamic p-prims that violate the *motion needs a cause* dictum and the specification that dynamic phenomena can only be considered through the lens of sequences of static states. One of the findings—more properly, it was a nonfinding—of dynaturtle experiments (diSessa, 1982) was that, although people often ignored the preexisting motion of an object when it was pushed, they had no objection at all to the continued motion of dynaturtle in the absence of pushing. Within the small confines of motion on the screen, not a single subject questioned the turtle's continued motion or suggested any reason for it. An object continuing forever is one thing, but relatively limited nonforced motion is not only not problematic, but it is also expected. And there was no indication that subjects were inclined to combine the cause of continuing motion with externally supplied pushes. If one retrenches to allow nonlocal causes such as the initial push of a hand in a toss, Newtonian physics is not in contrast to *motion needs a cause*, because one may properly speak of the push as the supplier of momentum and, hence, as the cause of the motion.

Another counterexample was provided by the student who had the more static shock-absorber image rather than oscillations attached to springs as default behavior but who, nonetheless, conceived of other dynamic events such as *bouncing* as "what is going on" when one throws a brick onto a spring. Except that it occurs in a particular context, there is little basis for distinguishing the release part of the press-and-release concept from a situation such as a manual toss of an object not involving a spring, in which there would be no doubt that the object could be thrown into the air. More particularly, there cannot be a distinction between the release phase of press and release and the rebound phase of the throw onto the spring based only on a sequence of static states. The maximally compressed spring is static-state identical in the two cases. To the student, the two are distinguished by one being in the midst of a bounce. The distinction may sound strange, but it is identical in form to the physicist's insistence that velocity, being in the midst of linear motion, distinguishes motion from rest. The choice of what a thing may be in the midst of is the only distinction. Indeed, the very notion of a body experiencing a force, which is naively unproblematic in some cases, implies a class of goings on different from what can be "seen" in snapshots.

In experiments on circular motion—a ball on a string, say—children at various stages of development see different things going on. Thus, what is natural change and what needs intervention is neither fixed nor universal. Early on, children may see circular or at least curvilinear motions as primitive goings on. At more advanced stages, more often they see the object engaged in linear motion that is disrupted by the string. In both cases, children often follow (sometimes articulately) a heuristic that contradicts *motion needs a cause*. They say that what is going on will continue unless some sort of intervention is made (Globerson & diSessa, 1984). In this context, we saw young children who predicted that motion should stop altogether when the string holding it in the circle was cut, not because the cause of motion had ended, but because the ball "would not know

which way to go." More telling, reactions to a simulation of a ball stopping when the string was cut were not approval but subjects' announcements that there must have been an intervention to stop the object. Absence of motion, in the context of very rapid cessation, needs a cause other than the cessation of an external intervention.

To summarize, the sequence-of-static-states dictum predicts an unacceptable restriction on the class of expectations about motion in view of the rich phenomenology that the empirical bases of this work show. The naive sense of mechanism responds favorably and primitively to many essentially dynamic goings on. Some may need causes of certain kinds, but they by no means all categorically need constant, interventive causes. To patch the argument by asserting that only unnatural changes need interventions begs precisely the same questions about what constitutes the categorization into natural and unnatural changes.

3. *Knowledge in pieces.* It is time to discuss a specific competitor to the ontological proposals, which, naturally, is drawn from the theory sketch and details of the naive sense of mechanism as they have been laid out. My basic contention is that the static predisposition is a relatively broad but still idiomatic systematicity that is not categorical. In particular, I identify a general but not a universal dynamic impoverishment. The elements and, more generally, attributes of the naive sense of mechanism are skewed toward static phenomena, particularly at the highest priority levels. Thus, although dynamic phenomena are perceptible and readily used, when it comes time to think carefully and explain, thinking moves (a) toward statically perceptible attributes such as geometric position and orientation and (b) toward the higher priority causal primitives such as the interventive *force as a mover* or *continuous force*. Thus, although everyone knows that motion perpetuates itself, it is tempting to think in terms of an internal intervention as a deeper mechanism if the issue is specifically raised. But, although it may be suggested, there is simply not enough structure in the knowledge system to support that interpretation universally, and changes in the situation would revive less mechanistic p-prims, such as simple "return to equilibrium."

This impoverishment with respect to dynamic descriptions and gradient in confidence favoring statically describable phenomena should not be surprising in terms of the properties of our sensory system with its strong reliance on vision and spatial relations. Phenomenology consists, at first, of minimally abstract interpretations based on strong vocabularies. If our touch sensitivity were as structured as vision (e.g., one could see forces as positions in force space), and, indeed, if we had remote touch-sensing capabilities instead of being confined to where we can put our fingers, things would likely be different. Instead, we make use of whatever we can readily see that correlates with the structure of motion. Thus, for example, figural p-prims stand prominently to be abstracted, and these are only undermined and replaced very slowly by the weak force of evolving priorities. I have already gone some distance toward assimilating the insights of the

two ontological proposals within the broader framework of knowledge in pieces. Let me continue doing so.

First, I have localized the *change needs a cause* dictum to phenomena similar to *force as a mover* and *continuous force*.[35] This move has the advantage that what counts as change is specified by the local knowledge elements, not by some universal frame. We do not have to decide what qualities of motion are essential to motion in order to define the static predisposition. Defining qualities essential to motion was difficult for Aristotle, and even if we, as theorists, can do it, it seems unlikely that children solve the problem intuitively in any general way. If we take this conservative position, that the problem of causality is at best solved locally, it need not concern us if in a situation of clear symmetry, circular or return-to-balance motion needs no interventive explanation, but outside of those circumstances it requires intervention. We need not concern ourselves with the dubious task of defining change in terms that contrast short-term continuations of motion (which in general need no explanation) from perpetual motions (which more often appear to need explanation). The knowledge-in-pieces view is that many kinds of change need explanation but that there is no universal characterization of change that covers the circumstances in which people feel the need, or not, to look for deeper causation. Instead, these predispositions are distributed according to the kind of change; that is, they are embedded in the primitives that connect to the particular circumstance.

A piece of insight at the root of the snapshot ontology is that, within the naive sense of mechanism, the at-rest condition is a very special goings on. Being at rest is an important attribute of situations that determines the way people think about them. Thus, rest accumulates many coordinate attributes special to it. In general, although not universally (e.g., sudden stopping is an exception), rest needs no explanation, and it participates with interventions in very particular ways. For example, rest is expected to be a terminal condition with indefinite continuation in noninterventive situations. (Motion dies away to rest, which continues indefinitely.) Or, rest is self-perpetuating prior to an intervention. These terminal and self-perpetuating attributes for rest make it difficult, although not forbidden, to conceive of rest as a transient phenomenon, as at the top of a toss.

In contrast, rest and motion are only accidentally distinguished in a Newtonian frame. The at-rest state of an object is, to a physicist, not a particularly distinguished class of goings on. It is in no way intrinsic to the phenomenology of any situation. The very fact of nonmotion is dependent on the accident of picking a frame of reference with the same velocity as the at-rest object. To a novice, things such as acceleration evidently belong to the phenomenology of things in

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[35]This needs qualification. There seems little doubt that *change needs a cause* is an early developing notion. Children take spontaneous motion of certain sorts as something that needs explanation; in fact, they take it as a primary cue to "alive," at least in situations in which the issue is to determine whether a thing is alive or not. But it is one p-prim among many; it does not follow that children cleanly and with high reliability encode the general principle that change needs a cause.

motion. They need specific consideration in cases of rest ("top of the toss" implies no acceleration misconception) to be seen as applicable at all. A physicist generally does not treat at-rest situations differently from those involving motion.

One of the theoretical advantages of this assimilation of the insights of ontological proposals to the knowledge-in-pieces perspective is that one thereby has a more uniform view of the naive sense of mechanism. Instead of singling out a particular class of elements, relations, and systematicity (e.g., static elements, some particular notion of change or cause) for special treatment, we can see all of the things that people know about motion in a uniform light. We no longer are challenged to compare the status of categorical aspects of the knowledge system—aspects such as ontological knowledge—with all the bits and fragments that we can easily see people using in reasoning about the physical world. Facts such as that objects move continuously or that there exist only certain kinds of causal interactions (mechanical, not directly willful causes for an inanimate object's motion) do not need to be patched into the snapshot view as subsidiary conditions.

Finally, the ontological proposals miss entirely the substantial structural changes that occur in the sense of mechanism. The knowledge system starts as distributed and fragmented, and it evolves to one that, on the basis of a broad integration, manages to think about a very broad range of situations on the basis of a few universal causal mechanisms. These physicist universals include the lack of need to explain uniform motion in a straight line and the possibility of explaining all other changes on the basis of a very restricted class of interventions (i.e., mechanical, gravitational, or electromagnetic forces). In contrast, ontological and indeed all categorical proposals treat naive and scientific senses of mechanism as if they were on par, suggesting that one learns by trading one ontology for another.

COGNITIVE MECHANISM

The ultimate goal for the work represented in this monograph is a computational theory of common sense and intuitive knowledge and its evolution into scientific understanding. Although this work is still relatively far from implementable precision, one may still benefit from clarification and further motivation of the assumptions about mental mechanism that have been used as a descriptive language for empirical observations. This would both clarify the meaning of statements made in terms of the mechanism and better specify the intended range of the theoretical perspective. I take it as a nontrivial contribution of this monograph that it joins important phenomenology of learning physics to simple, formalizable cognitive mechanisms (structured priorities). With the exception of the final subsection, this section will likely be of interest mostly for those readers concerned with issues such as choice of modeling language and the relation of cognition as modeled to cognition as abstracted from protocol behavior.

The predominant use of *mechanism* in this section, of course, refers to mental mechanism rather than to the physical mechanism that has been the dominant focus up to now. This monograph is recursive, however, in that it attempts to provide a sense of mechanism about certain activities of mind. This section is an attempt to point the way from an orienting, although not compactly and rigorously specified, sense of mental mechanism toward a simple core.[36]

I improve the description of the model of mental mechanism in steps: First, I review the motivations for the program of research that are relevant to selecting the way cognitive mechanistic substrate is modeled; second, I clarify the mechanistic model itself; third, I clarify the context for interpreting data in terms of the model; and, finally, I abstract and extend slightly the observations that have been made about the systematicity of naive physics to the point of understanding how they might be relevant to other areas, such as intuitive "social relations" and schemes of story comprehension.

Motivating the Modeling Language

That knowledge comes from experience is a truism. Yet much of the research in cognitive science in the area of developing expertise, mental models, and novice—expert differences has been on the basis of assuming powerful knowledge representation schemes and processing organizations that seem to presume far more uniformity than the texture of experience indicates. Compare production systems' universal activation in well-specified circumstances to the vague impressions one has of productive or unproductive directions in problem solving or of relative satisfaction with a solution in contrast to termination of an algorithm. How do we model impressions and their effects?

Empirical results, such as those presented here, indicate complex, conflicting, and unreliable strands of reasoning in which students may be guided by aspects of the circumstances that they cannot articulate or check. This also suggests care in modeling. Do we simply not consider the fact that students may never be able to reinstantiate a particular mental state that accounted for a judgment (a "once-in-a-lifetime" production?), in strong contrast to experts who can simply "solve the problem again"?

Using powerful processing or knowledge representation schemes without the constraint of understanding how the particular forms of knowledge and reasoning are learned may well miss some of the most basic and difficult parts of learning. Even if we can roughly describe the data and processing schemes of one level of competence, understanding the development to the next level may force us to look for invariants in the pieces of encoding. How does the descriptive sys-

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[36]The core, however, cannot operate as a theory without interpreting phenomena such as those described in previous sections. This is similar to the relation of formulas and propositions to the broader sense of mechanism that I have argued is important even in expert physics.

tem that specifies the conditions for actions develop? The descriptions of new conditions are unlikely to be simply constructible combinations of attributes easily available from prior stages of competence, at least if substantial conceptual change is at issue. Instead, one may need to rebuild on lower level or just different primitives. Sensory schemata at fairly low levels may need to be recrafted or reselected to "see the world in a different way." Building the descriptive capability and the systematicity necessary to instantiate a rule reliably in a relevant context might be a substantial problem for knowledge systems of the type described in this monograph. Hence, it would be very easy to gloss this concept-specific development with the insertion of a rule and presumption of powerful and generic rule-processing capability.

Similarly, goals as computational constructs that operate in relatively clean planning or problem-solving schemes may well be some of the last kinds of mental objects created in a knowledge system; fundamentally, they may be optimizations in the overall control of an already-operating system with adequate descriptive capability. Certainly it makes less sense to have goals if one cannot reason hypothetically about alternatives. But, considering some of the empirical features of intuitive physics, reasoning about the merits of alternatives, say, different interpretation strategies, seems a rather advanced state. (See the further discussion of "aesthetics" that follows.) It seems more likely that less reliable, more situation-specific "accidents" of cuing drive a naive attempt to understand a system than a collection of preformed goals that organize search.

To take another reasoning scheme, predicate calculus is as difficult to learn as the physical laws whose development is at issue here (Wason & Johnson-Laird, 1972). We certainly should not assume that kind of reasoning infrastructure in modeling how students learn and use physics knowledge, most especially in everyday contact with the world.

Put in computational terms, the symbols or data structures one writes in making a model of a knowledge system may seem compellingly to contain the knowledge we attribute to them. However, data are dependent on the interpreter that operates over them for any meaning they might have. I believe we have little reason to suspect that any natural, general, highly reliable interpreter exists in the mind. Certainly there is, if anything, negative evidence that high-level schemes such as predicate calculus are a built-in interpreter capability. So our epistemological program must include building the interpreter (or more likely, many micro-interpreters) as well as specifying the data, rules, or propositions.[37]

Take the case of production systems in a bit more detail. Structured priorities is a much restricted modeling language compared with typical production systems. To show this, we can model a p-prim as a production that fires (turns on)

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[37]The connection between data and procedures operating on them is so intimate at the low levels of mechanism presumed here that the distinction is useful only to contrast the modeling language used here with high-level systems that depend strongly on such a distinction.

under certain conditions. In a production system, however, knowledge is distributed across (a) the set of productions, (b) a language in which to write conditions for the productions, and (c) a language of mutation for the action side of productions, that is, a particular system for changing internal state. In a structured priority system, the elements themselves constitute the descriptive language; there is no separate language, if we think of this as a "language" at all, to rapidly put together descriptions of conditions. The language of mutation—the set of actions that can be taken—is also exceedingly limited. Roughly speaking, a p-prim may become active or it may turn off. Further implications for the state of the system must follow from the specific connections in the network and subsequent firings of other p-prims.

