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The Ontological Coherence of Intuitive Physics

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diSessa's theory is a deeply articulated, thought-provoking account of the structure of intuitive physics knowledge. We agree with the spirit of the theory in most regards, with one or more important points of departure, which we discuss here. Specifically, we believe that there is more structure in intuitive knowledge than diSessa has suggested and propose a theory of ontological categories as an alternative to his theory of knowledge fragments. Indeed, diSessa briefly entertains the notion of ontological explanations in the context of exploring theoretical alternatives to his own view but provides only a sketch of the basic ideas. Because diSessa could not locate any substantial published defense of this position, we provide a brief description of our own version of this alternative theoretical view, which is either recently published (Chi, 1992) or forthcoming (Chi, Slotta, & de Leeuw, in press). But first, we highlight several of his assertions and then evaluate these assertions in the context of the ontological theory. Finally, we provide a short discussion of some preliminary empirical findings of our own that support the ontological theory.

IMPORTANT THEORETICAL ASSERTIONS

Instead of describing the important points of diSessa's theory, we find it more expedient to list what we feel are his major assertions, together with a brief comment or two. In most cases, his theory is consistent with our own view of ontological categories, and, indeed, the two may be reconcilable to some degree (i.e., phenomenological primitives, or p-prims, may provide a low-level instantiation of our categorical reasoning processes). Still, as the theory has been presented here, there are several assertions with which we find ourselves in disagreement, and we address these in the context of a brief description of our own theory.

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1. *Intuitive physics is simply our conceptual knowledge of the physical world, including a naive sense of mechanism.* We do not dispute this simple definition of what constitutes intuitive knowledge of physics.

2. *Intuitive physics is highly robust.* This is a statement about a well-documented body of empirical findings that shows convincingly that intuitive physics knowledge is highly robust and resistant to change, even when confronted or challenged.

3. *Intuitive knowledge is phenomenological, in the sense that it derives from a person's experience of reality and subsequent interpretation and assimilation of that experience.* This assertion explains the genesis of intuitive knowledge, which seems self-evident. This genesis also explains the next assertion.

4. *Retrieval of intuitive knowledge is driven largely by surface features (context).* Given that intuitive knowledge derives from our direct experience with physical reality, it follows that retrieval of naive concepts is likewise guided by concrete surface features.

5. *Intuitive knowledge is primitive in the sense that it often requires no explanation and provides the basis for higher level reasoning about physical processes.* In principle, we have no problem with the supposition that intuitive knowledge is primitive, because it is derived from seemingly self-explanatory experiences of physical reality.

6. *Intuitive knowledge is not a highly organized and coherent theoretical view of the world, in which physics novices refer to their own misconceived principles about the underlying structure of the physical world.* Although this is a highly contentious point, we agree with it in principle. The crux of the matter rests on how one defines *theory-like* or *theoretical.* McCloskey and others appeal to the Kuhnian-sense of the word *theory*, in which a large body of knowledge is coherently organized according to a few well-defined principles, so that all explanations can be deductively derived from the principles. Such a nomological definition (Haugeland, 1978) is entirely appropriate for describing the nature of scientific theories but may be inappropriate for capturing the structure of mental theories (Chi, 1992; Chi et al., in press). We prefer instead to think of intuitive knowledge as organized and coherent in the way of a schema or frame, as do Murphy and Medin (1985). We agree, therefore, with diSessa's assertion that intuitive knowledge is not highly organized in the strict nomological sense of the word *theory*, but we depart from his strong position concerning the fragmented state of intuitive knowledge.

7. *Intuitive knowledge is organized as a weakly coherent array of primitive schemata called p-prims. The main principles of organization are locally self-consistent patterns of cuing priorities. A p-prim's cuing priority is a measure of the degree to which the perceived context will cue recognition of the p-prim. Intuitive knowledge, as captured by p-prims, is fragmented, meaning that there is minimal underlying coherence.* We fundamentally disagree with the latter part of this assertion and propose a theory of ontological categories that affords a

certain level of coherence to intuitive knowledge while still allowing for the internally variable and context-sensitive reasoning displayed by physics novices in solving qualitative physics problems.

8. *"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" (diSessa, this issue). Because intuitive physics lacks important systematicities, it should, therefore, not be replaced so much as developed and refined.* Although we agree with diSessa that physics misconceptions (which derive from intuitive knowledge) cannot be confronted and overcome, we also disagree with diSessa about refining and developing intuitive knowledge so that it becomes formal physics knowledge.

