The Architecture of Intuition:

Converging Views from Physics Education and Linguistics

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Abstract

This paper analyzes two converging views of the architecture of intuition. A. diSessa and L. Talmy, working independently in different fields (physics education and linguistics), have formulated strikingly similar theories of intuition. Both view people's intuitions about forces as simple pieces of knowledge organized heterarchically. However, Talmy's *force dynamic patterns* have more system-wide structure than diSessa's *phenomenological primitives*. Using these primitives, people generate common sense explanations for a wide variety of situations. Moreover, people may build upon these intuitions while studying formal disciplines such as physics. However, several primitives directly conflict with physics concepts and may account for resilient misconceptions. Finally, intuitions may also provide the basis for understanding social and psychological phenomena.

Introduction

The whole of science is nothing more than a refinement of everyday thinking.

--Einstein (1950, p.59)

What do people do when faced with an unfamiliar situation? Newell and Simon (1972) have argued that they may resort to general purpose strategies such as means-ends analysis. However, they may also turn to their intuitions or their "common sense" for guidance. Lay people readily understand a wide range of phenomena in which they have little expertise. When asked to explicate a simple situation, such as a book on a table, physics novices typically provide explanations such as:[1]

(1) The table is stationary. It is not pushing up, it is just blocking the path of the book to the ground.

(2) What is the table doing? Holding up the book. (laughs) Um, I don't know.

(3) If the table didn't exert a force upward, then the book would be able to break the table in half and fall to the ground.

Technically speaking, the first explanation (1) is incorrect, the second (2) is ambiguous, and the last (3) is correct. Nevertheless, all three intuitive explanations are coherent and sensical. In this paper, we compare diSessa and Talmy's theories of intuition, which describe an array of intuitions and the cognitive structures that organize them.

diSessa and Talmy use different tools to explore intuitions from different angles. While diSessa studies novices explaining physical situations, Talmy analyzes linguistic expressions that refer to situations involving forces.

In diSessa's (1993) research methodology, an interviewer typically presents subjects with a simple situation and asks them to explain it. Researchers employing this methodology examine subjects' understanding of a discipline by asking them to elaborate their thoughts and discuss related situations (cf. Piaget & Szeminska, 1952/1941; Ericsson & Simon, 1984). Through his analyses of interview data, diSessa has identified different intuitions which he has termed **phenomenological primitives** (p-prims).

Recall, for example, explanation (1) for our book resting on a table. Many novices share this person's belief that the table merely blocks the book, preventing it from falling to the ground (Clement, Brown & Zietsman, 1989). According to diSessa, they invoke the *Supporting* p-prim:[2] "a strong or stable underlying object [table] keeps the overlaying and touching object [book] in place; [this is] strictly topological [with] no force implications. Supporting objects are not agentive" (1993, p.220).

In contrast, Talmy (1988) examines linguistic expressions (in English) and their syntactic constraints. Consider the differences between a force-neutral (4) and a force-interactive (5) sentence:

(4) The soccer ball is rolling through the tall grass.

(5) The soccer ball is rolling despite the tall grass.

In (5), "despite" emphasizes the grass's resistance to the ball's motion, whereas (4) focuses only on the ball's movement.

[1] Excerpts taken from interviews with high school students who have not taken a physics course (Chiu & Gutwill, 1991). All examples are ours unless otherwise specified.

[2] P-prims appear in italics.

Extending his argument over a wide range of grammatical evidence, Talmy (1988) constructs a case for **force dynamic patterns** (FD patterns), simple conceptual units that yield inferences about force-interactive situations. Four basic dimensions—force entity, intrinsic tendency, relative strength, and result—reflect many of the linguistic constraints on English speakers' references to force. First, an opposition exists between two **force entities**, the soccer ball (Protagonist) and the tall grass (Antagonist).[3] As in (5), the Protagonist and the Antagonist are typically denoted by the subject and the object. At issue in all force-interactive sentences is whether the Protagonist can realize its **intrinsic tendency** (toward rest or motion) in spite of the Antagonist's opposition. In this case, the ball's tendency is toward motion. For the Protagonist to realize its intrinsic tendency, it must have greater **relative strength**. The conjunction "despite" indicates the soccer ball's greater strength relative to that of the grass. The verb phrase typically announces the **result** of the interaction ("is rolling"). Talmy noted that many sentences describe force interactive situations that exhibit this pattern of Hindering:[4] "The [Protagonist's] intrinsic tendency is ... toward motion, and although there is an external force opposing it, the [Protagonist] is stronger, so that its tendency becomes realized in resultant motion" (1988, p.55). In short, sentences indicate force interactions through the use of grammatical forms that capture the force entities, their intrinsic tendencies, their relative strengths, and the result.