Is it good to use primitive, noncommittal modeling languages, such as a cuing network? It is clearly not a good idea if the aim is to model knowledge such as routine skill or "instructions following" where one can presume some basic epistemological problems (e.g., reliable, reinstantiatable representation) have been solved, and, therefore, the processes that solve them can be absorbed into the modeling language's capabilities. On the other hand, in some cases it is appropriate for the theorist to take much more responsibility for understanding the evolution and microstructure of the descriptive and mutation languages, in which case, using structured priorities makes more sense. The impediment to learning a production that is part of expert problem solving might not be lack of an occasion for learning it but the very capability to describe and check the circumstances in which it is apt.

I am not making an in-principle argument against any particular modeling languages, but I am highlighting the issue of choice of grain size and the importance of separating the modeling system's intrinsic capabilities from those modeled by the system. Thus, predicate logic and perhaps productions are abstractions and formalizations of a certain level of human reasoning. But, if we are to understand the genesis and detailed functioning of that level, we may need to push to a more fine-grained level where it is not at all obvious these are perspicuous. We must be constantly on guard to prevent the power of the modeling language from trivially explaining and glossing the details of the higher level functioning ("All you need is X production, Y axiom").

In net, my choice of grain size and of assumed inherent processing capabilities for the purpose of investigating the intuitive sense of mechanism is different from those for which many other current knowledge and process representation schemes seem best suited. Although one could possibly handle this with care in the use of the modeling system, I have chosen to handle it by avoiding those schemes and by assuming uniform but very weak representation and processing capabilities. Luckily, these seem to deal relatively effectively with the empirical phenomena at hand, such as context sensitivity, lack of articulateness, and lack of confident application in many instances.

Pop epistemological notions such as *fact* and *theory* are yet more problematic as terms in which to investigate the foundations of knowledge. They are problem-

atic, in particular, for understanding the systematicity or lack of it in naive knowledge. Unless one gets the grain size and the knowledge system's relational structure at least approximately correct, studying systematicity is a hopeless task. Concepts, theories, and facts are loaded with unspecified assumptions about mechanism, modularity, and systematicity. Facts are independent items that must be true or false; theories presume some unspecified but rich internal structure, presumably a structure similar to theories in the highly cultivated and social process of professional science.

Consider the characterization of *force as a mover* as a fact. If a fact is known, it should presumably be taken to be true independent of mental context. Yet, that may grandly overstate the circumstances in which a fact will be thought relevant. How should one describe the relation between *force as a mover* and alternative notions that sometimes compete with and replace that fact, such as figural primitives? One needs something like applicability conditions or a weaker version thereof, such as cuing priority. Characterization as a fact captures nothing of genesis and encoding, such as the use of attributes like pattern of effort, aspects that may help explain the character and applicability of the notion and some of the larger scale characteristics of the system of which it is part. Empirical work couched in pop epistemological terms stands little chance of refining those terms into technically acceptable computational notions that do justice to the empirical features of the sense of physical mechanism.

My intention is to build an epistemology based on fragments of experience, with a commensurate grain size, that makes no *ab initio* assumptions (within the focal sense of mechanism) about modularity, universality of reasoning processes, and other such large-scale issues; the theorist's responsibility to describe and display systematicity will then be evident. One needs a mental mechanism that provides a similarly neutral and unassuming epistemological base on which to pursue questions of the properties of the knowledge system expressed in terms of that mechanism.

As described before, learning is a particularly important constraint when making assumptions about mental mechanism and, hence, implicitly about the grain size, basic relational structure, and assumed (rather than modeled) capabilities. Again, unless one gets such assumptions at least approximately correct, development may appear either magical, "inserting new knowledge," or hopeless. I have been careful to build the concept of p-prim so that genesis is relatively unproblematic— establishing small, rememberable descriptions of events. Similarly, the model provides for development in terms of simple learning events through changing priorities bit by bit, elevating some knowledge structures toward universal prescriptions. Further, any reasoning built into the system will have to be constructed from low-level patterns. Indeed, the development of intuitive knowledge should not at all be expected to reach the systematicity of professional scientific ideas, as we are used to seeing them displayed, in breadth, depth, or quality. Contrast the systematicity that arises from common attributes (base vocabulary) to, say, an axiomatic deployment based on operational definitions.

I presume that conceptual development is a large-scale phenomenon involving substantial reuse of knowledge elements that existed for their roles in previous stages of competence. If it is true that expertise consists of very large vocabularies (e.g., Chase & Simon, 1973), then we should be prepared to look for similarly large systems constituting the competence of common sense. After all, expertise and common sense are built by the same machine over similar periods of time, although their operating characteristics might be very different.

An independent strand of motivation for the presumed mental mechanism comes from considering the basic machinery humans have available to implement knowledge. One of the most remarkable facts about human cognition, especially reflected in expert problem solving, is the quickness and versatility of the information processing. Yet all of this must rely on neural machinery, which has a time-dimension grain size on the order of a few milliseconds. In comparison, the time-scale for operations involved in present computer implementations of cognitive models is about three orders of magnitude shorter, at the microsecond level. Evolutionarily, slow machinery suggests that in order to react quickly to, say, a glimpse of a tiger, humans would need large numbers of recognizers and comparably large connectivities so that any of a huge number of perceptual patterns could construct on short order an appropriate flee-from-the-tiger response. The interest in connectionist models of cognition is inspired, in part, by similar feelings that some basic architectural differences between human processing and von Neumann machines have consequences (e.g., Rumelhart, McClelland, & The PDP Research Group, 1986). The latter have arbitrary data connectivity, but they are serial and hence have limited procedural connectivity.[38] Structured priorities are a mechanism that should be relatively easily refinable into connectionist-style machinery, which does not have limitations typical of von Neumann formulations. I return to these real-time constraints in the Interpretive Summary as they relate to core properties of the sense of mechanism.

Clarification of Mechanism

I have so far mixed functional and structural levels of description of p-prims. Thus, although explanation and providing a "sense of satisfactory description" are functions of interest, structured priorities are intended to be function-independent computational terms. In this and the following subsections, the structural mechanisms and their relation to my use of them are clarified. First, I give a notion of p-prim in purely structural terms and discuss the changes in connotation that result. This description is of a greater degree of precision than currently necessary to support the interpretations I intend but less precise than necessary to implement these ideas. The point is to establish a context for interpretation

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[38]In Lisp, for example, any data element may be connected directly to any other, but procedural entities are connected only in series or recursive hierarchies.

that will correct some misimpressions about the meaning of p-prims that one might get from the examples given. This also sets a better context for the intended direction of future work. Second, I review the connection of these ideas with the empirical context.

The model of mechanism that follows is a fairly generic connectionist system. Consider a set of discrete mental entities, each with an activation level. These are to represent the structural equivalent of p-prims, and if it is important to distinguish them from the functionally defined objects, I call them structural p-prims, or s-p-prims. In standard connectionist terminology, these would be called units or nodes. S-p-prims have an external activation level, in addition to their internal one, that is supplied by connections to other s-p-prims. The external activation should be something like the sum of the (external) activations of all connected elements weighted by positive (activating) or negative (suppressive) factors. A dynamic is required that specifies the time-varying internal activation of an s-p-prim on the basis of the histories of the external and internal activations. A simple model would involve discrete time steps, and it might assign the value of the external activation at one step to the internal activation at the next. Or, in the case of a continuous model, one could use the current values of the external activation to specify the derivative of internal activation with, say, the derivative being proportional to the difference between the internal and external activations, which would lead to the internal activation tracing the external with some lag. A plausible feature of the dynamic would be a nonlinear threshold beyond which external activation would cause the s-p-prim to "lock fully on" and a lower threshold below which external activation would allow the s-p-prim spontaneously to return to zero activation or at least to well below lock-on levels. Of course, many variations and complexities might be convenient, but they are beyond the needs of the current exposition.

This model has a natural direction of activation from node to node, with no feedback unless by specific connections. In it, *cuing priority* refers to the topology and the weights of connections into a selected element from other elements whose activations are not relatively directly affected by the state of the selected element itself. *Reliability priority* refers to the topology and the weights of connections from elements that are (relatively) directly connected back to the element of interest. That is, *reliability* refers to the structure of feedback paths that return to the selected element in short order from activations that proceed away from it. A *context* would heuristically refer to an ambient, although subthreshold, external activation (in most cases of relatively long-term duration), which functionally prepares an element to fire on the basis of some critical set of activation links. Strictly speaking, the model is the network of nodes, their connections, and weights. Cuing, reliability, and context specifications are qualitative descriptions of the network that are intended to have fairly simple interpretations in terms of subjects' behaviors, such as fleeting responses (high cuing in the context) or confidence (high reliability).

I spoke before about "relatively closely connected nodes" to imply that effective cuing from the activation of any single element will generally be limited to directly connecting s-p-prims or, at most, chains of s-p-prims a few elements in length. Longer chains will exist only in cases of well-practiced, probably enormously redundant and reliable activities, or else they would depend in a critical way on contingencies that ought to be captured with reference to the cuing possibilities of specific other s-p-prims.

To this point, I have implicitly identified p-prims with specific knowledge structures that are basically abstract descriptions of entities, their relations, and attributes. Impressions of meaningfulness, however, are irrelevant to the structural interpretation of p-prims. Indeed, these impressions will be supportable only in the more dense regions of the knowledge network. It is unlikely we can use standard lexicon (e.g., "identification of some class of objects engaged in a class of actions") to securely define individual p-prims. Instead, the higher level cognitive structures implicated by terms such as *identifying, objects,* and *actions* involve relatively integrated systems with substructure to allow reliability loops to check applicability (e.g., "Is this a teapot?"), specifically to support appropriate persistence (e.g., "Should I abandon this line of reasoning?"), and to support use in multiple contexts and with other subsystems, such as language, logic, or other reasoning patterns (e.g., the very capability to verbalize considerations as noted before). The particular p-prims I have described here are likely to be of intermediate status, less data driven and context localized than elements descending toward low-level sensory elements but with substantially less surrounding structure than consciously accessible notions. They are likely to be some of the highest priority elements that still are generally hidden from introspection and probably not sufficiently captured by describing them as recognizing standard-ontology entities, such as objects, attributes, categories, and actions. This skewing of examples toward the top of the phenomenological heap (but below the "consciously conceptual heap") may, in part, be due to methodological difficulties: Lower level mental entities will not be directly reported by subjects even in approximation, and they will not typically direct the flow of reasoning the way the current list of p-prims can when they constitute significant insights into the way a physical system works. In considering lower priority elements, we as theorists must face in extreme form the problem that the words we have readily available to describe p-prims' meanings are essentially all drawn from higher priority levels.

To correct this in-principle skewing of examples, some examples of less meaningful primitives that are likely to exist may be helpful. Consider two different actions (or meanings) that may be appropriately cued by some configuration that happens to be both easy to see (involves elements with high cuing and reliability priorities from sensory elements) and characteristic of both actions (meanings). It may be useful specifically to encode that configuration as a p-prim. For example, fight and flight responses are both readied by perceived aggression. So a fight-or-flight state element would be useful. The two cued options, however,

belong to rather different action patterns. Thus, our usual strategies of disambiguating ideas might push the classification of the fight-or-flight element toward one or the other meaning or, more likely, toward a very different state: the logical disjunction of two higher priority notions as considered by a sophisticated human. Disjunction suggests a modularity of processing, checking two separate conditions, that might not exist.

Closer to the realm of researched topics, remembrances of a word or person's name might include s-p-prims having to do with broad, possibly idiosyncratic classes of letters or sounds. *M*, *N*, or *L* might share a common prim because of common phonemic characteristics. In fact, experiments by Klahr and Chase (1983) suggest that access to various pieces of information about the alphabet occurs first through the particular chunk in the "alphabet song" in which the letters occur. One may interpret this in the present model by asserting the existence of chunk prims attached directly to each letter that can initiate something similar to an internal singing of the letter's segment. This, in turn, gives access through monitoring to needed information such as "predecessor" and "successor."[39]

What is described as the tone of a situation might be elements of a class of prims partially representing situations through extremely ambiguous combinations of factual or emotional attributes. Here, ambiguous means capable of describing a broad range of situations rather than either unspecified or consisting of several disjunctions. *Déjà vu* could be incidents of extraordinarily rich activations of these prims, which, however, do not serve to lock in some particular memory.

More generally, s-p-prims could represent contexts in the sense of classes of mental states that have broad, uniform affects on other aspects of processing. Thus, s-p-prims might be involved in the implementation of reliable serial processes, marking phases of a deduction or inference, say. The meaning of those s-p-prims might be indescribable outside the connectivity of the activation network in terms of preparing and suppressing possibilities. In other cases, a p-prim may encode ambiguous but not useless information about the environment without the overhead of becoming assertions or even conscious hypotheses. Wherever they come from and whatever their functional niches, a rich vocabulary of mental contexts would seem extraordinarily useful to building fluid and rapid control mechanisms.

From a more developmental point of view and, once again, closer to the level of empirical investigation represented here, those p-prims that constitute essential

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[39]There is a subtheme in this model of alphabet knowledge that is suggestive of problems of using intuitive knowledge. If humans have these alphabet chunk prims, why do they not use them in other circumstances, for example, as redundant codes for recalling the spellings of words? The reason may be that the only mechanism of access involves the time-consuming act of mentally singing, a complex coordination of metrical and other internal sensations and responses. Although the knowledge is there, the mechanism of access is so clumsy as to be practically unworkable in general situations. Alternatively, humans may simply never have learned that such a bizarre thing as singing a song of letters might be useful in memorizing spellings. In either case, mechanisms of access limit usefulness of the knowledge either through intrinsic clumsiness or through limited, context-specific cuing.

parts of the sense of mechanism at one stage might merge into the background of internally useful but not legitimized high-priority elements of the next. So, for example, agency, pruned and refined, serves a role in the distributed encoding of $F = ma$. It tags a member of the pair of entities involved in a situation of force. This tagging may function, for example, to allow retrieval of the member for its role in later stages of problem solving, say, when force needs to be computed and properties of the agent, such as its distance from the patient, are relevant to that computation. Despite this productive role in the implementation, agency plays no sanctioned role in the explicit scientific theory of Newtonian mechanics. In general, conceptual change may or must reuse elements from prior systems in substantial ways, yet it may change the overall context of operation enough to render elements of the previous system, by themselves, meaningless. If we interpret s-p-prims as symbols, they are not at all arbitrary but are dependent on their mental operating context; hence, that context constitutes a strong constraint on the development of new symbols. The strong version of this principle of continuity is that the symbols that constitute the encoding of expertise must be built gradually out of the operating symbols of intuitive physics.

