What Do “Just Plain Folk” Know About Physics?

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Introduction

Humans have a lot of interchange with the physical world. They lift heavy and light containers; push or roll objects across slippery or rough surfaces; move, twist, and spin themselves; bump into walls; toss and catch balls. In addition to “inter-change,” just plain folk manifest a certain degree of competence at all this. Most of us run into walls only occasionally and rarely miss-guess the weight of objects so much that we accidentally toss a surprisingly light one into the air while trying to lift it.

Thus there is a prima facie case that people have some knowledge of physics—of mechanics, to be more specific. The central question of this chapter is what connection, if any, does folk physics have with the physics that is taught in school, with physicist physics? The answer to this question is marvelously complex, and probably surprising. It is also state of the art because our views of this relation have undergone two revolutions in the last 15 years. Indeed, the view expressed here is far from unanimously espoused by those considering the question today.

A First Look

In order to get some purchase and perspective on this problem, let us consider some a priori possibilities.

1. “Folk physics” has essentially no relation to school physics. It seems entirely possible that people are merely physically competent; they do not have anything that can be reasonably called knowledge of physics. Instead, their competence is inarticulate—they cannot talk about it. It is “bottled up” in motor reflexes and the like and just cannot interact, either productively or destructively, with learning physics in school.

There is both scientific and commonsense plausibility to this view. Scientifically, for example, Jerry Fodor is famous for his notion of modular competencies that are so hidden from our inspection and introspection, so disconnected from other mental
faculties that, apart from being able to exhibit those competencies, we might as well not have them. Language competence, according to Fodor (1983), is of this form. We all speak grammatically, yet those rules are so inaccessible that, it seems, we must learn grammar in school from scratch.

From a commonsense point of view, we all know how hard it is to describe things we can do intuitively, without thinking. Culturally, as well, people are taught that physics is esoteric and difficult. In the United States we would not even think of teaching it until late high school. Students and adults whom I invite to think about some physics problems usually protest that they do not know anything about the subject, even if they have taken a course.

Until about 15 years ago, psychologists of learning and educators would likely have said the following: People have no knowledge of physics that is relevant to scientific physics. They need to be taught from scratch.

2. "Folk physics" is in some substantial ways like scientific physics. To elaborate on this possibility, we need to begin making some theoretical distinctions. Be forewarned that the short discussion below is simplified in various ways from what it would take to provide a state-of-the-art presentation. In addition, this chapter will focus on things like concepts and theories about which there continue to be serious scientific disagreements. Nonetheless, these simplified models are a good place to start.

Let us consider separately the form and content of folk physics. Answer 1, above, is really agnostic about content. It says, instead, that the form of our physical competence is so different from the words and ideas of real physics that contact is impossible. Presuming such a difference in form, we have no immediate reason to suspect a divergence in content. In whatever form it exists, intuitive physical knowledge (competence) would seem likely to be at least compatible with how physicists say the world works. Indeed, since intuitive and scientific world views (by this presumption) come in incompatible forms, it may be "only academic" whether or not they are actually compatible. It might not even be sensible to try to determine this.

Now, however, let us suppose just plain folk have some forms of physical knowledge in common with scientists. This is really what answer 2 means. Let us consider concepts, beliefs, and theories, three fairly prominent forms of ideas for physicists. These three forms of knowledge are roughly hierarchical. We really need to have some concepts before it is reasonable for us to have any beliefs. Think of concepts as a collection of terms in which we can say things. We might have the concepts of force, cause, and motion. With any given set of terms, many things can be said. We might say "force always causes motion," or "force never causes motion." Now some of these we may believe, and some we may not. Beliefs are a new layer on top of concepts that selects what we believe to be true from all the things we can conceive.

Theories are yet another layer. Theories are (probably) a complex but connected fabric of concepts and beliefs, not just any old collection of them. Theories are focused, about a particular slice of reality. While phenomena of light and mechanics are almost always conjoined in our experience, physicists have different theories
to explain these. Similarly it seems exceedingly likely that folk physics, the fabric
of concepts and beliefs we may have about the physical world, divides into mul-
tiple theories—if, indeed, it is theoretical. Theories also have primary concepts and
secondary concepts that are derived from those. They have primary principles and
derived principles. We do not have to decide exactly what a theory is to see that
it is probably not sensible to call any collection of ideas a theory. The key distin-
guishing factor is probably some kind and degree of integration and connectedness
—ideas that interconnect systematically and that are all about the same set of
phenomena.

Even this simple taxonomy of forms—concepts, beliefs, and theories—leaves a
lot of room for different possibilities for relations between folk and scientific phys-
ics. In this sketch, the foundation is concepts. A lot rides on the question of whether
there is sufficient overlap between folk and scientific concepts even to start a com-
parison. Probably the majority of contemporary researchers in this area think the
central action is here. In fact, the term “conceptual change” may be the most-
used term to describe what learners go through in learning school physics. This
presumes both folk and scientists have concepts, and we need to understand how
concepts change to see their world views in proper relation.

It is possible, if not widely believed, that physicists and physics-naive individu-
als have enough conceptual overlap so that the key difference is at the level of beliefs.
Everyone, after all, knows something about position, speed, and weight (physicists
use the term mass), and force is a familiar word, if not exactly in a physicist’s
sense. Perhaps ordinary people believe these are related in a different way than
physicists do.

What about theories? Do ordinary people have anything like theories of the
physical world? It seems the most plausible a priori position is “no.” Theories are
things that belong to formal science. Geniuses like Newton, Maxwell, or Einstein
build them.

But it turns out that there are good and long-standing reasons to keep this
possibility alive. The most compelling is that concepts never seem to come in iso-
lation. We always find families of ideas that reinforce and help interpret each
other. Thus it is families of ideas and concepts that get overturned in conceptual
change, not one concept at a time. These families may not be theoretical, but they
must have interesting and important family relationships among their pieces.
Whether we call them theories or not may be a semantic question.