In the book on the table scenario for instance, Talmy would argue that novices invoke the Blocking FD pattern: "While the [Protagonist, i.e., book] has ... a tendency toward motion, the Antagonist [table] is ... stronger and so effectively *blocks* it....The [Protagonist] is kept in place" [italics in original] (1988, p.55). Blocking fits the situation because the stronger table has a tendency toward rest and hence prevents the book from realizing its tendency toward motion.

P-prims and FD patterns have strikingly similar forms and functions. Both types of primitives are small, schematic knowledge units that people use for simple inferencing and prediction. The next section begins by comparing their internal structures and their connections. Then, diSessa's application mechanism provides the basis for discussing FD pattern activation, followed by a discussion of common features across several p-prims and Talmy's system-wide dimensions. Finally, we consider the range of phenomena that each theory covers, from the physical to the psycho-social.

Structure and Function

To illustrate the similarities among p-prims and FD patterns, consider the situation of pushing a cup at a constant velocity across a table. Is the act of pushing responsible for the continuing motion of the cup? Not in any direct way. The cup continues to move because it has momentum; pushing only nullifies the effect of the frictional force. Newton's Laws require the absence of a net force for an object to move at a constant velocity. However, novices typically invoke *Continuous Force* to make sense of this situation: "A directed impetus acts ... on an object [with constant effort]. Result is displacement and/or speed in the same direction" (diSessa, 1993, p.217). Likewise, Talmy's Propelling "involves a [Protagonist] with an intrinsic tendency toward rest that is being opposed from outside by a stronger Antagonist, which thus overcomes its resistance and forces it to move" (1988, p.54). In both types of primitives, an agent is in continuous contact with a patient and forces it to move.

P-prims and FD patterns are not identical, however. FD patterns embody an internal organization in the form of dimensional slots that p-prims lack. Hence, creating a new FD pattern to match a p-prim involves hypothesizing a new dimension and finding grammatical evidence to support it.[5] On the other hand, a p-prim can be generated easily from any FD pattern since p-prims are not constrained by internal structure.

FD patterns also adopt a particular subjective viewpoint, whereas p-prims do not. Specifically, the "result" dimension requires that a person choose a particular perspective when reasoning intuitively about a phenomenon. By distinguishing between two actors (Protagonist and Antagonist), people can view the same situation from different perspectives. For example, pushing someone across the room (Propelling) differs from being pushed across the room (Hindering). In contrast, p-prims assume an objective perspective which views both situations as *Continuous Force*. All p-prims employ a third-person perspective, while each FD pattern assumes a subjective perspective.

Systematicity—Connections Among Primitives

This section demonstrates similarities between the p-prim system and force dynamics by contrasting them with a competing theory of naive physics. Closer examination however, reveals differences in their connections among primitives.

McCloskey's (1983) *intuitive theory* theory argues that children intuitively develop an impetus theory, exemplified by the belief that "the act of setting an object in motion imparts to the object an internal force or 'impetus' that serves to maintain the motion" (p.306). A central tenet of the impetus theory, "continuous motion requires a cause" contradicts Newton's Laws. (Acceleration, not velocity, is the outcome of an applied force.) McCloskey claims that children's intuitive ideas form a theory of physical phenomena:

> The naïf is not merely ignorant, then, but already possesses, to one degree or another, a fairly complicated

[3] Talmy calls these actors the "Agonist" and "Antagonist," taken from muscle-pair terminology. We prefer the more widely known terms from literary analysis.

[4] For easy reference, we have named each of Talmy's patterns and underlined them.

[5] For a list of dimensions not mentioned in this paper, see Talmy (1988).

> world view. In short, the naïf has a system of beliefs, coherent to varying degrees depending on the individual, and more or less consistently held. (McCloskey & Kargon, 1988, p.60)

Novices, possessing a fairly systematic theory about motion, should reason in a consistent (if incorrect) manner.

diSessa disagrees. He argues that "intuitive physics is a fragmented collection of ideas, loosely connected and reinforcing, having none of the commitment or systematicity that one attributes to theories." (1988, p.50) Their impetus-like understanding of motion stems from a heterarchy of p-prims: *Force as a Mover*, *Continuous Force*, and *Dying Away*.[6] Moreover, he shows that students often vacillate between different intuitions, thereby supporting his claim that intuitive knowledge does not form a coherent system, but exists in pieces.