In a similar way, s-p-prims need not be generated as meaningful, abstracted descriptions of observed phenomena, as has been the prototype to this point. To talk of description in terms of elements and attributes might imply uniform mechanisms for localization and attribution that probably would not exist at lower levels of a knowledge system. One should more properly talk about attribute-like aspects of internal state than imply that these mental states may apply to a broad range of objects or that the knowledge system has the capability to determine what object of a sensory array is responsible for the attribute. Certainly it makes little sense to apply terms such as *true, false,* or even *appropriate* to an arbitrary mental activation engendered by a sensory experience.

The long-term progress of this perspective demands explication of any general mechanisms that might exist (description, attribution, retrieving binding, and so on) and of how they develop and are implemented from simpler, epistemologically neutral operations. Needless to say, there is no convincing account of this class of processes in neutral terms,[40] so I have not complicated discussion by avoiding what I take to be less problematic terms such as *abstraction* and *description*. In the long run, however, such terms are subject to the same criticisms as *fact* and *theory*.

Clarification of Empirical Context

The elaborated structural model might seem to be intended to provide a micromechanical model of cognition. Certainly many connectionists have this intention,

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[40]See, for example, Norman's comments on type–token distinction, variables, and other difficulties of connectionist modeling in the conclusion of McClelland, Rumelhart, and The PDP Research Group (1986).

and, for example, similar "spreading activation" models (Anderson, 1984) are intended to account completely for very short time-scale phenomena such as recall and priming.

This expectation poses problems if we put it together with the fact that the descriptions proposed here are intended to capture aspects of protocols lasting an hour or so. A complete micromodel of this would involve huge numbers of nodes. Priorities expressed as contingent activation would necessarily be extraordinarily complex. For example, the activation of an element might in principle take place under a huge range of circumstances, each of which might warrant description. Furthermore, the implication of the previous discussion of mechanism is that there is undoubtedly a large vocabulary of s-p-prims that is beyond empirical investigation in the mode of my interviewing studies.

The resolution of these difficulties relies on two assumptions about the interpretive context. First, note that the micro-mechanistic view allows that there may be major modularities; there may be very significant slices of any particular mental state that are irrelevant to the future activation of any given elements. In particular, the critical episodes in the protocols involve judgments of plausibility[41] and judgments of having adequately drawn out causally relevant structure. A subject may do a lot of things to generate candidate descriptions and behaviors to judge. She or he may consider many different versions of the problem that might cue different p-prims, or she or he may try to find features of the problems that are more relevant than the first-noticed ones. But, in each version of the problem and in each hypothesized behavior, a judgment must be made about the naturalness of some particular happening. These judgments are, we presume, the expression of the underlying sense of mechanism and are mostly modular with respect to other knowledge. To the extent that other reasoning is evident in the protocol, we hope to capture its net effect as presenting different behaviors or circumstances to judge or by slightly shifting the salience (degree of activation of features contributing to p-prim activation) of various aspects of a single situation, perhaps, therefore, altering plausibility judgments.

This suggests, in fact, that sparse networks might well be easier to investigate and describe than dense ones (providing that we can tell, at least approximately, when they are contributing). For example, in terms of its mental encoding, the naive sense of mechanism may be easier to investigate than the expert sense of mechanism.[42] If one can capitalize on presumed relative sparsity and modularity of the s-p-prim network, describing an s-p-prim's priorities relative to one or a

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[41]In this section, I use *judgment* as an intuitively accessible prototypical activity of the sense of mechanism, without intending to be exclusive or definitive.

[42]This contrasts with the presumption that, because of its explicitness, systematicity, and closely structured nature, it is easier to get a handle on expertise. These are not in fact conflicting presumptions. We may know more about expertise but, at the same time, know less about the encoding of expertise.

few particular contexts will provide reasonable information without undue complexity and commitment to modeling all aspects of the behavior.

Second, there are steps we can take to highlight the role of the sense of mechanism in our protocols and in their interpretation. We can set up our intervention to maximize dependence on the sense of mechanism. We can, for example, select questions that depend critically on judgments, not posing problems that are intrinsically complex or ones that involve much explicit search or practiced methods. We can use whatever we know about where and how the sense of mechanism operates to selectively interpret protocols, focusing on patterns of consideration and judgment. We can attend particularly to those aspects that are the best indicators of the judgments being made, such as confidence or the basis for terminating or extending a line of considerations. We can put aside (tentatively) other aspects of the protocol, such as struggling with which particular word to use or such as the processes that generate candidate behaviors to judge. So, for example, the order of selecting candidates is secondary or irrelevant to the judgments on them. We can, as suggested earlier, attempt to summarize lines of reasoning into a "net result" relevant to judgments, such as heightened or diminished salience of attributes of the situation relevant to judgments made.

To summarize, I make two presumptions that together make interpretations of protocols in terms of structured priorities plausible. First, the modularity presumption is that, even if elaborate reasoning is part of intuitive problem solving, still a substantial part of the basic physics is encoded in cuing and reliability relations in a relatively sparse part of the active knowledge system—the part we call the sense of mechanism. This is tantamount to saying judgments of plausibility and similar reactions constitute the core of intuitive physics rather than deduction, analogy, solution methods, and so on. Second, we can bootstrap on what we know about the operation of the sense of mechanism in setting up and interpreting protocols. We accept the fact that there might be many irrelevancies and idiosyncrasies about a particular protocol, but we still maintain that the kinds of questions we ask, including the selective focus we may take on interpreting behavior, may zero in on the critical sense of mechanism. These assumptions, of course, will need checking as our understanding evolves.

Systematicity in Weak Knowledge Systems

Most of the discussion here has been about specific elements and specific systematicities. In contrast, however, one can attempt to predict macrobehavior or typical patterns, as opposed to particular ones, based on entailments of the general modeling scheme, together with gross assessments of the operating characteristics of the system. A huge range of system types may be constructed out of structured priorities. What follows are some moves to reduce the ambiguity in general, structural terms: guesses as to structural characteristics of the intuitive-knowledge

system abstracted from our empirical base. The two structural characteristics I concentrate on have been mentioned previously: sparseness and the absence of high-priority knowledge structures.

Sparseness in this context means that, although the whole system may encompass many knowledge elements, few are invoked in any given situation. Systematic combinations are relatively infrequent. In particular, intuitive physics is not characterized by methods or extended reasoning involving the coordinated sequential activity of a significant number of elements. As a contrast, consider the complexity involved in being able to heed advice such as, "for ballistic problems, pick a frame of reference, choose a coordinate system, write down $\mathbf{F} = \mathbf{ma}$, and solve." Instead, interaction of intuitive physics elements is typically idiosyncratic to the situation, mediated at most by general reasoning processes that do not have much physics in them. Sparseness means, however, that application of p-prims can have the character of insights as it will be relatively localizable, at least in principle, and have important organizing effects on the thinking involved even if it does not determine sequential coherence. Sparseness also means that one cannot get a good view of the system from small numbers of contexts and that systematicity in general must be somewhat weak, not based on coordinated activity over relatively long time scales, like methods.[43]

I have already remarked that, although intuitive and expert physics share many features, indeed, many common elements, one of the most crucial differences is that the former lacks elements comparable in reliability to some expert elements. This contributes to the fluidity and data-driven appearance of the system. No strong commitment can be generated for most interpretations. Even if such commitment is generated, justification would be inexplicit. A change in point of view, either by changing the problem slightly or by a spontaneous shifting of perspective, might lead to a different interpretation. Many students in my interviewing study frequently talked themselves into qualitatively different understandings without seeming to notice. The systematicity of the knowledge is simply not of the quality to support relatively long-term coherent activity. This is not to say that naive and novice students are necessarily incoherent in their reasoning about physical situations but that whatever coherence is imposed does not come directly from the sense of mechanism: the coherence is not, for example, establishing a knowledge-based hypothesis (e.g., "Conservation of energy should work") or pursuing specific tests ("Can I find the kinetic and potential energies before collision?") that establish or reject the hypothesis.

More generally, one way of concretizing the implications of a sparse knowledge system with limited high-priority elements is to say that there are no hypotheticals.

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[43]Means–ends and other weak methods seem inappropriate for a weakly systematic knowledge system that, like the sense of mechanism, lacks hypotheticals and explicit access to its elements, say, operators. Still there must be appropriate strategies for getting the most out of the knowledge one has. Looking for such strategies (e.g., looking for applicable p-prims in analogies, simply repeating an analysis over and over, waiting for alternatives to be cued, or systematically changing the situation to enhance these cuing possibilities) constitutes an important avenue of future investigation.

For our purposes, a *hypothetical* is a knowledge element that is cued in circumstances in which its applicability is not obvious and that has an appropriate degree and kind of persistence to allow substantial reliability checks before it obtains the status of an assertion. By contrast, low-priority p-prims are never cued in a situation in which they are not more or less apparent; typically, the constituent and cuing parts of the p-prim are greatly overlapping. And one cannot follow up the hypothesis that a p-prim applies. If one does not know that a structure such as *Ohm's p-prim* exists, much less what its constituents are, how can one check circumstances for application? This means the system cannot support encoding of strong inferences like deductions. Only when the connectivity of the system has broadened considerably so that elements will be cued in nonobvious situations, and when systematic, knowledge-based means exist for asserting with confidence that a situation must be governed by a particular knowledge element, does it make sense for a knowledge system to bother encoding necessary entailments. In contrast to Piaget's view that hypothetical thinking emerges as a general capability, the present view is that hypothetical thinking is, as a default assumption, specific to individual knowledge systems.

To say that there are no hypotheticals does not mean that one cannot entertain hypotheses *about the behavior of a physical system*. Indeed, it is one of the central organizers of intuitive physics problem solving to consider the plausibility of some particular behavior. The limitation is in bringing explicitly into consideration the reasons for such behavior. Although behaviors (described in terms of high-reliability spatial or other terms) may be hypothesized, individual p-prims, in general, may not.

I call a knowledge system with the just-mentioned characteristics an *aesthetic*. The term is meant to be evocative of the functional characteristics of rich but structurally limited knowledge systems, which, notwithstanding their richness, appear fluid, data driven, and involve situation-specific reasoning (as opposed to plans and general methods) and idiosyncratic justification. These systems are better suited to provide judgments of similarity, of like or dislike, of relative confidence or insecurity in an analysis. They provide hunches and intuitions rather than pronouncements on what is true.[44] Similarly, aesthetics, such as a sense of mechanism, can reasonably encode a gradient of confidence, judgments that some ways of viewing a situation are likely to be more reliable. But they are far from appropriately encoding a reductionist program in which a broad class of circumstances must be seen as being explained by a limited class of mechanisms. Thus, a novice may sense that improved explanation of an event is needed and may search for that improvement. However, even when the search for improved explanation succeeds, which, in general, it may not, novices may settle

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[44]Art or literary criticism may serve as a heuristic model for such knowledge systems, hence the name. Indeed, these might well be good examples of aesthetics in this technical sense. I believe the meaning of such disciplines is lost unless one can project back to the p-prims of tone and feeling that must be the essence of the art. Papert (1981) discussed aesthetics as it relates to mathematical proof.

for increasingly more plausible analogies to understood situations involving similar or identical p-prims. Experts' knowledge, in contrast, supports judgments of isomorphism (i.e., that an event *must* be seen in a certain way, and events similarly analyzed are not just alike but also explanatorily the same). In such cases, an expert terminates his or her analysis for reasons other than having done as well as possible in limited time or having run out of ideas.[45]

Are there candidates for knowledge systems having the characteristics of aesthetics other than intuitive physics?

- I suspect that knowledge about interpersonal relations is structurally very similar, with abstractions from social phenomena providing the phenomenological primitives. People perceive threats and friendliness on the basis of inarticulate cues, and they take actions to cause other people to do things as if those actions stemmed from a sense for the psychological mechanisms that actually cause people to act in particular ways. Some of these intuitions are felt to be very secure and reliable. Yet others are vague, lower in general reliability, or insecure in their application to a context.
- Possibly related to social phenomenology, Wendy Lehnert's analyses of stories (Lehnert, 1981) identify what may be the equivalent of p-prims, some inexplicit but relatively high-reliability structuring schemes involving configurations of agents and sequences of actions abstracted to levels of who does good or bad to whom with what reaction.
- A phenomenology of personal functioning, reflections on the state and activities of one's own mind, could provide the basis for an intuitive epistemology that may constitute the meta-knowledge people have about knowing and learning. In the same way that intuitive physics knowledge can be more or less productive, intuitive knowledge about learning and knowing (diSessa, 1985) can affect how students go about learning and, thus, what they learn or fail to learn. A simple example might be the feeling of losing one's train of thought after an interruption in a conversation. In analogy to the questions I have pursued with respect to intuitive physics, we must ask how one learns to recognize such situations, what the internal descriptive vocabulary is that allows recognition, and what mental actions follow such a recognition.
- I believe that much of the heuristic knowledge of expert physicists remains at the level of an aesthetic.
- A class of aesthetics worth investigating involves those relatively small knowledge systems that decide whether or not an instance is an example

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[45]For a contrasting view, see Clement (1986). More recent work from Clement (see Brown & Clement, 1989) is more compatible with allowing (in experts) structural isomorphism, rather than, for example, only increasingly more plausible analogies, as the basis for causal explanations. The distinction between plausibility judgments and judgments of isomorphism is important here in distinguishing aesthetics or aesthetic-like behavior from behaviors that are produced by more systematic knowledge systems.

of a more general kind. Family resemblance ought to be a kind of aesthetic, the mechanisms of operation of which, if not the mechanisms of genesis, ought to be like those operating in the sense of mechanism. For example, in mathematics, definitions are supposed categorically to determine the set of examples of a class. But if students possess structurally limited knowledge systems, judgments will frequently be made on the basis of different and inarticulate knowledge, even if definitions are overtly endorsed. In the way a balancing situation may resemble a conservation of energy situation to a novice physicist, so may mathematical structures be seen through intuitive substructures.

Aesthetics seem good candidates for empirical investigation despite the fact that even the highest priority elements may not appear explicitly in verbal protocols. This is the generalization of the remarks in the immediately preceding subsection about the plausibility of investigating physics p-prims because of their sparseness. Compare cognitive processes at the level of general reasoning and logic. There one should find a structured priority system so well orchestrated that we are unlikely to be able to see the structural trees through the functional forest. Sparseness can be an advantage if it allows individual elements to stand out as, for example, insights. Another reason general-reasoning p-prims, if they exist, would be hard to investigate is that such knowledge is almost by definition applicable across a broad range of circumstances. Thus, the functioning forms of general reasoning are likely to be very refined, remote from whatever phenomenological roots it might have had.[46]

Among aesthetics, intuitive physics is at a particular advantage with respect to offering a good empirical window, because the phenomenology on which it is based is more open to inspection. The phenomenology is in some sense out in the physical world, which makes p-prims easier to guess and describe. (The problem with describing physical phenomenology is more to resist assimilating elements to conventional dictionary or physics-class vocabulary.) Compare a phenomenology of personal functioning, for which we have little conventional descriptive vocabulary. Similarly, it is easier to manipulate the world or to describe various physical situations verbally in order to probe a subject's physics knowledge than it is to manipulate or describe internal states or social interactions. Arguments similar to these, although from a contrasting perspective, are given in Hayes (1979b).