Let me situate these considerations more carefully in a historical perspective.
Toward the end of the 1970s and into the 1980s, a raft of empirical studies ap-
ppeared that demolished possibility 1, that there might be no relation between folk
and scientific physics. Known collectively as “misconceptions studies” (or, by some,
as “the disaster studies”) this work established the following:

a. In many or most cases, students do have uninstructed expectations and expla-
nations to offer about many simple physical situations. Their “knowledge of
the physical world” is not mute.

b. Their answers to a set of fairly simple, qualitative questions are not random or
simply mistakes. Instead, they seem conceptually based, if on a nonscientific set of concepts. Although a fair diversity of responses can be found, there are strong tendencies toward a few, most common answers.

c. These answers are surprisingly robust, extending relatively unchanged from before instruction at least through high school and introductory college physics. This is the "disaster" aspect of the work. Instruction does not seem to help much. (See Atran, this volume, chap. 28, for a similar conclusion about folk biology.)

One of the classic examples of a persistent "misconception" is how to describe a simple toss of an object vertically into the air. A typical folk physics explanation is that the hand imparts a force to the object, which drives the object up into the air against gravity. The hand force gradually dies away, eventually balancing gravity at the peak of the toss. Then gravity "overcomes" the force, and the object falls back down. In contrast a more scientific analysis denies that there is any force imparted by the hand to drive the object upward. The object merely starts with a certain speed or momentum, which would, in the absence of forces, keep it moving forever. But in this case, the force of gravity acts constantly to change the object's speed. At first it reduces the object's speed, eventually to zero. Then it continues the same process of changing speed toward the downward direction, which results in the object speeding up in downward fall.

A related example is that most people describe the pushing of an object across a table at a constant speed as an imbalance. The hand is pushing harder than the object (or friction) is resisting. Physicists see this as a balance of forces—friction and hand force—which leaves the existing momentum of the object unchanged.

Another especially nice example relates to the question of why an object rests without moving on a table, despite the fact that gravity is pulling it downward. A physicist says the table is exerting an equal upward force, canceling gravity. The canonical folk physics explanation is that the table just blocks the object's motion and that it is nonsensical to believe a passive thing like a table could be exerting a force.

These were exciting and frightening discoveries that propelled us from possibility 1 to possibility 2. Intuitive physics exists, it seems conceptual and articulate, and it opposes scientific physics. It looked like a key stumbling block to instruction had been discovered, although it was a formidable block that conventional instruction failed to remove.

Beneath this level of broad agreement, different researchers took somewhat different positions. The first position is perhaps the most commonsensical (which is not to say it is without sophisticated motivation as well). When we meet people in everyday life who say different things than we do, we tend to assign these differences to the level of beliefs. We have a democratic urge to believe people have mostly the same basic categories. They just differ in their beliefs about which of the many possibilities we can all conceive are true. If, as is the case in physics instruction, we have good reason to take some beliefs (folk physics) as misguided, we may proceed rationally to lay out both sets of beliefs and argue systematically
that one is correct and the other is wrong. Instructionally, "draw out naive beliefs, confront them with scientific ones and arguments for them, and convince students to abandon old beliefs for scientific ones" was a dominant theme.

Other researchers were more worried about the conceptual level. They doubted students had the same conceptual foundations, so arguing to change beliefs without first changing concepts seemed dubious. Indeed, the long and complex process of reconstructing or building new concepts might completely obviate the need for "belief changing" tactics. By the time students can understand physicists' conceptual structure, their beliefs might simply change as an unproblematic matter of course.

Ideas about "naive theories" were also split. Some researchers and educators were convinced by the empirical data that students had relatively coherent, uniform and systematic theories. Others were more cautious in announcing particular naive theories, but on theoretical grounds looked for systematicity and fully expected some version of global coherence would emerge. Still others disbelieved, or at least were agnostic about naive theories.

Because of its importance to later discussion, I mention one naive theory that Michael McCloskey and others have proposed, which he described as surprisingly articulate and systematic (McCloskey, 1983). It is a version of a theory discussed by philosophers in the middle ages. The "impetus theory" has it that a kind of internal force is imparted to an object when thrown or otherwise violently propelled. That impetus drives the object’s continued motion but gradually dies away spontaneously or because of the influence of other forces. This is essentially the naive explanation of the toss given earlier except that, instead of being merely an explanation of a particular event, it is claimed to be a theory that covers a broad range of situations.

To sum up, possibility 2 is that folk physics substantially shares knowledge forms with scientists’ concepts, beliefs, or theories. Given this presumption, it seems inevitable that the discovery of students’ uninstructed but articulate commentary on the physical world would be couched in negative terms as far as the content of these ideas is concerned—hence their description as misconceptions, “naive” theories or beliefs. It would have been shocking beyond comprehension if we discovered people spontaneously develop the same physics, both form and content, as held by physicists.

A New View

It is time for a transition from historical and a priori analysis to a more principled view of folk physics. After its initial blossoming, the "misconceptions" and "naive theories" approach to folk physics sputtered in the following ways.

1. No one could make the “naive theory” idea stick in any detail. Students and physics-naive individuals, on closer look, just did not seem consistent and systematic enough in their views. Explanations varied too much from person to
person and context to context. In addition, proposed naive theories just did not seem to cover enough ground. The impetus theory is, at best, about tosses and similar phenomena. It does not explain how people think about objects on tables, or balance scales, or orbits. . . . Nothing having the scale of coverage of Newton’s Laws appeared to exist. Of the three levels—theories, beliefs, concepts—theories faded fastest and most convincingly from consideration.

2. Beliefs did not have appreciably more success. A reasonable accounting of naive physics as a list of beliefs did not emerge. Moreover, the “articulate and counter with rational argument” strategy did not meet with resounding success. Instead and in contrast, various strategies that built on productive intuitive ideas showed promise. For example, Brown and Clement (1989) used contexts in which people had correct intuitions to bridge into contexts where they did not.

3. The concepts level of analysis did not fare so badly, but still it had only limited success in building a solid account of folk physics. No convincing decomposition into a basic set of concepts emerged.