9. *Development from intuitive knowledge to expertise involves a subordinating of the p-prims to formal principles, as well as a reorganization of them, in terms of their associated cuing priorities, so that they are recalled in a supportive fashion.* In light of our disagreement with the previous assertion concerning refinement of intuitive knowledge, we are skeptical about a theory of physics learning that involves the reorganization of intuitive knowledge, unless *reorganization* is defined in a specific way.

10. *Intuitive knowledge is not organized according to ontological attributes. Specifically, physics misconceptions are not the result of attributing the wrong ontology to a concept, perhaps because the proper ontological category is nonexistent or poorly developed.* Our theory is the antithesis of this assertion, and we intend to address this conflict in the following sections.

AN ONTOLOGICAL THEORY: EXPLAINING THE DIFFICULTY OF LEARNING SOME CONCEPTS IN PHYSICS

Our theory of learning certain science concepts relies on three suppositions: an epistemological one concerning the nature of entities in the world, a metaphysical one concerning the nature of certain science concepts, and a psychological one concerning the nature of conceptual knowledge. We briefly lay out these three suppositions, whose conjunction frames an initial theory of why some physics concepts are difficult to learn, and provides some insight concerning how instruction may best proceed.

An Epistemological Supposition

The first supposition states that entities in the world may be viewed as belonging to different ontological categories. Although this statement is simply a definition of the concept of ontology, what is more important is the character of these ontological categories. We propose three primary ontological categories, as depicted in Figure 1: MATTER, PROCESSES, and MENTAL STATES. There is also a hierarchy of subcategories embedded within each of these major categories (e.g., PROCESSES is divided into Events, Procedures, and Acausal Interactions; MATTER is divided into Natural Kind and Artifacts). These subcategories are shown in the figure, with category members appearing in parentheses and ontological attributes appearing in quotes. An ontological attribute is a property that an entity may potentially possess as a consequence of belonging to that category (or any of its subordinates). This contrasts with the notion of either defining or characteristic attributes, which are attributes that a category member either must have or most likely has, respectively. Thus, an ontological hierarchy of categories defines the world of entities in its most fundamental sense—in terms of their basic essence. Because we are early in the process of laying out the ontological tree in detail, we are not committed to this exact hierarchy. Other organizations are possible. Keil (1979), for instance, following Sommers (1963), divided OBJECTS (corresponding to our MATTER category) into Solids and Aggregates subcategories. Most important in our view, however, Keil and others have neglected the primary category of PROCESSES, whose subcategory of Acausal Interactions is prominent in our account of intuitive physics knowledge.

The PROCESSES category differs ontologically from any category of MATTER. Differences between ontological categories can be operationally defined by their nonoverlapping sets of ontological attributes. For example, in Figure 1, *hungry* can be applied to the category of Animals and all its subcategories, such as Humans. Therefore, Animals and Humans are not ontologically distinct. Basically, two categories are ontologically distinct if they occupy parallel (meaning "horizontally separate") branches of the hierarchical tree. In other words, two categories are ontologically distinct if the attributes of one category cannot be applied to members of another category. Returning to the differences between MATTER and PROCESS category members, "an hour long" is a predicate that may modify a member of the Event category but cannot be used sensibly to modify any member of the MATTER category, such as a dog. Thus to say "A dog is an hour long" is anomalous (known as a category mistake), because even the negation of that statement ("A dog is not an hour long") is nonsensical. On the other hand, if a member of a category is predicated by an attribute from the same ontology, then, at worst, the statement is simply false (e.g., "A dog is purple"). The psychological reality of the distinctness of ontological categories can be tested precisely by predicating an ontological attribute onto a category member and asking people to judge whether such a statement is sensible or anomalous (Keil, 1979).

A Metaphysical Supposition About the Nature of Physics Concepts

We propose that many physics concepts belong to a subcategory of PROCESSES, here called Acausal Interactions (elsewhere we have called it Constraint-Based or Acausal Processes), a relatively unfamiliar and elusive ontological category.