INTERPRETIVE SUMMARY

The remainder of the monograph takes a number of orienting perspectives on this work. In this way, I review basic features of the set of ideas presented here, commenting on strengths and limitations. First, I provide a sketch of the fun-

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[46]In contrast, however, bugs revealing context-dependent inconsistencies in people's logical abilities (Johnson-Laird, 1983) could well offer interesting opportunities to unpack the encoding of logical knowledge.

damental reasons that something like a sense of mechanism exists. Next, I review the basic characteristics of p-prims and the system of which they are a part, highlighting the role of the modeling language, structured priorities, in stating and validating these claims. Then I make some comparisons with a few noteworthy competing perspectives. Finally, I close with brief comments on educational implications.

Theoretical Claims

The sense of mechanism.   In broad brush, basic characteristics of the naive sense of mechanism and its evolution into expert physics are determined by a number of fundamental cognitive and physical facts. To begin, the function of the naive sense of mechanism is as an explanatory framework for reasoning about the world. After all, humans have a lot of interchange with the physical world, and understanding it better can serve them in many ways. Understanding should evolve toward *compactness*, involving few principles that are as general as possible. In a sense, compactness is the essence of explanation, identifying general mechanisms beneath differences. Compactness should imply *abstractness* in the sense that it is unlikely deep principles could be immediately evident in particular details presented in each of the full range of instances of the principles. If a breadth of situations is covered by a single principle, one would expect much specific knowledge (distributed encoding) that connects the principles to different situations of application. This specific knowledge might be particular forms of the principles for particular situations or strategies adapted to do the work of interpreting diverse situations in common terms. Energy comes in various forms, each of which is differently recognized and computed.

Although compactness is an in-principle advantage for explanatory systems, the physical world is, unfortunately, extremely *diverse*. One measure of this is how complex it is to use Newton's laws across the full range of their application. Fluid dynamics, to take an example, might in many respects be reduced to Newton's laws. Yet it is worth multiple textbooks by itself. Another measure of this diversity is the richness empirically found in the naive sense of mechanism. A compact sense of mechanism that still deals with this diversity must be tremendously coordinated, with a wide range of specific knowledge properly connected to the compact core. If such coordination is hard to achieve, including finding the right abstract and general principles, the easier alternative is a broad but relatively shallow sense of mechanism such as appears to exist in physics-naive individuals.

It happens that Newtonian mechanics is, by and large, relatively compatible with the naive sense of mechanism. This provides a great opportunity to develop expertise by revamping naive knowledge, both to encode basic laws and to connect those laws to specific situations. *Continuity* is a fundamental learning principle. Knowledge is complex and difficult to come by. Humans need to build new from old. To be sure, there are hitches in that rebuilding that may appear

as "misconceptions." Yet, I claim, much of an expert's sense of mechanism is reused intuitive knowledge.

Why should an expert's sense of mechanism not completely merge with his or her other physics knowledge (like knowing algebra and, literally, $\mathbf{F} = m\mathbf{a}$) but retain characteristics that make intuitive knowledge elements evident in it? Most prominently, I believe that diversity still rules, given *human processing limitations*. People have limited ability to quickly compute highly reliable, yet situation-specific inferences from a small set of principles. They need to have levels of analysis such as legitimized phenomenology that gloss details of usually ignorable phenomena in favor of quick, situation-specific reasoning. Yet, experts must, upon need, be able to refine that specificity to more careful and general analyses. The effect of compactness is achieved by experts, not by reducing each situation directly to first principles but by coordinating quicker and more situation-adapted knowledge. Sucking from a straw is, in the first instance, a phenomenon that is immediately familiar. At the next level of explanation, air pressure "causes liquid to move" (*force as mover* p-prim) along "channeled paths" (similar to *guiding*). Beneath that, field equations determine pressure gradients that accelerate elements of liquid, and retarding viscous forces are generated that damp potential oscillations. The reduction to more general principles proceeds only when it is required and, even then, in stages.

Elements and system properties.   Perhaps the most central theoretical claim of this work has to do with the quality and grain size of elements in the naive physics knowledge system. Here, I heuristically situate the size and quality of p-prims in comparison with more familiar units (i.e., chunks of language). Roughly speaking, p-prims are about the "size" and complexity of words, although in several senses they are clearly smaller and simpler than words. In the first sense, lexical items often have clusters of meanings; polysemy is general, if not universal, in word meaning. P-prims are, by contrast, more comparable to a single sense of a word; they are the smallest, context-invariant mental activations. Consider a word such as *force* compared with p-prims such as *force as a mover, continuous force, force as a deflector* or *as a spinner*, or force meaning *violence*. Consider *balancing* compared with *dynamic* or *abstract balance* (the latter likely itself decomposable), or compared with overt balancing actions such as a person acting to keep a tray in balance or the nonagentive "gradual oscillatory return to equilibrium." See also the multiple meanings of *resistance* listed in the Elements section.

Words also benefit from a structuring that allows them to be integrated systematically into larger structures. In particular, they have grammatical classification attached to them. No comparable structuring appears to exist for the intuitive sense of mechanism. Instead, a typical relationship in a problem scene would be the simple joint assertion of a number of p-prims, respecting the contingencies of cuing and reliability among the set. (Recall that *cuing* refers to processing

that leads to activation of an element, and *reliability* refers to postactivation processing that might "check" that the conditions for using the element are satisfied.) Even what I have referred to as a phenomenological syllogism (stiffer implies less motion, less motion implies faster) may amount only to the simultaneous use of two relatively strong coordinate attribute bindings rather than a true deduction.

More substantially, p-prims are weakly persistent. Words, on the other hand, by virtue of the ability to keep a word literally in mind, allow substantial reliability, hypothetical use, and even explicit reasoning about their use. One can easily ask, "Is that really an instance of a 'teapot'?" The equivalent questions can hardly be posed for, say, *Ohm's p-prim*: Even if one were conscious of the notion, the scene features that cue it are not explicitly known; how would one know where to focus one's attention to check applicability? It has been the contention here that these limitations in intuitive physics are substantial and characteristic of the system and that building toward some of the capabilities that words seem to have is one of the key developments that must occur in learning school physics.

Although debating the fine points of a comparison between language objects such as lexical items and p-prims is problematic without common theoretical ground, these comparisons become less problematic as one moves up the ladder of complexity. One would be hard pressed to think of a p-prim as a proposition. Even if one accepts a form such as "In circumstances x, y happens," which might subsume many p-prims, the inexplicitness of circumstances and lack of other reliability checks make such attributes as universality, truth value, and participation in general reasoning patterns (approximations to logical reasoning) highly dubious. Needless to say, I believe use of even higher level terms to describe the system of p-prims, such as *theory*, is unenlightening and misleading with regard to the level of systematicity that actually exists.

The notion of structured priorities is a linchpin of my theory sketch. It has played two roles. First, structured priorities is a deliberately weak, epistemologically neutral language for describing structural relations within knowledge systems. In terms of it, we can discuss such properties as sparseness and limited reliability. In the Cognitive Mechanism section, I described the advantages of epistemic neutrality, particularly in comparison with using informal terms with vague and implicit assumptions. I have also discussed the advantages of a weak mechanism such as structured priorities compared with other conventional modeling languages such as propositional calculus and production systems which, although not ruled out on in-principle grounds, would seem to be tailored to higher, more systematic levels of cognition, levels that may benefit from assumptions of uniform connectivity of declarative knowledge and strong reasoning engines, such as predicate logic, that operate over it.

The second role for structured priorities is as a more or less direct interpretive frame for expressing empirical results. Elements that appear early in a protocol have been interpreted as having a high cuing priority relationship to salient

features of the problem situation. Similarly, later appearing elements or ones that persist throughout the protocol have been interpreted as having high-reliability relations to aspects of the situation that I have tried to specify in most cases. Defining relatively global priorities (with respect to the particular problem) tied to salient elements (technically, elements of high cuing priority) in the problem scene is rather strongly dependent on the knowledge system's being sparse.

The sense of mechanism is only part of physics cognition. Modeling it is not the same as modeling general methods or strong reasoning patterns. To the extent that strong reasoning patterns are important to the naive sense of mechanism, structured priorities is an incomplete model. The claim, however, is that they are not important, although they cannot be ruled out as contributing.

To draw an analogy, the sense of mechanism is more like a judge than like a lawyer. Its job is to judge plausibility, not to do the work of marshaling data or arguments. Someone trying to understand a situation might invoke many more-or-less conscious strategies, invoking metaphors, trying out different hypotheses and kinds of description, or thinking about a related problem. These moves are not explained, in themselves, by charting the sense of mechanism. Instead, the judgments occasioned by these moves are explained by the sense of mechanism. (However, I also intend some of the functions of these moves with respect to the sense of mechanism to be explained, for example, that they activate relevant p-prims.[47])

Because strong methods and reasoning are not encompassed, the sense of mechanism evidently does not capture many aspects of an expert's Newtonian mechanics. This is most evident in the part that is formalizable, although, I reiterate, that is hardly all of expert Newtonian mechanics. Formalizable aspects of mechanics ignore at least many heuristic connections experts use to solve problems and ignore the connection of the formalized theory to experience necessary to solve problems posed in commonsense terms. I have tried to sketch some of the connections between more evident, articulable, and formalizable parts of expert cognition and p-prims, for example, in the discussion of the simple harmonic oscillator.

P-prims, it seems, lie systematically at the interface between experience and formalizable physics, both in the genetic sense (providing an important knowledge base for learning physics) and, later, for interpreting the real world in terms of the formal theory and vice versa. They interpolate between the "blooming, buzzing" world of sensory experience and the much sparser world of conscious, explicit ideas. Structured priorities constitute an attempt to see development from the former to the latter in uniform terms.

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[47]Roschelle (1991) provided a model of learning to problem solve that separates the sense of mechanism from (a) literal and articulate descriptive capabilities and from (b) specific problem-solving schemata. He showed, in some degree and in a particular case, how these different modules interact and how basic to understanding the sense of mechanism is.

A gap in the present sketch, as opposed to a presumption or choice of what to model, is the lack of specification of the mechanisms that decide when and how priorities should be changed. Although the model can easily accommodate descriptions of various kinds of change, specifying exactly which change happens when constitutes a central unelaborated aspect of the theory. To be sure, probably useful heuristics are not hard to come by. Use begets increased priority. Conscious reductions of an explanation based on one set of p-prims to another based on a different set probably enhance the priority of the latter set and reduce the priority of the former. Similarly, I have not troubled to model exactly how activations of p-prims are read out into feelings of satisfaction or dissatisfaction.

Structured priorities are adapted to describe what may be called problematic learning — learning involving initially severe systematic limitations, such as sparseness and descriptive impoverishment, or involving the need for substantial reorganization of an existing adapted knowledge system such as preconceptions reveal about intuitive physics. Contrast problematic learning with skill acquisition, which seems to work relatively reliably and has been captured to some degree by such learning models as Anderson's (1983) ACT* theory. There have been fewer well-motivated theoretical investigations of problematic learning, despite the fact that deep and long-standing problems such as that of general intellectual development may yield results when viewed as problematic learning. More conservatively, I hope and intend that the present theory sketch will contribute to understanding meaningful learning in which students perceive a subject such as Newtonian mechanics to be a natural evolution of their own sense for how the world works rather than a competitor or a totally disconnected and abstract subject.

Finally, I have deliberately decided to model p-prims as "pointalist" nodes, connected, nearby, to their constituting features and, more peripherally, to nodes that represent other p-prims related by cuing and reliability relations. I do not mean to join arguments about localized or distributed forms of representation in connectionist nets by this move. I have no vested interest in nodes per se compared with p-prims being "resonances" in a field or other ways of modeling them. Assuming nodes simply seems to be the easiest first step that gets at some of their essential properties.

Competing Points of View

The theory sketch as it stands is incomplete in view of the previous discussion and in other ways. By nature, it is also, like biological evolution, not ideally suited to critical experiments and direct confirmation or refutation. For example, elements are by hypothesis hard to observe; they may be essentially impossible to manipulate experimentally one by one, and they are dependent on the characteristics of their equally intractable "neighbors" for their meaning and implications. In this light, may one not view the data presented in this monograph as

yielding to a loose descriptive frame rather than supporting an evolving theory? Could any view of intuitive physics not be recast as a p-prims view?

Part of the leverage of a theory is what it rules out or makes implausible. This section takes that tack. A number of views exist that are nearly directly antithetical to the one presented here. Contrasting views can show that the present view is not compatible with any data or with any explanation of that data. I treat one comparison, that with the views of Michael McCloskey, in some detail. Other cases are abbreviated.

McCloskey's impetus theory.   Michael McCloskey may still be the most widely read and cited researcher concerned with naive physics, despite the fact that his work was done during the early 1980s (McCloskey, 1983a, 1983b, 1984; McCloskey et al., 1980). His views, beyond the data level, contrast almost point for point with those developed here. He claims that the core of naive physics is a "surprisingly articulate theory," which varies only a bit from individual to individual and which strongly resembles the medieval impetus theory of professional scientists (philosophers).

Schematically, the impetus theory holds that the free motion of bodies is caused by an internal force, called *impetus*, that is imparted to the object when originally impelled in its course. The impetus gradually dies away, whether due to an intrinsic tendency or interference of other influences, such as gravity or friction.

An excellent example of impetus thinking, perhaps the best, is found in students' descriptions of a vertical toss. Students will frequently declare that the tossed object rises because of the force imparted to it by the tosser. The impetus (subjects almost always use the term *force*), however, gradually dies away. At the peak of the trajectory, the impetus is exactly balanced by gravity. Gravity then overcomes the upward impetus, causing the object to fall downward. Early and enlightening characterizations of impetus-like explanations as involving a "supply of force" were provided by Viennot (1979), followed by Clement (1982) and McCloskey. There is no question that students sometimes give descriptions like these. The issue is what one makes of such data.