My conviction is that the fundamental limitation in what has been said so far is a theoretical lack. We cannot rely on nearly commonsense knowledge terms like concept and belief to account for folk physics and its properties in relation to scientific physics. Instead, we need to be theoretically innovative and more precise. In the same way that quantum mechanics had to invent wave functions and particle waves to progress beyond “matter,” so “concepts, beliefs, and theories” need to be abandoned or substantially transformed to do the necessary work. What follows is a short version of my best current account of folk physics.

The Evolution of Complex Knowledge Systems

Four general principles define this approach to understanding knowledge, and folk physics in particular.

1. **Diversity**: There are many different mental forms, modes, levels and contexts of knowledge that need to be taken into account. In particular, most accounts of knowledge skew toward “big” and formal types of knowledge, like facts, concepts, and methods. In contrast, I believe the most pressing need is to understand more subtle, “smaller” knowledge elements. “Impressions” seem vague and not very knowledge-like. Yet impressions and subtle judgments may constitute a critical core of folk physics.

2. **Complexity**: Any individual’s knowledge state, as a backdrop for change, is extremely complex. In order to understand change (or lack of change), say, from folk to scientific physics, we need to engage this complexity. Complexity implies that we may need to know a lot about particular individuals to understand properties of their understanding. But even if there is a uniformity across individuals, the complexity of knowledge systems implies there is a lot to know.

3. **Systems level of analysis**: Although the forms of analysis I prefer to use rely heavily on element-by-element analysis, I believe many important properties of
an individual’s knowledge are system properties. For example, I believe the apparent robustness of folk physics ideas is a systems matter. Consideration of systems and interactions of subsystems is critical.

4. Knowledge level analysis: Some analyses of cognition rely on an articulation of general “cognitive machinery” (typically, work related to artificial intelligence). In contrast, this analysis focuses primarily on “the architecture of knowledge,” postponing in some measure a more mechanistic stance.

My expositional strategy will be to provide a short, but I hope telling, list of “new” knowledge forms along with comments on their properties and on the knowledge subsystems of which they are a part. In particular, each form has: (1) characteristic properties and behaviors in its use; (2) specific relations with other exemplars of its type and with other knowledge subsystems; (3) characteristic patterns of development—both in individual-element and systemic properties—in transformations like that from folk to scientific knowledge of physics.

P-prims

By far the most important knowledge type in understanding folk physics is the “phenomenological primitive,” or “p-prim” for short. P-prims are intended to account for most of the observed properties of folk physics. The key move here is that p-prims are subconceptual; they are much smaller and more fluid pieces of knowledge than concepts or beliefs. I am slipping in a new and different layer beneath concepts, beliefs, and theories.

Humans have hundreds if not thousands of p-prims that they recognize more or less easily in situations and behaviors in the world. The “p” (phenomenological) in p-prim is intended to indicate this connection to the rich, experienced phenomenological reality, which makes the world and happenings in it familiar and comprehensible. Specifically, p-prims account for our feelings of naturalness or unnaturalness, for judgments of plausibility and explanatory sufficiency. The “primitive” part of p-prim indicates that they typically constitute explanatorily primitive descriptions of events; if a p-prim applies, nothing more needs inquiry—that’s the way things are.” Heavy things need harder pushes to move. Things are drawn into vacuums. There is nothing much to say in response to “why?”

Use of p-prims tends to be fluid and data driven. Frequently, we may shift from one p-prim to another with nothing more than a shift of attention, or a minor change in the situation considered. In situations where multiple p-prims conflict, it is unusual that we have specific knowledge to resolve the conflict. As a system, p-prims are diverse and loosely coupled. There is no strict hierarchy, no global levels of importance, nor any logical chain from primary to derived p-prims. Some p-prims, of course, are more important than others, and knowing the more central ones tells us a lot about folk physics. Similarly there are family resemblances and relations among p-prims. But still, the complexities and diversity of the experienced world dominates the possibility of a simple, concise description of the pool of p-prims.
Developmentally, p-prims are likely to originate in relatively simple abstractions of familiar events, abstractions that come to serve more explanatory roles as they are found to underlie a broader range of situations. Learning, of course, sometimes means developing new p-prims. But more often it means a shifting in level of importance, in the context in which a p-prim is felt applicable, and in the typical-use connections with other p-prims and with other types of knowledge entirely. Reorganization and refinement are much better starting metaphors than replacement when considering the transition from folk to scientific physics.

P-prims are problematically related to language. People do not know they have p-prims the way they know they use various words. P-prims are hard to express in language since their natural "language" is one of visual or kinesthetic pattern. Even if we can say or explain a p-prim, getting it hooked up to the feelings of confidence and appropriateness that are the essence of p-prims' function is difficult to imagine through purely linguistic means. For all these reasons, and others besides, one-shot learning at the p-prim level is unlikely. A person's p-prims shift and change gradually through experience. Let's consider some examples:

1. **Ohm's p-prim**: A central and important p-prim that I call Ohm's p-prim is recognized in situations where there are three interconnected loci of attention. First there must be an energizing force or impetus. People may prototypically supply such an impetus, but so may machines and even inanimate objects. Second, there is a "result," typically some form of motion or action. Finally, there is some resisting or interfering effect between impetus and result. The natural patterns of behavior that are expected when Ohm's p-prim applies are that increased impetus produces increased result, increased resistance produces decreased result, and so on. Ohm's p-prim applies to all sorts of situations, from pushing harder or less hard against heavier or lighter ("weight resists motion") objects, to "working harder" in school to get better grades, and to convincing someone by wearing down his or her resistance or by "increased force" of argument.

2. **Force as mover**: In our everyday experience, things happen as we continue to make them happen. We push a chair across the rug; it moves in the direction we push it and only so long as we continue to push. Force as mover is a directed (vector) form of Ohm's p-prim that prescribes that the motion of an object follows the directed effort making it move.

3. **Balance and equilibrium**: Humans have a rich and deeply felt phenomenology of balance and equilibrium. Something "in balance" will be maintained perpetually in that state. Things that are perturbed or "out of balance," return naturally to equilibrium. A particular version of balance that I call dynamic balance is the state where two competing influences (forces) exactly cancel each other, resulting in no effect.