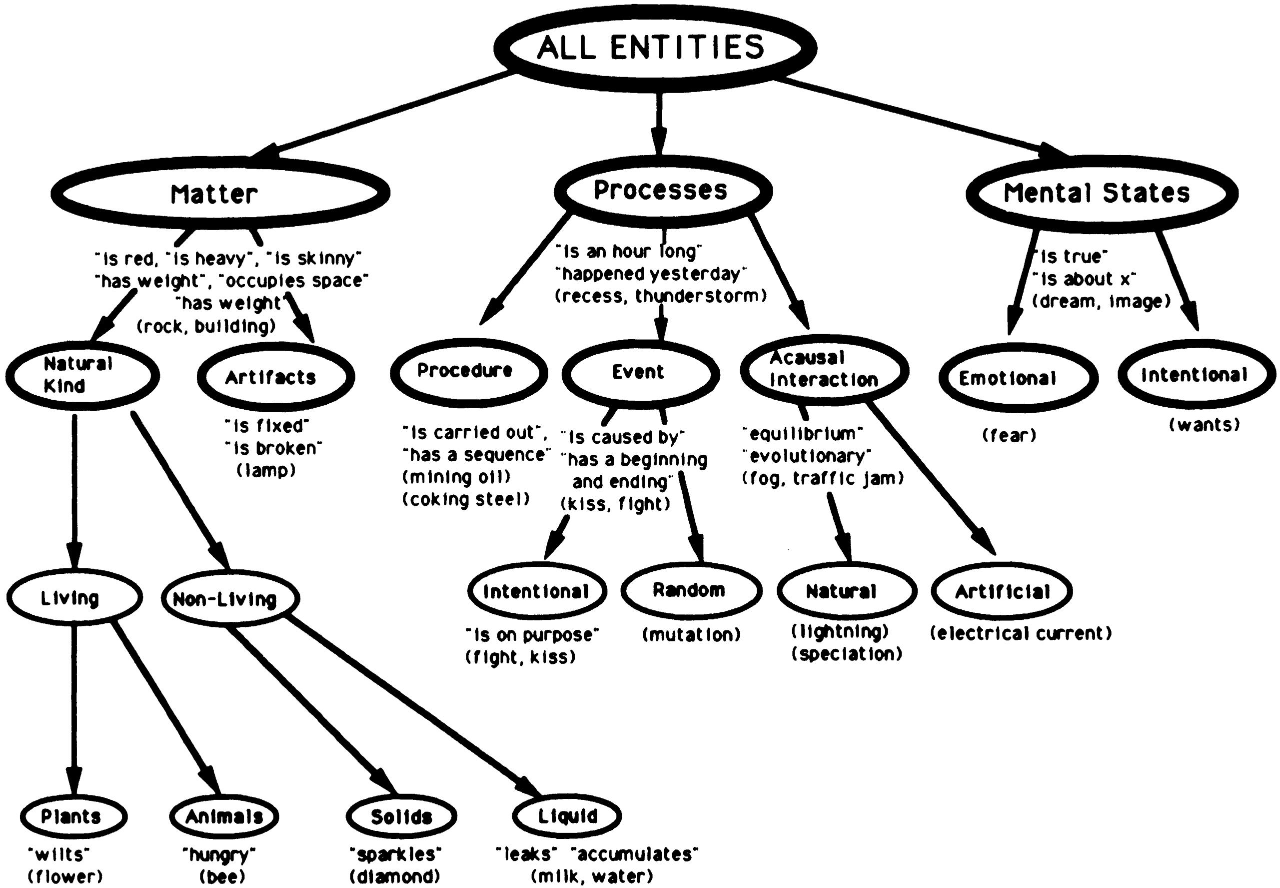

FIGURE 1 One possible organization of ontological categories.

The following examples illustrate members of this Acausal Interactions category. Consider the concept of gravitational force, which involves a mutual attraction between two massive objects directed between their respective centers of mass. There is no direct causal agent of this force, at least within the formalism of classical mechanics. Similarly, an electrical current exists when electrically charged particles are free to move in the presence of an electric field. This can be seen as an interaction between the source of the field (e.g., some difference in electric potential between two points in space) and the moving charged particle, again with no particular causal agent involved. Such reasoning can be applied to the concepts of heat, light, and others, whose veridical (scientific) conceptions all belong to the Acausal Interactions category.