McCloskey claims that there is a circular branch of the impetus theory. When an object is constrained to move in a circle and then released, it has acquired a circular impetus. That impetus is said to impel the object to continue moving in a circle for a period of time (although the object usually is described as spiraling outward). Several situations are used to support the existence of circular impetus. A ball may be spun horizontally in a circle on a string, and the string breaks. A version of this is that a ball is propelled through a tube bent into a part of a circle (C-tube), and the ball emerges from the tube. A more than superficially distinct problem involves the pendulum problem introduced in the Systematicity section. Recall, the question is what path the bob travels if the string holding it breaks. McCloskey says many answers to these follow impetus analyses.

A final piece of the impetus theory accounts in a minimal way for an apparent exception to impetus theory predictions. Objects dropped from a moving object, such as a bomb from a plane, are frequently not seen to have acquired any impetus. This is explained as a separate principle: "Carried objects absorb no impetus."

Let me begin my critique of McCloskey's theory by noting some very broad differences. McCloskey (implicitly) accepts conventional and popular epistemological distinctions as being clear and relevant. The intuitive impetus theory is *false* and has been superseded by Newtonian mechanics. He accepts that it is appropriate and informative to describe intuitive physics as a *theory* without elaboration of what, exactly, that entails. He expects intuitive physics to contain presumed relatively universally valid notions. Thus, McCloskey's ideas are an example of what I call "theory theories," which claim intuitive ideas are theoretical. And McCloskey has, in fact, sought to find the origins of naive ideas in direct misreadings of reality, in visual illusions (McCloskey, Washburn, & Felch, 1983).

In contrast, I claim that all such intuitive epistemological terms, theory among them, are problematic in their imprecision, inexplicitness, and, most especially, in their application to sparse knowledge systems such as intuitive physics. I claim intuitive physics is the residue of a complex and extensive process. Simple readings or misreadings of reality will not do to explain it. Although genesis of individual elements may come closer to "readings of reality," the priority network is established in a gradual sorting of ideas to build an abstract explanatory framework, albeit one with some fairly dramatic limitations of systematicity.

Let me now consider in more detail the differences between knowledge in pieces and McCloskey's theory theory. I believe the case that follows is already compelling, even though I have not explicitly undertaken to collect data that challenges McCloskey.[48] But this exposition is also intended to provide a framework to suggest particularly interesting focused experiments and lines of criticism that may be pursued in future work.

How can knowledge in pieces deal with the basic phenomenon, the kinds of predictions that people give in response to tossing problems, pendula, or C-tubes? For this, we need only look at those phenomena with p-prims in mind. It is not difficult to see in the toss many of the generally most prominent p-prims described here. *Force as a mover* describes the hand-in-contact throw part. Although this part of the motion requires explanation from an expert's point of view, it is entirely unproblematic from the intuitive point of view. Thus, the throw per se is not mentioned precisely because it is unproblematic. We should be chastened to

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[48]I mention, but will not here pursue, a different line of criticism. McCloskey's citations from protocols that supposedly implicate an impetus theory have much more charitable readings. The key to these readings is realizing that impetus and momentum (or energy) are, in fact, much alike. Indeed, it is technically correct to say that force is a flow of momentum "that accumulates in an object." It is also appropriate to say, informally, that momentum causes an object to continue moving. So, the linear impetus theory looks like a rather benign use of nonstandard terminology along with a confusion of a flow (force) with an accumulation (momentum).

note that, although the expert's stance toward physics problems is to reduce them to explicit, fundamental explanatory principles, the naive explainer will generally not comment at all on what is evidently unproblematic and will pursue only what may be less immediately assimilable.

In this light, the intuitive thinker does have a problem to solve in the toss. There is a conflict, posed probably by *continuous force*, in that the ball goes up for a while, whereas gravity would cause it to go down. This conflict is sometimes stated directly, and I believe it is the source of much of the explaining students do. They need to explain how it is that the ball can act as an independent agent against gravity. Of course, they know this agency has come from the tosser, so that fact is expressed as a transfer or communication of some form or other.

There is other evident phenomenology in the toss. Thinking intuitively, the top of the toss fairly exudes some *equilibrium* or *balancing*.[49] Indeed, the impetus or internal force might be the thing that is balancing gravity. It is, after all, that which counteracts and overcomes gravity at the start of the toss.

Some weakening of the impetus is implicated during the motion from the throw to the apex, a transition from *overcoming* (the hand overcomes gravity) to *dynamic balancing*. In that it is common knowledge that all induced actions die away (*dying away* p-prim), impetus coming into balance with gravity makes good sense. Finally, as the upward impetus dies away more, gravity *overcomes* it and, finally, gets its way.

This redescription of the toss has the following properties. First, it highlights some of the prominent attributes of the situation that are relevant to the sense of mechanism as sketched here. There is conflict and a restricted agency in a tossed object. Second, it gives a point-by-point analysis of the process of toss, now decomposed into several p-prims that have already been argued for by independent means, notably *force as mover, dying away, dynamic balancing,* and *overcoming*. And critically, the analysis sets a context in which impetus, as described by McCloskey, can essentially tie up all the loose ends by giving a name to the agency imparted to the object that counteracts, balances, and finally is overcome by gravity.

Compactly, I maintain impetus is not a systematic and coherent theory. It is an abstraction particularly salient in a relatively small class of situations, of which the toss is archetypical. Essentially all of impetus's properties follow from the confluence of independent p-prims that happen to apply to the situation. In this reinterpretation, impetus will only be observed occasionally; it may, in fact, be encoded in some degree separately from the constituting p-prims (in which case, its genesis might be precisely as noted here, from consideration of the problematic aspects of a toss). But the impetus theory will not exhibit strong integrity.

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[49]In recent work, we videotaped a sixth-grade student insisting an object stops and "teeter-totters" for an instant before reversing direction. Some college students in recent interviews have explicitly implicated balancing at the peak of the toss as the root of believing there is an impetus-like force in the tossed object.

Decomposition into independently motivated elements is the core of my critique. Let me continue based on some of the criteria discussed in the Method section.

1. *Principle of invariance*. As noted in the prior discussion of each of the previously mentioned p-prims, we see these in other situations. We do not see an integrated impetus theory. The sound of a bell *dies away*; the force of a spring may *overcome* the force of gravity to toss a brick in the air (p. 139). Arguments on the basis of equilibrium, in particular *dynamic balance*, are prominent in a broad range of circumstances, notably relatively static ones that do not resemble the toss in any direct way but in which *dynamic balance* fits appropriately. So, I argue that p-prim pieces better fit the criterion of invariance.

Contrastingly, the impetus theory must have extensive and as yet unarticulated applicability conditions. In particular, the brick-on-spring situation (How far down must you press the brick on a spring to cause the spring to toss the brick into the air?) can be interpreted as an impetus problem. From a physicist's point of view, it is appropriate to say the issue is whether the spring has supplied sufficient impetus (momentum) to the brick by the time it has extended itself so that there is a remnant to carry the brick into the air. (More technically, if the momentum of the brick is positive at the point the spring is fully stretched, the brick will continue into the air.) But instead of impetus in students' explanations, one sees only *dynamic balance* and *overcoming* p-prims.

The spring in the railroad car is a better example. (See discussion in the first subsection of Systematicity.) There, the gravitational force of the earth provides an impetus to the attached object, which should be, according to impetus theory, gradually used up in continuing to compress the spring after the push of gravity has passed. But this is precisely what students miss. Instead, they see springiness and a figural symmetry that dominate impetus, even when the violent, blow-like nature of the gravitational force is pointed out to them and accepted by them.

As noted, impetus does not seem to apply frequently in cases of carrying. This is an unmotivated "patch" to the core impetus theory, which McCloskey explained, as mentioned earlier, as deriving from a visual illusion. Within a knowledge-in-pieces perspective, it makes more sense. In principle, we expect fragmented application. More particularly, if there is no violent (*force as a mover*) toss, there is no evident agentive source of impetus. In addition, an independent p-prim that unproblematically applies to everyday situations, *released things fall (straight down)*, can help account for different predictions in these cases.[50]

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[50]To be fair, McCloskey's proposal that the "straight down" belief comes from a frame of reference illusion seems to have been moderated in later work. In Kaiser, Proffitt, and McCloskey (1985), naive stages of comprehension are described, more plausibly, simply as a holistic belief that all released objects fall straight down (cf. *released objects fall* p-prim). The visual illusion is said to act only to prevent some learning that might overcome this belief. Generally, this later work seems to be more sensitive to complexities in the development of naive notions. But, for example, in citing

The principle of invariance applies problematically to circular impetus. A more knowledge-in-pieces interpretation is that people have abstracted the loose principle that things keep doing what they have been doing (see the discussion of empirical adequacy in Systematicity, p. 171, and also *generalized momentum* in the list of p-prims in Appendix B), but people do not hold strictly and blindly to such principles. Everyone knows that a sling flings a rock away from the slinger. Many people have a sense for centripetal force that may be seen to pull an object out of a circular path. So they reason a nice compromise: An outward-spiraling path makes more sense than strictly to adhere to circular impetus. I pointed out as well in the previously cited section on empirical inadequacy that children sometimes react very differently to simulations as opposed to the visual gestalt presented by static drawings. "Theories" that depend on the mode of problem presentation are perhaps more delicate than warrants the use of the term.

Carried objects appear not to acquire impetus in linear situations. Then why should similarly propelled objects such as a ball on a string or an object released from a turntable acquire circular impetus in circular situations? This lack of invariance demands alternate and better descriptions of impetus explanations. Within the present perspective, it is easy to understand that we may simply have different p-prims to deal with in different circumstances, such as the *interference* of gravity (in the toss) and *falling* (in the moving drop) that may explain part of the difference between linear and circular contexts.

In general, there is a fine structure to the application and the drawn conclusions of the impetus theory that we need to attend to. In the category of application, how do we understand, beyond asserting that it happens, why carrying is not viewed as the same thing as tossing, which would lead to impetus explanations in either case? If we understand the importance of patterns of amplitudes, the particular p-prims that depend on these, and competitor p-prims, the differences are easier to explain. Consider also the fact that subjects may change their minds on viewing a simulation. What accounts for this difference in application? In the category of drawn conclusions, why do we get spiral predictions rather than strictly circular paths from circular impetus? This fine structure is below the level of grain that McCloskey's theory can capture.

2. *Principle of coverage*. Although balance and overcoming are arguably (but not, I think, convincingly) part of the impetus theory, springiness and figural considerations are not. The impetus theory leaves us with an embarrassing state of affairs. It appears to cover some set of things that people say, but all the rest is entirely disregarded. All the other things they say about tosses, about C-tubes, and about pendula have no described status at all. McCloskey's data themselves claim impetus-like explanations in, for example, 51% of subjects' responses to

the C-tube problem and only 30% of subjects' responses to the cut pendulum (McCloskey, 1983b). (The figural and static answers to the pendulum problem, schematized in Figure 7, p. 164, are relevant here.) What are the rest of these subjects saying to us about intuitive physics? My take is that they are showing us other p-prims and other kinds of reasoning that are just as much a legitimate part of intuitive physics.

Is it reasonable that people would have developed a core theory of physics that covers only an odd collection of projectile problems? Is it reasonable that what they say about every other event in their experience bears no relation whatsoever to their "intuitive theory of mechanics"? The impetus theory does not cover the fact that a pencil may be balanced on a finger and returns to equilibrium when perturbed slightly. It does not cover square orbits (Figure 8, p. 165). It does not cover any of the qualitative relations that correlate quantities, such as that more effort begets a faster toss or a higher toss. It does not cover any notion of combining multiple influences. Surely an intuitive physics must have something to say about situations in which multiple forces or tendencies come to impinge simultaneously.

The lack of coverage of the impetus theory is as striking in terms of form of knowledge as it is in terms of content. Although we may remotely believe that impetus explanations are theory-like, what concepts does the theory have to offer to describe the many much less systematic things that people say?

Lack of coverage is not a strong in-principle criticism. Every theory has bounds. But the impetus theory needs to articulate principles for its boundaries, and it has an existing, broader competitor in knowledge in pieces, with which it may be specifically compared.

3. *Principle of continuity.* The impetus theory offers no systematic account of the development of intuitive physics. If an intuitive theory of impetus exists, I claim knowledge in pieces already offers a better developmental account of it than is provided by McCloskey. Each of the p-prim pieces is independently motivated; learning little things such as p-prims is, on the face of it, easier than learning and becoming committed to a complete theory. Each p-prim I have described comes with plausible contexts of abstraction (principle of unproblematic genesis); *force as mover* is an abstracted toss; *dying away* is an assertion that explains immediately evident patterns of fading amplitude in all instigated motions; *overcoming* happens every time you fail once and push harder. *Ohm's p-prim* can regulate hundreds of personal events every day.

At the system level, a gradual sorting of priorities makes much less claim on strong mechanisms of development than those, whatever they are, that result in a theory.

Continuity also helps explain much of the vocabulary, in the sense of internal descriptive capability, that seems to be involved in impetus-like explanations. This begins at the root notion of agency, which must evolve in early years of life and

extend gradually to understanding the inanimate world in circumstances in which it is effective.

Continuity is similarly left out of the future of intuitive physics in McCloskey's account. McCloskey is left with the fallback of all misconceptions research, that these misconceived ideas must be confronted and replaced by alternatives.

> It may be useful . . . for physics instructors to discuss with their students their naive beliefs, carefully pointing out what is wrong with these beliefs. . . . In this way, students may be induced to give up the impetus theory and accept the Newtonian perspective. (McCloskey, 1983b, p. 319)

He provides no discussion of the nature of the replacing knowledge, except that it is different, and there is no discussion of the source of the materials that form the replacement. In contrast, one of my most basic claims is that an expert's sense of mechanism is built on a fundamental continuity in form and content with intuitive physics.

4. *Principle of dynamic.* Finally, McCloskey makes nothing of the dynamic that may be evident in a clinical interview when students are left to think through more than first guesses or are pushed or proposed alternatives. There is much to learn about impetus—its integrity, its components, and its competitor intuitive notions—by looking at the trajectory of extended interviews. My claim here is that intuitive physics in many situations can be fluid and adaptable as much as it is robust and ungiving. I make only one empirical reference here. In exploring an analog to the C-tube, a sling in which a rock is spun in circles and then released, Globerson and I (Globerson & diSessa, 1984; also see diSessa, 1988) discovered that, when prompted, many subjects preferred an explanation they could not themselves spontaneously generate. When reminded of centrifugal force, these subjects combined the forward tendency of the rock with the centrifugal tendency and proposed a 45° outward trajectory. This is very remote from impetus in any form. The 45° prediction combines influences. The fact that many subjects preferred this prediction to any of their own spontaneous ideas implies a degree of flexibility not hinted at in theory theory proposals such as McCloskey's. (In contrast, many other suggestions were rejected by subjects out of hand; therefore, rigidity and flexibility depend on the nature of the perturbation.)