4. **Overcoming**: If one of the influences in a dynamic balance increases or the other diminishes, the stronger influence "overcomes" the other and "gets its way." People are familiar with a particular pattern of actions associated with changing strength of influence: A situation comes into dynamic balance from
dominance of one influence (and hence also of its effect) and emerges with dominance of the other.

5. **Dying away:** Lack of motion or activity is the natural state of inanimate objects. Any induced action or motion naturally fades, unless the agent of induction continues (as in force as mover). A struck bell’s sound dies away.

6. **Blocking and guiding:** Motion can be blocked or stopped by solid, stable objects. Unlike a physicist’s explanation that requires a counteracting force (e.g., counteracting gravity in the case of a book on a table), blocking is primitively explanatory to ordinary folks. Similarly, trains are guided along tracks, or objects moving in a tube follow the tube’s course without any need for deeper explanation.

Readers may already see how these p-prims can account for naive conceptions such as those listed earlier. I will present one case in detail shortly.

**Mental Models**

Mental models are frequently instructed compound knowledge forms that, unlike p-prims, can be the basis for extended and articulate arguments in the course of developing or displaying explanations or in problem solving. Mental models rely on elaborate and well-developed descriptive components, which prototypically reflect the human ability to describe and reason about spatial configurations. In addition, there is a focused notion of basic causal events within a mental model, which perhaps we can understand as the selection of a few relevant p-prims. Logic and hypothetical reasoning are engaged easily in using a mental model, and we may check our reasoning in an explicit way, which is very atypical, if it is possible at all, with p-prims alone.

Instructed models of computer execution are excellent examples of mental models. One imagines a basic repertoire of places (e.g., variables) and actions (e.g., moving or clearing symbols) that can be chained into elaborate and checkable predictions and explanations. Similarly, instruction in electrical circuits relies on topological (geometric) descriptions of elements and connections, along with primitive behavioral or causal models of the components. Some particular systems involving mental models may be too complex to allow full analysis easily. But individuals who understand the mental model will still feel they understand the device “in principle.”

A particular mental model seems to be of critical importance in learning Newtonian mechanics. I describe this as a moment-by-moment accountable model of motion. Basically, we may describe any object’s motion by considering it a succession of instants, at each of which only a specific few entities interact to determine what happens next. Without going into detail, at each moment all we need to know is where an object is, what velocity it has, and what forces act on it. Velocity tells us where the object goes next, and force tells us how velocity changes from one instant to the next.

This moment-by-moment accountable model is notable for its sparsity. Only a very few elements are involved, and each one and their relations are easy, in
principle, to see and check. P-prim analyses, in general, cannot be accountable in
this way. Even if people knew they had knowledge elements like Ohm's p-prim,
they would not know how to check details of its application. In addition, folk and
p-prim analyses in particular are frequently synoptic, describing the beginnings
and ends of fairly complex causal chains, without any need to do a moment-by-
moment, local causal analysis. We may say, "The earthquake caused the books to
fall," without a micro analysis of geometric lines of propagation of vibration or
any account of how the shaking actually caused the books to move off the shelf.

Narratives

Given the backdrop of misconceptions research, it may be surprising that some
parts of mechanics are easy to learn. But easy accomplishments are as telling as
difficulties about the nature of folk physics and its relation to scientific physics. For
example, the discovery of Ohm's p-prim was a consequence of considering why
Ohm's law of electrical circuits seems so simple to most learners.

Narratives are a particular class of easy accomplishments that we find among
physics students. These are basically stories of familiar events over which an ex-
planatory physics story is cast. A classic example of this is the energy story in a
toss. "The energy in a tossed object starts out entirely kinetic (energy of motion)
and gradually shifts into potential energy (energy in elevation) until at the peak
of the toss, kinetic energy is zero and all the energy is potential. After that, energy
is converted from potential to kinetic in the fall." Virtually no one taking physics
fails to learn this story easily and thoroughly.

A not-quite-so-familiar narrative is that of terminal velocity. A dropped object
falls faster and faster because gravity acts on it. But as it increases in speed, friction
drag (an upward push) also increases until it balances gravity, at which point the
object ceases gaining speed.

Narratives are probably easy to learn both because the events depicted are lit-
erally familiar or easy to remember, and because the overlaid "physics story" in-
volves little interpretation beyond naive ideas. For example, conservation is a
powerful intuitive principle, and energy in motion is easy to "see" in the toss.
Terminal velocity is a simple p-primish story of "coming into balance."

Nominal Facts

Students, and also people who have not been instructed in physics, frequently
know a few "basic facts" of physics. "Gravity acts equally on everything," is a ver-
sion of Galileo's story that heavy and light objects fall at the same rate, neglecting
air friction. Other such facts are "Everything is relative," and "For every action
there is an equal and opposite reaction." Nominal facts frequently have simple,
memorable formulations as sentences and sometimes have a surface (p-prim)
plausibility.

Developmentally, perhaps the most notable thing about nominal facts is how
little effect they have on learning. The problem is that the terms in them
frequently have so little meaning for students that the meaning and implications of the facts are haphazard consequences of the situation in which students try to use them.

Committed Facts

Once in a great while, students (and possibly others) build an articulate commitment to a principle of their own formulation. An example is, “It takes unbalanced forces to move something.” A critical difference between these and nominal facts is that the person involved has espoused the fact as a result of a sometimes extended and memorable consideration of the fact, what it means, what the alternatives are, and why those are implausible. Committed facts are perhaps the closest thing to “naive theories” that I believe exist. But even these do not have the range and rich substructure that typify scientific theories. Furthermore, they are rare and probably provoked more frequently by instruction than they are spontaneous.

To sum up, these five categories of knowledge—p-prims, mental models, narratives, committed facts, and nominal facts—are conjectured to be a first cut of a richer, more theoretically accountable and empirically tractable view of the diverse pieces that constitute a knowledge system such as folk physics. Of these, p-prims are by far the most important for understanding folk physics. It would not be a bad approximation to say folk physics is the rather large, diverse and mildly organized collection of fairly simple phenomenological ideas, which are p-prims. On the other hand, spontaneous mental models, narratives, and nominal and committed facts exist, if relatively rarely (and dependent on the p-prim substrate). And during instruction, we are almost guaranteed to see these other knowledge structures develop and change in interaction with p-prims.