Although concepts in this Acausal Interaction category are acausal, in the sense that they proceed strictly according to constraining relations among their components and not because some external agent or internal intention is driving them, certainly some causality, external to the concept, may be involved in defining the onset of the process. For example, in electrical current, an external causal agent might be the flipping of a switch to connect a battery to the circuit; similarly, English peppered moths' evolution from a relatively light color to a darker color can be seen as causally related to the smoke from nearby factories. Smoke itself, however, did not change the color of the moths; smoke was the external agent that caused a change in the moths' environment, after which the acausal process of evolution proceeded to change the color of the moths. Thus, these concepts become defined only after such initial external causes, but the concepts exist from then on in the absence of any cause.

The best way to characterize the attributes of this Acausal Interactions category is to contrast them with other Process subcategories, such as Events. The first of two major attributes has already been described in the preceding paragraph: Acausal Interactions lack a causal agent, whereas members of the Events category do have a cause. The second salient attribute can be described in the following ways. Acausal Interactions have no obvious beginning or ending, in contrast to Events. For instance, in the Event of a baseball game, certain things happen at the beginning of the game, and other things happen at the end, so that these attributes are well defined. Acausal Interactions do not have this kind of predictable progressive quality: There is no characteristic pattern over time or space, because the process is uniform and simultaneous everywhere. Thus, some of the terms or ontological attributes that can be used to describe an Acausal Interaction are: no beginning or ending, no progression, uniform magnitude, simultaneous, static, ongoing, steady state, and equilibrium.

This broad characterization of Acausal Interactions also applies to science concepts outside physics. For example, within the topic of evolution, there are Acausal Interactions crucial to a complete scientific understanding, such as mutation, genetic equilibrium, and so on. Thus, concepts of the Acausal Interaction category are not limited to disciplinary bounds, although it may be the case that there are more of them in physics than in other science domains.

A Psychological Supposition About the Nature of Intuitive Physics

The psychological supposition concerns the ontological status of naive physics knowledge. Students tend to consider concepts such as heat, light, forces, and electrical current as belonging to the MATTER category, either as material substances or as properties of material substance (Reiner, Chi, & Resnick, 1988; Reiner, Slotta, Chi, & Resnick, 1992). For example, students often think of force as a kind of impetus imparted to a body or as an intensive property that a body can possess (similar to velocity), and they believe that this impetus (or "oomph") can be used up. diSessa's monograph contains a multitude of examples of such misconceptions. Although diSessa deals mostly with the concept of motion, substance-based misconceptions are prevalent and homogeneous across several physics concepts, as synthesized and reviewed in Reiner et al. (1992).

Under this supposition, many of diSessa's p-prims are elementary descriptions of physics novices' conceptions of the behavior of objects in a physical, friction-full world. *Dying away* aptly describes the trajectory of a thrown object if that object contains impetus stuff that eventually wears off. Likewise, *force as a mover* and *Ohm's p-prim* both accurately describe directly observable behaviors. In this sense, we agree entirely with the spirit of p-prims and applaud diSessa for seeing the regularity in the pattern of students' descriptions. Nevertheless, the ontological theory seems to provide some extension concerning the underlying knowledge structure that motivates and controls the generation of phenomenological primitives.

The *ontology* supposition and the *nature of physics knowledge* supposition provide a level of coherence to intuitive knowledge. That is, even though naive physics knowledge may not be theory-like in the nomological sense, it is coherent in the sense that concepts are represented as members of particular ontological categories (e.g., the MATTER category or the Event category). Such coherence can be observed empirically within physics novices' use of certain predicates to reason about qualitative physics problems (to be reviewed later). Contrary to diSessa's view, we do not feel that intuitive knowledge is fragmented, except in the sense that students can draw upon a number and variety of attributes of a particular ontological category in explaining a phenomenon or situation. But the underlying nature of these attributes is one of coherence, in the sense that they all ascribe to a specific ontological category.

At one level, the ontological explanation is more elementary than diSessa's theory of p-prims, and, at another level, it is superordinate in scope. For example, diSessa would consider *blocking* and *bouncing* to be two distinct p-prims, because they describe two common but distinct phenomenological situations. In our theory, however, they are both derived from the MATTER ontological attribute of "occupy space." Hence, the ontological category of MATTER provides a more elementary account of the varied nature of p-prims. At the same time, the ontological explanation is more encompassing than p-prims, because the nature of the ontological category itself provides unity and coherence for the variety of underlying ontological attributes that manifest themselves as different p-prims, depending on the physical contexts.