People are not "pre-(Newtonian) revolutionary" scientists with systematic theories of their own about how the world works. Nor are they incompetent, possessing a bundle of powerful misconceptions from predilections or from misreadings of the world. Instead, they possess a rich and sometimes flexible sense of mechanism drawn from years of sorting through diverse experiences. Their sense of mechanism can offer predictions in extremely varied situations, some of which are enough beyond normal interest and outside normal contexts of application of their expertise that their ideas appear misconceived. These same

ideas, however, are powerful enough to provide a basis for developing expertise in physics.

Other comparisons.   A less strong but similarly striking comparison can be made to Siegler's work concerning children's conceptions of such physical situations as relative speed and duration of motions, and the balance scale (Siegler, 1978; Siegler & Richards, 1979). He views early developmental stages in terms of a failure to encode explicitly encodable dimensions (e.g., distance from the pivot on the balance scale). He does not seek to understand whether and how children spontaneously assess those dimensions as relevant to the issue at hand or how recognizable phenomenology (such as pushing perturbs a balance) can contribute to those assessments. Siegler charts development in terms of the acquisition of a small number of rules, on the order of a half dozen or fewer. Evidently, his estimate of the size of the evolving knowledge system is very different from mine. Even a modular slice of the sense of mechanism that deals with balancing, equilibrium, weight, and distance must be substantially bigger than this. If interpreted as p-prims relevant to a particular, narrowly defined context, a small number of rules makes sense. However, such an interpretation is dubious in view of Siegler's aims at rigorizing Piaget's rough observations concerning major developmental changes in intellectual competence, such as formal operations. An interpretation more in line with my point of view is that Siegler charted the surface of a much richer and broader development. Whether p-prims or rules are involved is partly an issue of choice in modeling language and partly an issue of the form and substance of knowledge, as explained in the Cognitive Mechanism section.

The reasons I characterize this comparison with Siegler as less strong than the one with McCloskey are the differences in age level, in broad theoretical frame (development as opposed to learning), and, possibly, differences in problems investigated. Thus, it is not clear there is a conflict so much as a concern for different issues, which gives rise to answers of substantially different form. It is not my impression that this is the case, although it is impossible to argue the issue in this abbreviated context. However, I note two studies that are relevant to the issue of whether or not one should view Siegler's tasks and focus as different enough to explain differences in conclusions. Kliman (1987) shows a much richer phenomenology and more flexibility in conceptualization of the balance scale if subjects are allowed more open interaction. Metz (in press) demonstrates similar fine structure in local conceptual development, and she implicates judgments of causal relevance, not just encoding or acquisition of rules, as an important factor in development.

Finally, Forbus and Gentner (1986) sketched an ambitious theoretical perspective on the development of common sense and scientific understanding. To begin, there are some commonalities in point of view. They stressed the importance of simple abstractions of events ("proto-histories"). They used "processes" (which

I interpret as behavioral p-prims) as the basis for naive physics. They noted the importance of qualitative proportionalities, such as "Bigger things are slower." They also stressed coherence-driven learning—the sort that probably drives some of the systematicities I find in the naive sense of mechanism.

The contrast between their view and the knowledge-in-pieces view is most striking at the earliest and latest stages of competence. According to Forbus and Gentner, young children evolve their first senses of lawfulness out of rich and essentially literal memories of real-world events. In contrast, my view is that p-prims constitute the basic encoding of the naive sense of mechanism. They are in no way literal, and they need no such precursors. They are not individually "rich," in any obvious sense, although they are likely to be abstracted in regions of a child's current knowledge that are rich. P-prims constitute impressions of lawfulness, but they must exist in large numbers at the earliest stages of competence with the physical world. Empirical work showing babies' sensitivity to different causal scenarios reinforces this last presumption. Babies seem to be surprised at scenarios apparently showing interpenetration of solid objects or at scenarios of causality without physical contact (Leslie, 1982, 1984; Spelke, 1991).

The very notion that rich and literal descriptions of relevant events exist prior to any sense of mechanism runs counter to what I take to be a typical developmental pattern—that involving the accumulation and coordination of p-prims to achieve reliable (hence, retrievable) descriptions.[51] If young children have strong literal-memory capabilities, my contention would be that these only concern aspects of events for which there exist strong and elaborate descriptive capabilities, aspects such as static spatial deployment. If a sense of the underlying mechanism is involved in the memorial reconstruction of an event, there is ample evidence that children suffer from serious inability to recall events literally. One simple example, among many in Piaget (1974/1976) and Piaget and Inhelder (1966/1971), is that young children will draw the path of a tiddlywink through the air, immediately after watching it, in horizontal and vertical segments (see Figure 9A). Another example, to which I made reference in the section on figural primitives (p. 165), is that children will draw the level of water in a tilted jar as in Figure 9B. These I take as strongly suggestive that a (mistaken) sense of how things work can often predate and undermine literal memory.

The contrast between Forbus and Gentner and myself concerning expertise, the other extreme of mechanical understanding, is also enlightening. They see quantitative capabilities, such as the ability to use algebraic formulations of the laws of nature, as the last and highest stage of achievement. I have presented little data to argue specifically against this view, although it is clearly not in the main line of development I have been charting for the sense of mechanism. One bit of evidence from my MIT interviews is, however, particularly relevant. None of the students in my study, all A or B students in MIT freshman physics, had

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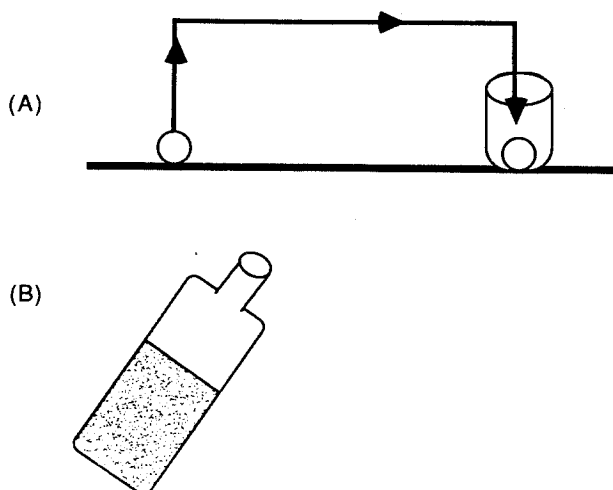[51]See also Minsky's (1980) discussion of the evolution of literal memory.

FIGURE 9   (A) The path of a tiddlywink as drawn by a child watching it. (B) Water level in a tilted jar, drawn by a child.

the least difficulty with algebra or other mathematics involved with the course. Yet, many still had substantial difficulties with simple qualitative analysis of physical situations. They also had difficulties applying equations that were appropriate and that they remembered correctly. This suggests that precise mathematical competence appears last only because it requires meaningful use of equations. If, as seems likely, meaning comes from appropriate qualitative causal conceptions, then, at least for this class of student, quantitative skills in physics follow trivially on qualitative ideas.

I mentioned an agreement with Forbus and Gentner on the importance of processes in naive physics. Yet, even here there are substantial differences. First, reliance on processes defines a stage of development for Forbus and Gentner. It is difficult to understand what this stage corresponds to in my sketch of development, because both very early stages and later ones involve extensive use of non-process-like p-prims (e.g., figural prims in the former case and, in the latter case, *abstract balancing* and the situational, geometric causation needed to understand Newton's third law). More deeply, Forbus and Gentner's stages are defined by ontologies. The second stage is defined by the causality of a sharp class of correlations (i.e., cause statements). The third stage is defined by a similarly sharp class (i.e., processes). I have argued against the sense of mechanism being localizable in such a way, although I do not doubt the utility of theoretically separating kinds of p-prims.

Forbus and Gentner are concerned with two classes of reasoning. The first comes from Forbus's qualitative process theory. The problem is that this set represents reliable methods of computing consequences (albeit with important

limits on selecting unambiguous conclusions) based on relatively complex and uniform data structures, which run counter to the proposed limitations of the nonexpert sense of mechanism. Processes know exactly when they "turn on," and one can compute a complete set of future possibilities, if not select the one that will occur (Forbus, 1984).

The second class of reasoning is analogy. Although Gentner wishes to see learning from complex structure mappings from one situation to (memories of) another, I doubt these are possible at the important level of mechanism as opposed to within better developed descriptive systems (e.g., commonsense verbal descriptions of objects and their spatial relations) where such problems as persistence do not exist. It is difficult to see how a sparse, dynamically limited system can manage to compute and assess very complex maps. Further, analogy may be seen in an entirely different light in the context of p-prims. Rather than learning via assessing the structure of complex maps, simple and abstract schemes such as p-prims drive the recognition of similarities between situations, and they are also the basis of judgment of similar mechanisms acting in the two situations. The sense of mechanism is shallow, particular, and dynamically limited. It does not draw reliable, context independent conclusions based on general criteria such as depth and breadth of a map.[52]

Educational Implications

A theory of knowledge and its development ought to be significant for education. Naturally, I do not attempt here to present compelling examples of analysis or instructional design. Instead, I conclude this monograph by roughly locating some areas of implications of knowledge in pieces.

1. *A target of instruction.* Traditional views of learning science target, for example, concept development and problem-solving skills. The principle implicit educational claim of this work has been that the causal sense of individuals — what phenomena are seen to be self-explanatory or problematic, relevant or irrelevant to various circumstances — is an almost-separable aspect of learning physics, if not all sciences. To be sure, this causal sense must be involved with concept development and problem solving, but its role in this and even its very existence have not been acknowledged. For example, Reif (e.g., Labudde, Reif, & Quinn,

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[52]These criticisms of structure mapping as a basis for analogies and learning from analogies are not the pragmatic ones — "Structure depends on the goal toward which the analogy is aimed" — proposed by Holyoak (Gentner, 1989). Instead, I claim that there is a distinguished and contentful (not purely structural) "causal judgment" module, not dependent on local goals, that cannot be written out of analogies — the comparison of different situations for the purpose of understanding physical mechanism. Although Gentner might seek to take into account causal judgments by incorporating them into her model of the "initial structure of the domain," such judgments are frequently problematic and will, therefore, become an ongoing part of analogical processes.

1988) characterizes learning scientific concepts substantially as learning procedures of identification and use; there is no role for judgments of plausibility. Misconceptions or alternate-conceptions views of naive knowledge recognize, in some way, naive judgments but, in general, propose no role for them in expert thinking. Functions of naive elements in expert thinking that I have listed include becoming part of the infrastructure of knowing laws themselves (distributed encoding), cuing instructed ideas in appropriate situations, and serving as legitimized phenomenology to mediate the gap between the complexities and particularities of common situations and general physical laws.

In addition to relatively direct instrumental effects related to problem solving and conceptual development, cultivating the sense of mechanism as an instructional target may have vital indirect importance. It may contribute a backdrop that allows bootstrapping for, and provides stability to, developing concepts. Concepts that are felt to be plausible and have rich connections to familiar situations are much easier for students to debug and extend on their own. The sense of mechanism can similarly provide a heuristic framework that helps students gradually refine their abilities quickly to develop adequate scientific models of situations.

Perhaps the most devastating implication of ignoring the sense of mechanism in instruction is that building an unwarranted wall between prior knowledge and scientific understanding may alienate students. I am convinced that one of the most problematic parts of current instruction is that students do not feel that they can really participate in physics instruction, that learning physics is a matter of accepting and memorizing counterintuitive, if not meaningless, formulations from experts. One of the most striking findings from the interviewing studies on which this work is based is that MIT undergraduates, when asked to comment about their high school physics, almost universally declared they could "solve all the problems" (and essentially all had received A's) but still felt they "really didn't understand at all what was going on." My interpretation is that their naive sense of mechanism was not engaged and refined. This leaves students at sea both with respect to solving qualitative problems and also with respect to a feeling of security that the physics they learn in the course really represents how the world works. If I am correct that an appropriate sense of mechanism is an essential part of experts' knowledge, these students' impressions of incomprehension are ironically more correct than their school assessments: They did not understand, even though they could perform.

2. *An account of learning difficulties.* What do we say when students have difficulties learning? This work provides suggestions at two levels. First, it suggests that learning difficulties are a system issue. In this, it conflicts with some views that localize problems in a few misconceptions that can be individually targeted and remediated (e.g., McCloskey, 1983b). Instead, I have pointed out that sometimes broad and coordinated changes must be accomplished to turn a shallow, naive sense of mechanism into an expert's. In addition, knowledge in pieces prepares us to understand the individual work, and support that we might

need to give to it, that might be necessary in the diversity of personal senses of mechanism that are likely. This contrasts with believing that all students have one particular task to accomplish—unseating a competing theory to Newton, as theory theories of intuitive physics would have it.

In addition, the hypothesized system characteristics of the sense of mechanism provide further focus. Loosely organized and inarticulate knowledge systems pose particular problems for instruction. Evoking and considering individual p-prims might be problematic or impossible.

At the second level, p-prims provide specific accounts of particular conceptual difficulties. Some misconceptions may be the influence of a particular p-prim (e.g., *force as a mover*), and some might be the concerted influence of a number of p-prims (e.g., the impetus theory). Other difficulties lie in basic descriptive vocabulary involved in perceiving mechanical causality, such as a shift from agent–patient schematizations to geometric causality, or the abandonment of figural primitives in favor of local dynamic evolution.

3. *Resources for instructional design.* We may consider implications for instructional design, again, at general and then at more specific levels. At the general level, the contention that substantial naive knowledge is involved in expertise means that strategies aimed at engaging this knowledge are necessary. Discussions of principles and procedures that do not include reference to everyday phenomena, for example, are much less plausible than would otherwise be the case. Consideration of everyday events, which can easily become very engaging and animated in class discussion, now can be seen also to be central in contributing to legitimate scientific understanding. Thinking about everyday phenomena is not just making an analogy or providing helpful scaffolding; it is invoking the very resources out of which expertise is built, and it is also exercising a component of developing knowledge not engaged in more schematic problems.

At a more specific level, the microstructure of p-prims related to particular developments may describe conceptual resources and positive contributions of naive ideas, in addition to locating some difficulties. We can understand how realizing the springiness in everyday objects might provide an essential step in making action and reaction acceptable and workable across a broader range of circumstances. We can understand the positive roles of "primitive" ideas such as "heavier things move more slowly" and "stiffer things vibrate faster" in fluent expert comprehension. But we also understand how the intuitive plausibility of Ohm's law provided by *Ohm's p-prim* should not be mistaken for understanding the deeper physics causality involved.