J: Knowledge Forms in Action

In this section I present segments of a case study of a student whom I call J. This research was part of a larger study of the “local dynamics of conceptual change.”

J was a female university freshman whom I interviewed for about seven hours, an hour at a time, with interviews separated usually by a week while she was taking introductory physics. J had taken high school physics, a course she liked and felt was well taught. She did not appear to be either unusually adept at physics, or to have particular problems. She was perhaps a bit more willing than some to talk for an extended period of time about her ideas about physics. But in most respects she provided interviews that were comparable to many others I have conducted through the years even if her interviews were sometimes unusually dense in intuitive ideas.

I present excerpts from analyses of J’s protocols for the following reasons:

1. These will illustrate most of the knowledge forms, and even many of the specific examples listed above, in a real context.
2. Protocols generally are more convincing than abstracted argument that these forms are actually informative of intuitive thinking.
3. While much too limited to be convincing by themselves, these protocols and analysis provide data in support of the general claims made here.
4. The protocols are rich enough to provide grist for readers’ own analyses, and raise important issues beyond the short sketch of theory provided above.

Near the beginning of the interview sequence, J was asked to describe the toss of a ball into the air. Her first description was quite professional. She used scientific terms in an account that is difficult to fault (except perhaps for expository form). In particular, note that she twice emphasized that, after the ball leaves your hand, there is no longer any force from the hand in play. “The only force on that is gravity.” Note also clear reference to the energy narrative. Emphasis has been added to mark especially relevant sequences.

J: Not including your hand, like if you just let it go up and come down, the only force on that is gravity. And so it starts off with the most speed when it leaves your hand, and the higher it goes, it slows down to the point where it stops. And then comes back down. And so, but the whole time, the only force on that is the force of gravity, except the force of your hand when you catch it. And, um, it... when it starts off it has its highest speed, which is all kinetic energy, and when it stops, it has all potential energy—no kinetic energy. And then it comes back down, and it speeds up again.

After about 30 seconds of small talk, I asked J a seemingly innocuous question: What happens at the peak of the toss? Rather than produce a straightforward answer, J proceeded to reformulate her description of the toss. The reformulation is not instantaneous, but rather follows a few detours through abandoned and rejected hypotheses. Strikingly, she winds up with an “impetus theory” account of the toss. “Your hand imparts a force that at first overcomes gravity, but gradually dies away. At the peak, there’s a balance of forces, which is broken as the internal force fades further and gravity takes over.” Segments are numbered for later reference.

J: (1) Um, well air resistance, when you throw the ball up, the air... It’s not against air because air is going every way, but (2) the air force gets stronger and stronger to the point where when it stops. (3) The gravity pulling down and the force pulling up are equal, so it’s like in equilibrium for a second, so it’s not going anywhere. (4) And then gravity pulls it back down. (5) But when you throw it, you’re giving it a force upward, (6) but the force can only last so long against air and against gravity—(7) actually probably more against gravity than against air. (8) But so you give this initial force, and it’s going up just fine, slower and slower because gravity is pulling on it and pulling on it. And it gets to the point to the top, and then it’s not getting any more energy to go up. You’re not giving any more forces, so the only force it has on it is gravity and it comes right back down.

Shortly after this segment, J produced a clean reiteration of an impetus account.
From a p-prim view, this is a classic occurrence. A shift of attention (to the peak of the toss) brings a shift in analysis, in this case, from a standard scientific analysis to a folk physics, p-prim–based analysis. Furthermore, it is clear J is not applying an impetus theory so much as deriving it from more primitive pieces that she gradually puts together. Indeed, other data make it clear that she has not assembled a stable conceptualization that she will systematically apply in a broad range of circumstances. Instead, her “misconception” (“impetus theory”) is a construction that is mostly particular to this situation.

I first provide an idealized view of this construction in order to highlight the p-prim pieces. Then I will provide some additional analysis of aspects of the construction more idiosyncratic to J.

Asking what happens at the peak of the toss was a deliberate and strong move. Since p-prim physics is so dense and strong with respect to balancing and equilibrium phenomena, I intended to provoke these considerations. The peak is a stable, no-motion point, and likely explained by a balance. Even more, the switching of directions with a balance between may be an example of the extremely familiar overcoming scenario, where one influence loses dominance over another. Gravity evidently can serve as one influence, but another is needed. A successful candidate for the other influence is some force or energy communicated by the hand in the toss. Finally, why does that “force” (the term sounds too good not to use in a physics context) lose its dominance over gravity? Some sort of interference or wearing down would explain this. But in the absence of a clear interference, the dying away p-prim suffices. Thus p-prim pieces effectively generate an answer that appears to be an application of the impetus theory but, in fact, is a situation-specific p-prim-based answer to a particular question.

In J’s case, she takes the balancing and overcoming bait at the peak of the toss. But then she needs another force or influence. In segment 1, she tries out air resistance to fill the slot. (The comment about “air is going every way” implicates an idiosyncratic model of hers that I will not explain here.) Indeed, air perhaps cues the “terminal velocity” narrative, “air resistance gets stronger and stronger leading to a balance” (segment 2), which seems to fit what’s needed here. In segment 3, J seems to be restarting her analysis from the critical balancing point. She needs an upward influence to balance then succumb to gravity (segment 4). Finally, in segment 5, she “invents” the force communicated by the hand, and proceeds to analyze its fading (not the strengthening imported from “terminal velocity”). In segment 7, the interference of air and gravity are implicated in “dying away,” which she fairly quickly corrects, withdrawing air finally and entirely from playing a major role in the situation. In her final recounting (segment 8), she seems to emphasize that the imparted force dies completely away, leaving gravity alone to cause the ball to come back down.

The story of J’s explanations of a toss as they played out over further interviews is as wonderful and (possibly) surprising as its beginning. In this chapter, I have space only to sketch what happens and pull out two brief segments that relate directly to the main aims here.