The Incompatibility Hypothesis

The conjunction of these three suppositions provides the following theoretical framework: First, there is an ontological category called Acausal Interactions, about which physics novices have little knowledge but to which the veridical physics concepts belong; second, novices have encoded and interpreted their daily experiences in the physical world as belonging to the MATTER (and sometimes Events) category. Thus, *dying away* would be an apt description of the behavior of a thrown object. Misconceptions in naive physics result from the mismatch or incompatibility between the representation the student has of phenomena in the world (e.g., as MATTER or Events) and the veridical ontology of the associated physics concepts (e.g., Acausal Interactions). Because learning is primarily the assimilation of new knowledge into existing knowledge structures, this implies that physics concepts are preferentially encoded into the MATTER ontological category. Doing so prohibits the accurate understanding of physics concepts, which veridically should be assimilated into the PROCESS category and Acausal Interaction subcategory. Thus, to learn physics concepts of this nature requires that the Acausal Interaction category be developed (i.e., instantiated) in the mind of the physics novice so that the concepts can be correctly categorized.

This view of learning physics suggests that it is not possible to refine or develop intuitive knowledge to the point that it becomes the veridical physics knowledge; entities on separate ontological trees cannot be merged, because they cannot inherit each other's attributes. For example, the danger in using the analogy of flowing water to instruct about electrical current is that students will continue to assimilate newly taught information about electrical current into the ontological class of MATTER. If students assimilated new information about electrical current into the Liquid subcategory (see Figure 1, near the bottom), the concept might also inherit properties such as "has volume," "occupies space," and other ontological attributes of the MATTER category. This explains why misconceptions about electrical current often include statements such as "It can be stored in the battery" or "It can be used up." Pfundt and Duit (1988) cataloged over 1,500 studies that address misconceptions of this and related natures.

Some Empirical Support of Coherence

We now briefly describe a study that we carried out to capture the ontological coherence underlying intuitive physics. We designed pairs of isomorphic problems that appeared similar in the physical situation they described; they differed in that one member of the pair pertained to an acausal interaction physics concept (e.g., electrical current) and the other pertained to a substance (e.g., water). For example, one of the physics problems concerning electricity required students to predict the result of closing a switch in a parallel circuit containing several light bulbs at increasing physical distance from the battery. The material substance isomorph of this pair was a situation requiring students to predict and explain the result of turning on a water faucet that supplied a series of water sprinklers extending away from the faucet along a hose. In both cases, students were asked to predict which light bulb (or sprinkler) would illuminate (or spray water) first—the one nearest the battery (or faucet) or the one farthest away—or whether they would all respond at the same time.

To code students' explanations, we derived a taxonomy of predicates by enumerating the various ontological attributes from the MATTER and Acausal Interaction categories. Attributes of the MATTER category resulted in predicates such as *block, contain*, and *supply*, whereas attributes from the Acausal Interaction category yielded predicates such as *transfer, interacts*, and *simultaneous*. Subjects' explanations were transcribed and coded according to these predicates (e.g., comments such as "bounces off" were coded as a *block* attribute, and comments such as "They all see (the voltage) at the exact same time" were coded as a *simultaneous* attribute). Figure 2 shows the results from 14 novices and 2 experts. The two parallel solid lines show that novices used predominantly Matter-based

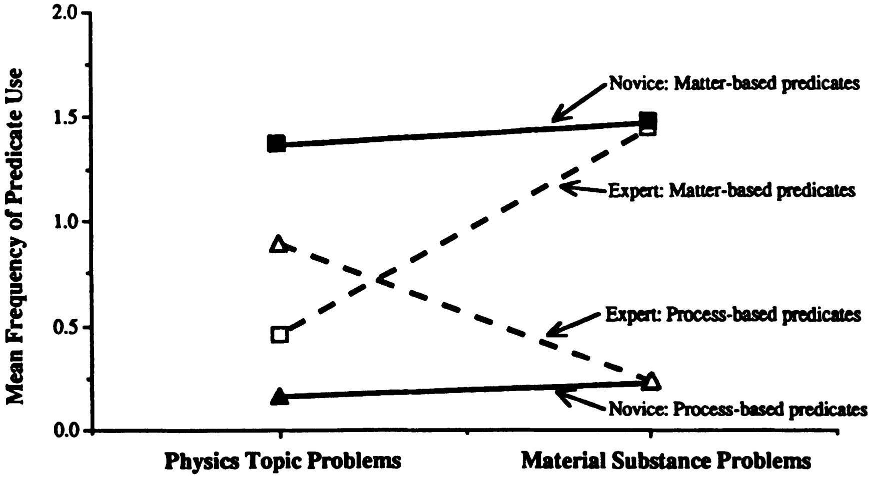

FIGURE 2 Use of Matter-based and Process-based predicates by novices (solid lines) and experts (dotted lines) for physics topic and material substance problems.