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APPENDIX A: CASE STUDIES OF P-PRIM ANALYSIS

Ohm's P-Prim

Ohm's p-prim makes a good case study. It is among the better developed cases, and it shows many of the heuristic p-prim identification principles (Method section, p. 120 and following) in action. I reference these principles parenthetically as they apply here. Rather than presenting an abstract case for the p-prim, I provide a narrative for easier and equally (if not more) informative reading. The narrative does double duty, showing data used in the development of the theoretical frame as well as their use in discovering, refining, and validating descriptions of p-prims. Of course, the narrative is a reconstruction, and the chronologies should not be taken too seriously.

The discovery of the *Ohm's p-prim* began by considering a class of simple everyday events. How do people know to push harder on bigger things to make them move (principle of obviousness)? Initially, it seemed plausible to me that no p-prim might exist here, only inarticulate muscle control schemata. However, I anticipated this would be an important p-prim class, because it is so common and critical to choosing actions in order to accomplish everyday tasks (principle of functionality). It seemed evident that a large class of situations was essentially isomorphic at this level of description, although such intuitions warrant skepticism (principle of diversity). I was at the time considering different versions of *force as a mover, continuous force, force as a spinner*, and so on. These all could use the same principle to modulate effort and result, provided a schematization suitable to all of them could be found (principle of coverage, principle of abstraction). It seemed evident that any of these phenomena could be a context of abstraction for such a p-prim (principle of unproblematic genesis).

Many years before, I had hypothesized a central class of causal relations that I called "causal syntax." It involves a trio of elements: an agent or causal source, a legitimized causal connection, and a patient. It made sense to try such a tripartite relation, with emphasis on the amplitude of effort or intensity in the causal source, the amplitude of its result in the patient, and on some modulating effect in the causal connection. From evidence of intuitive equivalents of $\mathbf{F} = \mathbf{ma}$

(a heavy mass "resists" a push), I began to settle on some form of resistance as the mediating property, but the exact characterization of this was uncertain.

It was helpful that I knew even very young children had the ancillary knowledge to make such a p-prim useful. Reasoning on systems involving proportionality, inverse proportionality, and compensation had been studied by Piaget and others (principle of functionality, principle of scavenging data, principle of continuity).

Out of curiosity, I began to search for situations that violated this p-prim. After all, a principle that is universally true should have more than p-prim status. An early attempt involved looking outside of the domain of mechanics. I considered electricity. Instead of a counterexample, I ran across a stunning example, Ohm's law: Current flow in a circuit is proportional to the voltage and inversely related to the resistance. To that point, I do not recall having made the connection between an object's resisting motion and the resistance in an electrical circuit. (Having been an electronic hobbyist, "resistance" was to me a thoroughly dead metaphor.)

It made a great deal of sense that if a p-prim such as *Ohm's p-prim* existed, it would be applied by the discoverer of Ohm's law and frozen into the technical vocabulary used to describe it. It also helped that the British and German words for voltage are evocative of effort or latent impetus, *tension*. Plausibly these might even have arisen from bodily tension (principle of the body), although I never discovered how to follow up on the idea. Granted, essentially any semantic theory could rationalize the application of words such as *resistance* and *tension* to such a situation, but the use of both *resistance* and *tension* together was at least suggestive (principle of diverse evidence). I also noted with satisfaction that current is an almost ideal "result" in that it is motion of a sort that would seem to require a cause. The description of *Ohm's p-prim* as involving an effort or level of impetus (located in a generalized agent), a resistance, and a measure of result seemed to be succeeding.

It was also important that I knew Ohm's law is very intuitive and easy, in the first instance, to teach (principle of scavenging data, this time from instructional experience). Because my orientation had all along been that intuitive ideas are responsible for some of the learnability or nonlearnability of various technical concepts, now having an explanation for that particular fact with regard to Ohm's law was encouraging. This was also the first instance of an important class of functions I have identified for p-prims in more expert knowledge, serving as qualitative approximations to the technical concepts.

I looked through several texts to see if I could find examples of explicit invocation of *Ohm's p-prim*. It seemed to me that sensitive instructors would make use of it. Not only did I find such uses, but one of the texts I checked also contained an explicit warning that the schematization of Ohm's law as a result driven by an impetus, modulated by a resistance, is only metaphorical, as, indeed, it is. It is only a gloss on an expert's causal view of Ohm's law. (See related discussion in diSessa, 1988.)

Soon, however, I had a clear counterexample to *Ohm's p-prim*. Vacuum cleaners speed up when their nozzle is covered, whereas, intuitively, the covering hand would appear to provide a clear resistance or interference. Thus, I expected to find that people would predict the pitch would go down when the nozzle was covered.

A few of my early interviews were successful in this regard, but there were complications. First, many people had strange ideas about how pitch is determined in this situation. They believed some sort of musical or resonance phenomenon was responsible. In the end, I salvaged some such subjects by simply telling them that the pitch is essentially the speed of the motor, so that they could proceed with the core causal analysis in which I was interested.

Another complication was that many people simply remembered that a vacuum cleaner's pitch increases. Many of these also could be salvaged by asking them why such an increase occurred. Some subset of these gave unanticipated corroboration of the application of *Ohm's p-prim* to the situation. They asserted that an increased resistance or interference would cause the pitch to go up because the motor would have to work harder to "try" to compensate. Thus, an intelligent impetus (that understands *Ohm's p-prim*) could attempt to make up for an increased resistance by increasing its own efforts. A few subjects even retracted their assertion that the pitch would go up when I questioned, and they admitted as questionable the implied assertion that a motor could know to try harder (principle of dynamic). These short episodes underscore, if it needs emphasis, that answers per se should only with great care be taken to relate directly to p-prims, "misconceptions," or any encoded knowledge.

"Working harder" to some extent threatened my *Ohm's p-prim* interpretation of the vacuum cleaner. Some subjects never appeared to unpack it into its (I considered) *Ohm's p-prim* justification. But in the end, I considered working harder's existence to be a confirmation that motors are viewed as generalized agents. Thus, agent-like phenomena other than *Ohm's p-prim* should be on tap in situations involving motors and the like (principle of ready availability). The more I discovered the diversity of p-prims that students used, the less I was disturbed by variations, and the less I expected to see p-prims unpacked always into, what seemed to me to be, their evident justification or even their intuitive roots (principle of diversity, principle of impenetrability).

I puzzled for an extended time over two facts. The first was that, in order to cover all the instances I found of it, resistance or interference had to be very general categories (principle of invariance). Partly, I became less worried about this as I accumulated more and more p-prims that seemed to have comparably wide scope. Partly, as it became more evident that *Ohm's p-prim* is a central element, it seemed to me more likely and less important that there might be disjunctive cues to the inversely modulating quantity. Whether it is interpreted as interference or resistance, all the cued proportional and inverse proportional connections among "effort," "resistance or interference," and "result" can do the essential work of *Ohm's p-prim*.

The second puzzling fact was that the impetus level of the motor was apparently confounded with an indicator of effect. In the *working harder* interpretation, pitch indicates effort on the part of the agent. In the "the vacuum cleaner pitch slows down for increased resistance" interpretation, the pitch is an indication of decreased result. Several things lessened my concern. First, it became clear that reliably connecting p-prim slots to localizable features in a situation is a difficult accomplishment, implying more structure to p-prims than one should ordinarily expect. One should expect slipping and sliding in attribution. Also, it seemed to me agency is frequently ambiguous in this way. Results are frequently taken as measures of (less perceptible) effort. Finally, it seemed to me that the vacuum cleaner situation contained such a good exemplar of interference, a similarly good exemplar of impetus (a motor), that exactly how one made the attributions to the particulars of the situation was irrelevant to the fact that all of the aspects of *Ohm's p-prim* evidently existed, so that it would be seen to regulate the situation in any case.

More generally, I came to accept that p-prim analyses may not involve any single, clearly drawn model of the situation. For example, in instances of application of *Ohm's p-prim*, I ceased to expect to find a clear demarcation of (a) agent, (b) location and form of impetus ("effort" or tension) in the agent, (c) an articulable causal (perhaps even spatial) topology connecting the agent through a resistance or interference to (d) an evident patient, which was (e) the locus of a result measurement clearly independent of the impetus. Rough but reliable cues to *Ohm's p-prim*, and ready features to plug into relations of effort and result, were all that I felt were needed.

For the most part, although it entailed a number of complications that had to be sorted out, I came to consider the vacuum cleaner good verification of *Ohm's p-prim* at the same time that it refined my expectations about what exactly constituted this knowledge element (principle of discrepancy, principle of invariance in the form of predicting a "misconception").

Subsequently, I became aware that *Ohm's p-prim* might be implicated in interpersonal interactions, such as influencing and convincing. In his work on force dynamics in language, Talmy (1988) made similar observations that further reinforced the case for the reality of one of the starting points for *Ohm's p-prim*, causal syntax. Talmy used terms rather different from *agent* and *patient*, but the schematization is the same. Talmy also heightened my appreciation for the special role of *result*. In effect, result defines *patient* as the locus of effect of the (generally unaffected) agent.

Several other pieces of research in recent years have indirectly (via "strong vocabulary") added more data to the case for *Ohm's p-prim*, particularly with regard to the almost anthropomorphic attributions *Ohm's p-prim* makes with regard to agency of inanimate things. Work by Minstrell (1989) and Brown and Clement (1987) continued to indicate that agency in various forms is a central attribute in intuitive physics. Minstrell also developed data showing that very young

children can reason specifically about the effect of mass in *force-as-mover* situations (personal communication, July 1987). Again and again in my own analyses, agency has been implicated. For example, see the discussion of action and reaction (p. 151 and following). In addition, agency is a feature of children's thinking that Piaget emphasized (principle of continuity), although interpreted differently and in a very different overall theoretical context. Finally, some of my own work with small children (Globerson & diSessa, 1984) showed some extreme examples of anthropomorphic and animistic thinking. With such evidence for crude precursors of the more refined agency shown in *Ohm's p-prim*, I became much more comfortable with refined versions of agency and effort showing up in an adult p-prim.

Because it seems like a powerful methodological move, I mention two other examples comparable to the vacuum cleaner's role in the case for *Ohm's p-prim*, predicting misconceptions. First, the railroad-car-in-space problem (see the first subsection of Systematicity) was invented to satisfy two criteria. (a) It is apparently an occasion for apt application of impetus ideas to mechanical situations if such well-integrated conceptions exist and dominate intuitive physics (McCloskey, 1983a, 1983b). (b) I believed a different (p-prim) analysis would better capture subjects' answers. I was confident figural and *springiness* p-prims would dominate impetus in this context.

Similarly, if my p-prim decomposition of the impetus theory is correct, I should be in a good position to predict nuances in available data. So, I expected, for example, that simply releasing a body to fall would not elicit impetus explanations nearly as much as tossing it up into the air. I was able to confirm these predictions, roughly, by checking with researchers who had researched drop and toss problems (J. Clement, personnel communication, July 1986, referenced briefly in Clement, 1983). Both the railroad-car-in-space and dropping (as opposed to tossing) problems are good examples of the power adequate description should provide via the principle of invariance.

The Bell

My first encounter with the Montessori bell conundrum (see subsection on bells in the Development section), that thicker bells of the same other dimensions have a higher pitch, was instigated by a colleague who was puzzled by the fact. It seemed immediately evident to me that a p-prim must be involved, because people's reactions were so swift and sure (principle of obviousness). In fact, in some ways this behavior seemed exceptional in that, given such a counterintuitive result, very few people seemed to have any other way at all to think about the problem (in contrast to the principle of diversity). As my analysis progressed, however, I did find significant diversity in and across individuals.

My first take on the features involved was that people were reacting to mass. A greater mass in a harmonic oscillator leads to reduced frequency. I soon dis-

covered, however, that this was only true for a relatively small percentage of the population I interviewed about the problem. Most seemed directly to impute size as the controlling influence. This made sense in retrospect; it is more evident than mass (principle of ready availability). Mass would be more expected from physics-instructed individuals.

I was struck by how limited many people's penetration into the problem was. I discovered that some subjects had evidently abstracted the p-prim from direct phenomenology of size and pitch; a (informal adult) subject or two were entirely unaware that pitch had to do with frequency and vibration, yet were as secure as others in the belief that a bigger object should have a lower pitch (principle of impenetrability). Others did mention weight as probably the controlling factor. As with resistance and interference, I have not considered it critical that two versions of the bell p-prim might exist: one involving size, one involving weight. I suspected that, for those who responded to the weight connection, it would be considered more fundamental. Some informal data led me to believe that weight did have a higher reliability than size for most who had responded to both attributes (principle of dynamic), although it is not entirely evident why this should be so. After all, taking wavelength to be the determiner of pitch is physically as appropriate as taking mass. Perhaps high school physics does not teach waves as well as it teaches $F = ma$. Nonetheless, the mass connection seemed to have greater reliability priority.

Although most subjects were ready with analogies—church bells compared with jingle bells, xylophones, musical instruments of various sizes—I was struck that some initially could not produce any example of the phenomenon they identified to be at the root of the situation. This, along with the rapidity and expressed certainty of responses, heightened my confidence that a p-prim (or several) was at stake rather than analogy (principle of content over form).

The p-prim richness of the situation became more evident when, in later interviews, I pressed people for plausible explanations for the fact that thicker bells do have higher pitch. A few reactions are instructive. Some people responded that the bell would "not vibrate as much" (apparently referring to amplitude) because it was thicker. I did not pursue the issue of whether this was because thicker bells are more massive and so resist much motion or whether this was a result of stiffness. Because the bell did not move far, it could do so in less time. At first, these reactions puzzled me; I did not understand the logic. If it was being restrained from moving, surely it would move more slowly as well as not moving as far. Rereading Piaget on time, distance, and speed problems was instructive (principle of continuity, scavenging data). Young children seem separately to encode very simple heuristics, such as *if an object is ahead, it must have gone faster*, or, more relevantly, *if an object covers a reduced distance, it takes less time*. (This p-prim interpretation is, of course, dramatically different from Piaget's interpretation.) At least young children systematically ignore the contingencies

that make these conclusions justifiable, such as the presumption of equal speed that would seem to have to underlie the logic of *less distance implies less time*. Adults may also invoke these simple p-prims occasionally, when pressed.

The apparent use of *less movement implies less time* also underwrote the relative impenetrability of p-prims and the fact that they may frequently be used individually rather than in a reliable package of caveats and contingency checks. This also underlined the contrast to experts' application of scientific concepts. I also became less concerned about the fact that attributing very schematic p-prims to adults made their causality seem primitive. A sense of mechanism is elastic. It grows by considering possibilities that are plausible only in virtue of relatively unfiltered and abstract phenomenology. Low reliability priority p-prims that help make everyday experiences immediately familiar may sometimes be pressed into use in the place of more highly reliable p-prims.