In ensuing interviews, I brought J back again and again to the toss and related
situations to explore how she thought about them. Strikingly, J continued to use both her intuitive analysis and her more scientific, single force explanation, depending on circumstances. This was true despite gentle and sometimes stronger intervention aimed at helping her see the problematic nature of her impetus explanation and at helping her solidify and make more precise her scientific explanation.

It is tempting to describe J’s impetus explanation as a model of a toss, even if it is implausible to describe it as a theory. But according to the definition of model provided earlier, I claim J had no general model of motion, nor even a model of a toss. This is, in fact, one of the expected shortcomings of folk physics compared to scientific physics; for the most part, there are no models of central mechanics phenomena. I argue here that J does not have a moment-by-moment accountable model, rather than the more general claim that she has no mental model of any sort.

In the following two segments, which occurred in different interviews, I try to point out a central inconsistency in J’s impetus explanation. At the peak of the toss, she claims that the force imparted by the hand balances the force of gravity, but she also says the imparted force reaches zero, fully died away, at that point. To a physicist, this is a clear contradiction. A moment-by-moment accountable model implies you must provide an accounting of what values relevant physical quantities (notably force and velocity) have at each instant and why they have those values. In the following segment, J seems at first to follow the logic. She says initially that at the point of expiration of the imparted force, the ball would already have to have started its fall. I try to capitalize on her realization, but in her second contribution below she argues that the time between peak balance and dying out is too short to be worth worrying about. She will not accept accountability at the peak instant.

A: If it’s gone [the imparted force] though, how can it balance?
J: Well, at that second that it balances, which isn’t very long, is when it’s like it’s on its last, you know, it’s slowly, slowly dying out, and that one second is the one time when it’s equal. So it’s not gone at that second it’s, obviously. Or it else, if it would be, if it was gone that second, then it would have been falling earlier, and it would have been gone a little bit lower. But at that one, when it’s at its peak, it’s right before it’s going to be gone.
A: OK. That’s right before, so it’s gone some time after it starts the downward. . .
J: Well, when it stopped is when they’re equal. But obviously it dies at that exact point for the gravity to pull it back down. So I guess you can say that at that point it goes away. But when it was completely stationary, it was still there enough to have it not fall. But, it’s such a short amount of time, you know, it’s not like it goes up and hangs out there for a while and then, oh, it dies out and comes back down. It goes up and it comes right back down. So it’s like a really short amount of time. Just dies out.

In the following segment, J follows another tactic. She tries to maintain that even if you cannot say that the imparted force and gravity are equal in magnitude
(because the imparted force is zero), you can say that they cancel. Despite acknowledging the argument that a died-out force cannot balance and also seeing that I am trying to tell her something is wrong with her analysis, she reverts to maintaining that canceling exists, evading accountability to say what entities cancel.

J: ...At the top, the force is equal to zero because it's stopped. But, I guess you can't say they're equal to each other. I guess you have to say that they cancel each other out.
A: Which two forces cancel each other?
J: I'm obviously wrong. [Laughs.] About something.
A: I'm just trying to get all the details.
J: When it's at the top it only has one force on it. Downward. And—
A: So, what's canceling out?
J: I guess nothing's canceling out. ...I still think forces are canceling out, but I don't know which ones they are. [Laughs.]

J continued to use both explanations, the physicist's account and the "impetus" account, after this discussion. Nearing the end of the series of interviews, I took J into a tutorial sequence based on some computer materials aimed at having her fill in all the details of the physicist's one-force model. J learned from the tutorial and during it only wavered slightly at one point toward her impetus explanation. But alas, directly after the tutorial, I asked her one more time to describe the toss. Her initial explanation was flawless scientific analysis. Prompted to remove energy from her analysis and talk only in terms of forces, she fell directly back into the imparted force explanation.

A: Describe one more time what happens.
J: Okay. You give the ball an initial velocity, and that comes from the force from your hand. And then, it travels with that momentum, and once you let it go, it has no outside forces. The only force it has on it is one force downward which is equal to mg, the mass of the ball times gravity. And, so, it goes up and as it goes up, its kinetic energy decreases because it's not getting any energy from any outside forces. Until it gets to the point where velocity is zero for a split second. And that's where it has all potential energy and no kinetic energy because it doesn't have any more. And then, it comes back down. It starts off slow and then picks up speed because of the force downward. And then you catch it again.
A: Okay. So, um, could you describe that just in terms of forces.
J: Okay, starting from when it leaves your hand. Initially, it has force up and a force down. The force up is the force that you gave it. And force down is mg. And the force down stays the same all the time because...The force up is what changes. Because, it starts off big and then, as it goes up it gets smaller and smaller and smaller. So, it's just like the forces are adding, like vectors. And, so, at the top, when it has no velocity, is the point where the vectors are the same for a second. And then, this force stays zero, and this force overcomes it and then comes back down.
A: What vectors are the same at the top?
J: The up one and the down one.
A: The down one is what?
J: Mg. [Gravity.] And the up one is the external force that you gave it with your hand.

I have so far illustrated p-prims in J’s invention of her impetus explanation. We saw repeated use of the energy narrative in the toss despite the fact that she was consistently prompted to use forces rather than energy in her explanation. Plausibly, we saw the involvement of the terminal velocity narrative as the basis for J’s invoking air in a coming-to-equilibrium situation (the toss). And I argued that J did not have any mental model of motion generally, or of the toss in particular, at least by physicist standards of model. I need finally to illustrate nominal and committed facts, at least briefly.

J exhibited a common nominal fact and typical associated limitation in its influence on subsequent conceptual development. She consistently claimed that gravity acts equally on all objects, heavy or light. In contrast, the formula she used for gravitational force was \( F = mg \), where \( m \) is the mass of the object in question. She never acknowledged any inconsistency between her equal influence claim, and the correct formula she used for gravitational force. Indeed, attempts at provoking the realization failed: After one pronouncement that the gravitational force on heavy and light objects is the same, I put heavy and light objects in her hands and asked her what she felt. She admitted the heavy one pushed down more but claimed that one cannot feel gravitational force! To a physicist, one can feel the gravitational forces, the different \( mg \)'s of light and heavy objects. The story is too complex for details here, but J’s nominal facts simply did not connect well enough to her own experience or to other physical knowledge to either self-correct or produce changes in the other things she knew.