predicates (the upper solid line) whether they were explaining situations involving physics topic or material substances. Experts (the dotted lines), on the other hand, clearly reserved the Matter-based predicates for the material substance problems and used the appropriate Acausal Interactions predicates to reason about the physics topic problems. Furthermore, experts did not employ Acausal Interaction attributes when reasoning about the material substance problems.

These results from our study suggest two conclusions. First, novices treat all physical situations as ontologically similar, whether or not the situations contain physics (Acausal Interaction) concepts or material substance (MATTER) concepts; in contrast, experts clearly differentiate between the two kinds of problems. Second, there appears to be an underlying coherence in novices' intuitive knowledge, as derived from coding their explanations in terms of Matter-based ontological attributes. That is, our novice subjects consistently used Matter-based predicates to describe and explain the outcomes of the situations. Experts displayed the same consistency when explaining substance problems, but they further used the appropriate Acausal Interaction predicates when reasoning about physics topic problems. Thus, the experts obviously acquired the Acausal Interaction ontological category. (These results are described in greater detail in Slotta, Chi, & Joram, 1992.)

Such results imply coherence underlying both the novices' and the experts' explanations, although the explanations differ in terms of the specific ontological categories to which they appeal. In the science education literature, the incoherence of intuitive naive knowledge has often been assessed from the scientist's point of view, namely, viewing physics novices' explanations as coherent only if they possess central principles, as defined in a nomological scientific theory. In the past, this line of reasoning biased interpretations of data in both the developmental as well as the expert-novice research, in that the child's and the novice's competence tended to look inadequate, incomplete, and incoherent. In our own developmental work, we have always tried to seek coherence from the child's point of view (see Chi & Koeske, 1983), and in the expert-novice work, we have tried to understand the distinct nature of novices' representation of physics problems (Chi, Feltovich, & Glaser, 1981). Similarly, here, we attempted to seek coherence by abandoning the methodological approach of judging naive students' coherence from the lens of a scientist.

Open Questions About Instruction

We agree entirely with diSessa's view that there is a large qualitative difference between the very essences of expert and naive conceptual knowledge. We differ with diSessa in terms of how easily we think this difference can be reduced by instruction. diSessa correctly points out that the ontological view has two possible accounts for students' misconceptions: Either the veridical ontological category does not exist, or students have the concept placed in the wrong ontological category. As our suppositions and data have shown, both of these cases can occur. Our preliminary evidence strongly suggests that students assign physics concepts to the wrong (Matter-based) ontological category. Whether or not the Acausal Interactions category exists for novices remains an open question. We have found it to be a difficult category to describe and convey; hence, we would not be surprised if physics novices do not possess this category of knowledge. If the latter is true, instruction must proceed by describing (perhaps by way of examples) the nature of this ontological category, after which students can assimilate new information into this category of knowledge.

Although we agree in principle with the notion that a new ontology needs to replace the existing ontology as the category to which students can assign new conceptual understanding, we do not believe that the methods of replacement proposed in the literature, such as confrontation and challenges, will result in the acquisition or invention of this new ontology. Because the MATTER and Acausal Interaction categories are ontologically distinct, we cannot see how p-prims, which are predominantly Matter-based, can possibly be "refined and developed" into Acausal Interaction entities. More likely, intuitive knowledge may need to be ignored, in the sense that veridical conceptions must be taught afresh in a way that allows them to be embedded in the correct ontological category, while initial conceptions are allowed to die away or are reserved for use only in everyday contexts.

We concur completely with diSessa's assertion that it takes a wealth of experiences in order to establish a reliable new category of knowledge: "One needs to accumulate significant stores of knowledge specific to the many special contexts of application in order to classify reliably" (diSessa, this issue). Therefore, we cannot understand why he dismisses the ontological explanation by saying that a shift in ontology provides an unparsimonious account of the differences between naive and expert knowledge, because it "[misses] entirely the substantial structural changes that occur" (diSessa, this issue). We believe that it is precisely this substantial structural change in knowledge that must be undertaken in order for instruction to succeed.

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