APPENDIX B: LIST OF P-PRIMS

Ohm's p-prim

- *Schematization:* An agent or causal impetus acts through a resistance or interference to produce a result. It cues and justifies a set of proportionalities, such as "increased effort or intensity of impetus leads to more result"; "increased resistance leads to less result." These effects can compensate each other; for example, increased effort and increased resistance may leave the result unchanged.
- *Key attributes:* Resistance or interference, agency.
- *Prototypical circumstances:* Pushing a box with variable effort on different surfaces.
- *Relation to schooled physics:* Reused in Ohm's law. Glosses $F = ma$, with the force representing the causal impetus, m the resistance, and a the result.
- *Comments:* Central and very broadly applicable, from many physical to interpersonal relations such as influencing.

Force as mover

- *Schematization:* A directed impetus acts in a burst on an object. Result is displacement and/or speed in the same direction.
- *Attributes:* Violence.
- *Circumstances:* A throw.
- *Relation to schooled physics:* Glosses $F = ma$, but only from the state of rest. Responsible for "things go in the direction they are pushed" misconception.
- *Comments:* Involves Ohm's p-prim in reasoning about effect of impetus.

Force as deflector (cf. *force as a mover*)

- *Schematization:* A shove may act in concert with prior motion (momentum) to produce a compromise result, directionally between the two.
- *Relation to schooled physics:* May be a relatively low-priority p-prim "encouraged" by instruction because it is more compatible with $F = ma$.
- *Comment:* Frequently, subjects explicitly justified this, the evident deflection (after the fact), as a "compromise" in dynaturtle situations (diSessa, 1982). As many "combined effects" ideas, this seems to develop later and to have lower priority than categorical ideas ("the stronger influence gets its way").

Continuous force

- *Schematization:* As *force as mover*, but involving constant effort.
- *Attributes:* Steady effort.
- *Circumstances:* A car engine propels a car.
- *Relation to schooled physics:* May gloss $F = ma$. But when the result is taken to be speed (the early-on case) rather than acceleration (more sophisticated), it accounts for misconception of "motion requires a force."

Force as a spinner

- *Schematization:* Off-center pushes create spinning.
- *Circumstances:* Especially salient in cases of circular symmetry.
- *Relation to schooled physics:* Glosses torque laws but also undermine plausibility of linear $F = ma$ in such circumstances. Students think forces that create spin cannot simultaneously create linear motion or have a reduced effect in creating translation. This latter idea seems to involve a kind of principle of conservation of effect.

Intrinsic or spontaneous resistance (see *force as a mover*)

- *Schematization:* Especially heavy or large things resist motion.

Interference

- *Schematization:* Influences that do not directly aid or conflict may still interfere.
- *Circumstances:* For example, gravity interferes with horizontal motion (may explain dying away in such circumstances).
- *Relation to schooled physics:* This constitutes an impediment, but apparently not a great one, for independence of orthogonal forces.
- *Comment:* Interference may be causally evident (e.g., a hand on a rotating drill chuck) or imputed (e.g., gravity interfering with horizontal motion).

Dying away

- *Schematization:* All motion, especially impulsively or violently caused, gradually dies away.
- *Attributes:* Fading amplitude.
- *Relation to schooled physics:* Implicated in impetus misconceptions. It undermines the Newtonian principle of constant motion in the absence of force in the same way that continuous force does.

Working harder

- *Schematization:* More effort or cues to more effort may be interpreted as if in an effort to compensate for more resistance.
- *Circumstance:* Attribution to higher pitch, louder noise from a clogged vacuum cleaner.
- *Comment:* This seems to be a relatively primitive anthropomorphic association, but I have observed it in many adults' reactions to the vacuum cleaner problem.

Change takes time ("warming up")

- *Schematization:* Changes take time to "blossom."
- *Attributes:* Crescendo.
- *Circumstances:* Acceleration from cannon shot continues after shell escapes the barrel.
- *Relation to schooled physics:* Undermines instantaneous causality, for example, in $F = ma$.
- *Comments:* Probably relates to a collection of "gradualness" p-prims — that rapid changes require severe or violent intervention. Subjects react to rapid change especially in dynamic visual presentations, such as a simulation. May be less salient in static presentation, for example, drawings of angled trajectories.

Vacuums impel

- *Schematization:* Emptiness requires filling.
- *Circumstances:* Sucking.
- *Relation to schooled physics:* This p-prim must defer to forceful explanation; an outside influence must push things into evacuated space.
- *Comment:* May be cultural to some extent. It is obviously sanctioned by "Nature abhors a vacuum." Consider an extension: How do children explain the fact that sand fills in scooped-out space?

The Constraint Cluster

The following four p-prims have been studied in less detail; descriptions are less certain. Every member of this class must be undermined in instruction because forces must come to explain all these circumstances.

Bouncing

- *Schematization:* An object comes into impingement with a big or otherwise immobile other object, and the impinger recoils.
- *Relation to schooled physics:* Bouncing must cease to be primitive, come to be seen as macro-phenomenon involving springiness and (intuitive versions of) $\mathbf{F} = \mathbf{ma}$.

Supporting

- *Schematization:* "Strong" or stable underlying object keeps overlaying and touching object in place.
- *Attributes:* Strictly topological. No force implications. Supporting objects are not agentive.
- *Relation to schooled physics:* Centrally implicated in "book on the table" misconception that tables do not support by pushing objects up. This substitutes for the Newtonian explanation, which may involve *springiness* and must involve upward forces.
- *Comments:* The weight of the supported object is usually seen to be transferred into and through the supporter. Hence, scales may "weigh" objects, although, in the most primitive cases, only contact counts; objects weigh the same even in an accelerating elevator.

Guiding

- *Schematization:* A determined path directly causes an object to move along it.
- *Attributes:* Influenced by symmetry, other figural considerations.
- *Circumstances:* Railroad car moving along a track; ball follows a tube.
- *Relation to schooled physics:* Intuitively, the motion of a ball following a tube needs no explanation. In extreme cases, the ball may be seen to follow in the center line of the tube, needing no contact or forces. This must defer to force explanations in physics class; the sides of the tube must push to the inside of a turn to cause the ball to follow along.
- *Comments:* Generally of relatively low-reliability priority. Defers to blocking or impenetrability explanations. "Square orbit" (p. 165) seems to be a related figural manifestation.

Clamping

- *Schematization:* An object "clamped" by opposite forces (also when pulled simultaneously and equally in opposite directions) is held stably in place.
- *Circumstance:* A vice.
- *Relation to schooled physics:* Equal and opposite forces not only do not mandate rest, but also have nothing to do with stability under per-

turbation. Clamping does not seem to be problematic in instruction, because dynamics seldom involves analysis of clamped situations. Dynamic balance provides a productive alternative to *clamping*.

Rigidity

- *Schematization:* A cluster of phenomena relating to the presumption that most objects are effectively infinitely rigid. Typically, this involves lack of "give" and coordinated motion of all parts.
- *Attributes:* Solidity.
- *Relation to schooled physics:* Must defer to springiness; rigidity is less compatible with Newtonian physics than "stiffness seen as increasingly firm springiness."
- *Comments:* Rigidity may have perceptual origin in immediate visual perception of coordinated motion.

Springiness (spring scale p-prim)

- *Schematization:* Objects give under stressing force. The amount of give is proportional to force.
- *Circumstance:* Clay or couch pillow under pressure.
- *Relation to schooled physics:* Becomes much more fundamental than rigidity, but it only glosses more detailed analyses.
- *Comments:* Initially, springiness is associated with semistatic phenomena and situations: little connection, for example, to oscillation, which would be a natural physicist association.

Equilibrium

- *Schematization:* A system with multiple influences has a natural domain of stability within some range of parameters of the influences.
- *Attributes:* Stability, nonaligned influences.
- *Circumstances:* An orbit may be viewed as stable confluence of centrifugal, gravitational, and other forces. Equilibrium is like balancing, as in dynamic balance, where conflict may not be salient.
- *Relation to schooled physics:* Must come to defer to mechanisms of stability that are much more specific and complex than simple equilibrium.
- *Comments:* This is a powerful, central p-prim that generalizes dynamic balance. There are frequently figural considerations.

Generalized springiness

- *Schematization:* Disruptive influence on equilibrium creates a displacement from equilibrium proportional to strength of the influence.
- *Circumstances:* Pushing a pan balance "away from equilibrium."

- *Relation to schooled physics:* No useful work in early learning but does not seem to be disruptive of basic dynamical concepts. Must come to defer to specific, forceful mechanisms.
- *Comments:* This is a perfectly reasonable presumption of linearity. It is like springiness but without mediating deformation.

Dynamic balance

- *Schematization:* A pair of forces or directed influences are in conflict and happen to balance each other.
- *Attributes:* Conflict, equality, steady state.
- *Circumstances:* Two people push against one another.
- *Relation to schooled physics:* Dynamic balance is generally compatible with physics instruction. It may be used to gloss "canceling forces."
- *Comment:* This phenomenon prepares for (cues) *overcoming*, should one of the forces involved increase or decrease.

Overcoming

- *Schematization:* One force or influence overpowers another.
- *Attributes:* Changing relative strength. Accelerating effect of successful influence.
- *Circumstances:* A resisting force gives way; an animate agent increases effort.
- *Relation to schooled physics:* Generally this seems innocuous but not very helpful, either.

Abstract balance

- *Schematization:* Some quantities must balance—an imperative form of dynamic balance.
- *Attributes:* Frequently there are figural contributions.
- *Circumstances:* The monkey balancing a weight problem (p. 137).
- *Relation to schooled physics:* May be a useful gloss on algebraic constraints of various sorts.
- *Comment:* Differs from *equilibrium* in that changes in one quantity are necessarily followed by changes in the balanced quantity. This p-prim probably requires specific "reasons" to assume quantities balance, such as figural considerations or convertibility ("worth").

Canceling

- *Schematization:* An influence may be undone by an opposite influence. Generally involves sequential acts that result in no net effect.
- *Attributes:* Conflict. Comparable but opposite influences.
- *Circumstances:* Interprets dynaturtle kick (to move) and antikick (to stop).

- *Relation to schooled physics:* Becomes a mathematical scheme, interpreted by numerical or algebraic cancellation.

Equilibration
- *Schematization:* A return to equilibrium is the natural result of removing a disequilibrating influence. It needs no further explanation.
- *Attributes:* Disruption resolved.
- *Circumstances:* If a disequilibrating weight is taken out of a pan balance, it "returns to equilibrium."
- *Relation to schooled physics:* Must defer to specific mechanisms that force return to some other configuration that is otherwise judged intuitively as simply "more natural."
- *Comments:* This is a powerful self-explanatory principle of change without intervention. A typical assumption about the pattern of motion in returning to equilibrium is "gradual slowing"; less typical is diminished bobbing or sloshing.

Recoil
- *Schematization:* Released tension, as in dynamic balance, results in generation of opposite impetus.
- *Attributes:* Tension, release, violence in the recoil itself.
- *Circumstances:* Rope breaks in tug of war; pullers are "thrown" backward.
- *Comments:* Relatively unsophisticated and low-priority p-prim.

Released object falls (straight down)
- *Relation to schooled physics:* Implicated in some impetus data that carried objects do not have impetus and fall straight down on release.
- *Comments:* This is an everyday phenomenon but with low reliability, even in the naive view. It defers to reasoning on the basis of forceful intervention of gravity or natural tendency as a better explanation.

Wobbling
- *Schematization:* Slow movement (especially of small objects) is prone to irregularity.
- *Attributes:* Unusual slowness, irregularity.
- *Comments:* Consider genesis possibilities such as a marble slowing and thus moving irregularly on a kitchen floor, or try to walk very slowly (resulting in imbalance). This may be a good example of a common but low-priority p-prim.

Bigger means lower pitch (or slower)
- *Circumstances:* Bells, musical instruments.
- *Relation to schooled physics:* Comes to gloss a fundamental relation

in the simple harmonic oscillator—using slower (frequency) rather than pitch.

Stiffer means faster

- *Circumstance:* Vibration of objects.
- *Comment:* Comparable to *bigger means lower pitch* but naively much lower priority if it exists at all.

Figural Primitives

I do not provide an element-by-element analysis of figural gestalts and their causal implications, if such an analysis is possible. Instead, I note, as remarked in several of the p-prim descriptions, that the spatially evident form of a situation can influence judgment of naturalness of motion. In general, people behave as if considerations such as symmetry, similarity, and continuity of forms of various sorts have dynamical implications in situations where physicists do not. See the discussion of square orbit in the section on figural primitives (p. 165 and following) and the railroad car in space (p. 158).

Children's P-Prims

We take an abbreviated look at younger children's p-prims. Some of these come from interviews with children (Globerson & diSessa, 1984), and some come from p-prim analyses of others' data.

The set of time, speed, and distance p-prims that follows helps explain Piagetian results in the present theoretical framework. These expectations are generally true, all things being equal, but children apply them without caveats. They are used by adults at low priority or in more elaborate combinations to achieve more reliable use. See the discussion in the Bell subsection of Development. To understand children's perception, *faster* may be better paraphrased as *harder*, involving more intensity or more effort (see Piaget, 1946/1971b, p. 175).

Being ahead implies having gone faster. (May ignore relative starting position.)

Getting to a goal first (or completing an act first) means having gone faster. (May ignore relative starting position.) Filling a cup may constitute reaching a goal, independent of considerations of how tall or wide the cup is. Thus, goal reaching may supersede distance considerations such as the vertical height gained in filling the cup or the final height achieved.

Passing (overtaking) means going faster.

Smaller objects naturally go faster. (Bigger things are slower.)

Lighter things go faster. (Heavier things go slower.)

Less distance covered means less time. This is stable only later than some of the previous ones, as distance covered (distance conservation) is a problematic concept in the beginning.

Winding up ahead implies stopping later (independent of "observed" order). Judgments of relative timing may be distorted by net accomplishment.

Going faster (more intensity, more effort, "going harder") *means going for more time.* This is obviously judged to be incorrect by adults, but it apparently exists enough to be articulated by children at relatively low priority. Perhaps it may be abstracted from the fact that faster things generally go farther, but, as well, one must go for a longer time to go farther.

Generalized momentum

- *Schematization:* Things generally continue to go as they have been going.
- *Comments:* This seems a very early recognition of momentum, but it is not restricted to linear or even circular cases. Some children articulate the principle and may believe that even fairly arbitrary patterns can be "trained" and will be extended after release. A shook object may continue shaking. An object run in a square may continue doing so after release.

Things move in the direction they are facing

- *Comments:* Children appear to anthropomorphize inanimate objects in this subtle way. Young children will explain their reactions to the cut-string circular motion by saying the object merely went the way it was facing, whether it was facing directly outward (probably figural reasoning) or, more consonant with momentum, in the direction it was going.