Finally, J developed a committed fact that has an astonishing outcome. In one interview I asked J to consider the situation of pushing a book across a tabletop. I asked her to compare the force of her hand on the book to the countering force of friction exerted on the book by the table. J’s initial intuitions were a little mixed. At first she tried “equal and opposite” but was troubled by the feeling that unless the force of friction was “overcome,” there could be no motion. At one point, I “helped” by reminding her that Newton’s famous \( F = ma \) formula requires that, if there are unbalanced forces (leaving a net, nonzero force) there has to be an acceleration. J saw the conflict with her unbalanced forces account of the constant motion (no acceleration) in pushing on a book. After a long chain of consideration, J concluded that she really did believe you needed unbalanced forces to produce motion, and that \( F = ma \) simply did not always apply to the real world. It was just a case where “those darn equations aren’t applicable to every single thing; they’re not always true. You can’t live by them.” J never recanted the claim that unbalanced forces are needed for motion. It did not seem to trouble her beyond this interview that the central, defining equation of Newtonian mechanics is “not always true,” nor that it is not true, in particular, in the simple and almost paradigmatic case of pushing a book across a table.
In preparation for the next section, on educational implications, it is worthwhile reviewing what is evident in and suggested by J's case. First, it should be clear that many times, if not always, the answers students give us to questions are fairly complex constructions based on a rich underlying cognitive ecology. J's impetus explanation emerged in a process, which we were lucky enough to catch, that exposed pieces of her construction of it. As simple an observation as this may seem, it has important ramifications for both researchers and educators. The literature on intuitive physics is unfortunately full of lists of students' answers that are labeled as "misconceptions" with little or no analysis of the underlying reasons for the answers. An adequate account of conceptual development needs to dig deeper than this. Educationally, it is also tempting but misguided to teach to these apparent "misconceptions," treating symptoms rather than causes.

The second lesson we can learn from J is that the hidden world of folk physics is, itself, rich and complex. If my account is correct, we cannot expect to find "the folk theory of physics" or any other compact formulation underlying students' ideas. Indeed, p-prims—which I propose are the elemental pieces of intuitive physics—are unfamiliar knowledge types. They are not facts, concepts, theories, or beliefs, and their properties in development and application need attention beyond commonsense assumptions. In addition, there are many and diverse particular p-prims. We need a subconceptual psychology in the way we needed quantum mechanics as a subatomic physics.

The third point to make is that J clearly maintained multiple explanatory frameworks. Her intuitive account of the toss stood side by side with appropriate scientific accounts. Clearly, there is no exclusion principle that means science must displace other ways of understanding. The traditional method of focusing instruction only on scientific concepts may fail to displace other ways of thinking.

On the other hand, the failure of my attempts to get J to accept the contradiction of saying both that the force imparted by the hand in the toss is zero at the apex, and also that it cancels gravity at that point, suggests limits in the strategy of simply adding arguments against folk ideas to traditional instruction of scientific ideas. The "logic" by which we seek to undermine intuitive conceptions may not be at all apparent to students. In this case, J did not seem to think moment-by-moment accounts of motion are particularly definitive. She refused accountability of her own explanations (to name and justify the balancing forces at the peak of the toss) to the standards that would cause a physicist to reject them as inadequate. Not only conclusions but also patterns of reasoning and standards of judgment must be learned.

**Educational Strategies**

Education is a complex social practice, and creating social and material structures that aid learning is an equally complex matter of design. It follows (if it needs argument) that there is no one correct way to teach. Scientific accounts of knowledge and learning provide powerful descriptions and constraints that must be
observed. But an excellent learning environment is a melding of many short- and long-term goals, a complex negotiation of many overlapping contexts, so that I feel it is quite unreasonable to expect the outlines of practice to follow directly from science. This ought to be familiar. Science provides many resources to the designers of airplanes, but never a particular design.

In this section I summarize implications of the existence and character of folk physics in four heuristic principles for educational design. Then I describe in a bit more detail one particular strategy that follows all four heuristics and has been successfully implemented in a number of instances.

1. Count on extended, cumulative learning to achieve deep conceptual change. J’s persistent use of an intuitive explanation of a toss, despite extended discussions, argument, and even focused instruction, is emblematic of the difficulty facing teachers in reaching the results we hope for. Researchers of misconceptions have extensive documentation of similar difficulties. Moreover, the theoretical frame through which I interpreted J’s protocols provides support for the idea that we must recalibrate our expectations. P-prim is many and diverse and they do not have verbal “handles” that would make them easy to evoke and consider. Deep change must be distributed and systematic. One-shot learning makes little sense at this level. Curricularly, “less is more” should rule, at least if we want students to experience any substantial shift from folk to “real” physics.\(^5\)

2. Engage experiential knowledge. J’s case makes clear that accumulated experiential knowledge (p-prim) provides alternative paths for students’ developing knowledge, not just a pool of static “conceptual beliefs.” J constructed her impetus analysis of the toss and decided, on reflection, that “it takes unbalanced forces to move objects” is a better principle than \(F = ma\) in many circumstances. These are moves she might not have made under other circumstances. What I have not been able to demonstrate sufficiently here is how often and how effectively naive p-prim can be used as part of learning conventional physics, although the easy accomplishments of energy and terminal velocity narratives are suggestive.\(^6\)

Traditional instructional strategies have no stance whatever toward folk physics, which means folk physics’ most positive aspects are not capitalized on, and its negative influences are not negotiated either. A global stance—on the one hand wallowing in p-prim soup without seeking to build sharper, more systematic and accountable (by new standards) descriptions and explanations or, on the other hand, systematically attacking folk conceptions as misconceptions—is unlikely to be maximally helpful. Instead we need multiple appropriately fine-grained strategies. There is no a priori reason to favor engaging naive knowledge through appropriately designed discussion (some of which may mimic my interviews with J) or through more directly experiential encounters with physical or computer materials. Indeed, in some of my own work, discussions about physical situations mediated by computer simulations and formalisms have proved productive (diSessa, 1995).

3. Focus on explanation and description. Conventional instruction concentrates on problem solving to the near exclusion of exercising descriptive and explanatory skills. Taking a close look at how students think reinforces the importance of
learning to explain and describe. Indeed, misconceptions and other research (e.g., Larkin, McDermott, Simon, and Simon, 1980) show how misleading problem-solving capability can be as a measure of conceptual change. J’s protocols and much other work suggest there are two levels of learning to explain. Of course, students should come to give more physicist-like explanations. But a parallel and perhaps deeper accomplishment is to help students adopt an evaluative stance toward explanations that is more accountable to physicists’ aesthetics. I refused such accountability in her description of the peak of a toss as balanced.

4. **Seek to learn more about students’ cognitive ecology and develop strategies to suit.**
Heuristic 2, engage experiential knowledge, leaves plenty of room for both theoretical and empirical development to aid us in instructional contexts. The complex knowledge systems approach implies that details are extensive and important.

J’s behavior in most respects appears unexceptional, even expectable against the theoretical background presented here. Yet it is safe to say most physics instructors would be surprised if not shocked by her performance. In my experience, physics teachers complain that the subjects in such interviews are unusual, that the interviewing technique is faulty, or that the problems posed are unusually hard or tricky. Whether or not teachers need well-developed theory and instructional design by researchers, I strongly believe that a lot could be gained if teachers were familiar with these learning phenomena, sought to have their classrooms serve, in part, as laboratories to tune up their own perceptions of them, and developed their own repertoire of strategies to deal with them.

**Benchmark Lessons**

I conclude this chapter with a brief description of benchmark lessons, which are a genre of full-class, teacher instigated and scaffolded discussions developed mainly by Jim Minstrell. This sort of lesson illustrates all of the heuristic principles listed above in a coherent and well-developed instructional practice. Consult diSessa and Minstrell (in press) for an extensive discussion.

Benchmark lessons are typically introductory lessons aimed at getting central issues and conceptions (intuitive and otherwise) on the table. The selection of topic is critical. It needs to evoke a rich set of perspectives about a situation that, eventually, may become a cornerstone accomplishment of reconceptualization. Discussing whether or not a table exerts an upward force to counter gravity and how to describe a toss may be excellent targets.

Benchmark lessons are designed to be memorable, as the term suggests. Students are expected to reflect on them as landmarks in conceptual development. An instructor expects to refer back to benchmarks on many occasions.

Students carry the main burden of benchmark discussion. For this and other reasons, the subject of discussions needs to evoke multiple positions on the central issue. Luckily, the richness of p-prim physics means this is not unusual. One of the teacher’s many roles is to ensure that diversity gets organized into a number of alternatives that illustrate principled approaches to the problem rather than, for example, a more chaotic dispute.
Another critical role of the instructor is to prompt for reasoning and, in general, to highlight principles and reasoning rather than conclusions and answers. To emphasize this, while experiments or demonstrations may be part of benchmarks, the point of these (just as the point of the whole discussion) is almost never expected to be universal agreement and clarity. Benchmarks are the beginning of a long process. Prompting for reasoning and justification targets both content-level knowledge—concepts and principles—and also standards for argumentation.

Ownership is a critical feature of benchmark lessons. The teacher guides and in some measure organizes. Yet students supply almost all proposals, arguments, and judgments. The teacher may make suggestions. But these are almost always neutrally posed, without the weight of authority behind them, and they are as likely to be “devil’s advocate” rather than “nudging in the ‘right’ direction.” In contrast to other popularized strategies like cognitive apprenticeship (Collins, Brown, and Newman, 1989) and reciprocal teaching (Brown and Palincsar, 1989) the instructor makes no extensive display of expertise to emulate and does not explicitly coach students through sticky issues or through expert procedures. Neither teacher nor textbook defines the terms (e.g., technical physics terms) for discussion.

Benchmarks are cumulative constructions for a teacher. They make use of much experience in hearing what students have to say, of knowing what may be expected and what needs to be prompted, and of learning how students may respond to particular tactics and rephrasings of student-proposed issues.

In summary, benchmark lessons are intended to instigate conceptual development productively and to help lay the groundwork for an extended learning process (heuristic 1). They make use of the richness in students’ naive ideas, which are the central focus and driving force behind the discussion (heuristic 2). They are intended to highlight explanation and processes of reasoned and rational consideration (heuristic 3). And finally, benchmarks capitalize in one particular way on teachers’ cumulative expertise of anticipating and making productive use of students’ ideas (heuristic 4) while not undermining the spontaneity and diversity that is the hallmark of letting student conceptions into the arena of discussion.

Conclusion

In this chapter I have argued two fundamental points: First, intuitive “folk physics” is a reality. It imposes important constraints—but also provides numerous positive opportunities—with which instruction in physics must deal to be effective. Second, the “flora and fauna” of the cognitive ecology of folk physics is complex. It requires a subconceptual psychology with innovative categories, like p-prims, extending or replacing commonsense terms like concept, belief, or theory. Such a “complex knowledge systems” approach to learning does not straightforwardly prescribe instructional techniques that are bound to be successful. Instead, it supplies new suggestions on how to think about instruction as well as critical phenomena (such as J’s invention of the impetus explanation of a toss, her
extended maintenance of it simultaneously with more scientific explanations, and her refusal to accept physical standards of accountability in her explanations) that can serve as landmarks to guide design. One also hopes that the complex knowledge systems view will supply further riches if pursued as a progressing research program.

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Notes

1. Speaking “ungrammatically” generally means speaking with a different, unsanctioned grammar.
2. To anticipate later discussion, almost everyone with whom I talk winds up spending hours discussing physics. And most even find it interesting.
3. David Hammer and Bruce Sherin are the other contributors to this study.
4. In diSessa (1988) I conjectured essentially the “derivation” of the impetus theory that exhibits on the basis of the p-prim pieces I had already discovered, starting with balance, conflict, and overcoming as extremely salient in this situation.
5. There is growing evidence that students’ understanding of the nature of their own physical knowledge and the required transformation to it is a critical feature in successful learning. Thus experiencing this change may be an important bootstrapping step toward broader accomplishment.

References