Talmy's FD patterns provide a similar explanation. Novices use one or more primitives to make sense of a physical phenomenon. Instead of an impetus theory, naive reasoners invoke Engage, Propelling, and Discontinue to make sense of a shoved object coming to rest.[7] Here, the critical component of intrinsic tendency (toward rest) may account for much of the impetus notion.

To illustrate the similarities and differences among the three theories, Figure 1 shows the interaction between formal physics and intuitive knowledge for each theoretical perspective. The representation of McCloskey's view emphasizes the cohesiveness of the impetus theory. He argues that intuition and physics differ primarily in content, not in form. Furthermore, the separation of the two domains reflects McCloskey's pedagogical contention that students must "be induced to give up the impetus theory and accept the Newtonian perspective" (1983, p.319). Hence, McCloskey's view of intuition precludes the possibility of building upon naive ideas to develop formal physics knowledge.

In contrast, the diagrams of diSessa's and Talmy's views represent the heterarchy of individual primitives, some of which are required for developing scientific knowledge (diSessa, 1993). The distance from each intuition to physics knowledge represents their relative difference. Primitives that do not cue formal concepts are furthest away (e.g., *Dying Away*, Discontinue), while those that form the basis of formal physics (e.g., *Ohm's Law*, Engage) overlap with the physics realm.[8] Activation links between some primitives indicate their propensity to excite one another.[9]

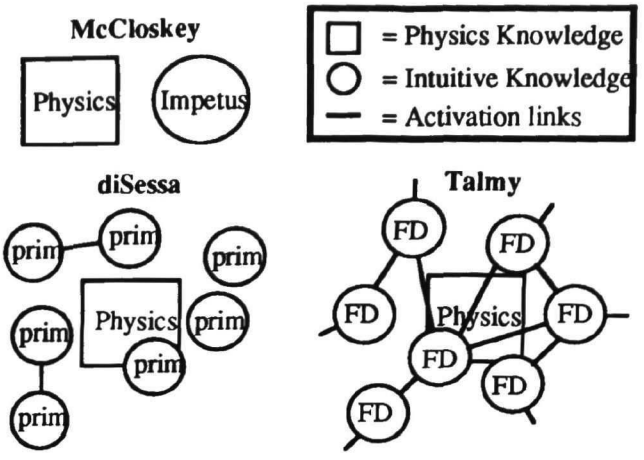

Figure 1. The interaction between physics and (pre-formal) intuitive knowledge in the theories of McCloskey, diSessa, and Talmy.

Both diSessa and Talmy argue for a heterarchical knowledge system, but closer inspection reveals important differences. P-prims are loosely connected (some form clusters), whereas FD patterns are linked systematically. Based on his data of students making contradictory remarks during individual explanations, diSessa argues that intuitions are not connected systematically. In contrast, all FD patterns share the same dimensions, so they are systematically linked. These dimensional relations may explain the difficulty of altering any particular force intuition without modifying others in the system.

In short, diSessa's p-prim theory and Talmy's FD theory share a heterarchical architecture of intuition but differ on the number of connections between intuitions.

Application

diSessa (1993) hypothesizes a specific process for applying p-prims to everyday phenomena. Stimulated by sensory data, one or more p-prims are activated according to their **cueing priorities**. Then, each p-prim's **reliability priority** determines its applicability. Although loosely connected, one p-prim may reinforce consonant p-prims and inhibit conflicting ones until the knowledge network settles down to a quiescent state.

Talmy does not explicate a cognitive mechanism for cueing and utilizing FD patterns. Nevertheless, a cueing and

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[6] *Force as Mover* schematizes "a directed impetus acts in a burst on an object," resulting in "displacement and/or speed in the same direction" (diSessa, 1993, p.217).
Dying Away characterizes the belief that "all motion, especially impulsively or violently caused, gradually dies away" (diSessa, 1993, p.219).

[7] Engage "involves a stronger Antagonist that comes into position against a [Protagonist] with an intrinsic tendency toward rest, and thus causes it to change from a state of rest to one of action" (Talmy, 1988, p.57).
Discontinue "is a non-prototypical type of letting ... where an Antagonist that has forcibly kept in motion a [Protagonist] tending toward rest now ceases impinging on this [Protagonist] and allows it to come to rest" (Talmy, 1988, p.58).

[8] *Ohm's Law* p-prim: "An agent or causal impetus acts through a resistance or interference to produce a result" (diSessa, 1993, p.217).

[9] We can view FD dimensions as activation links. FD patterns with common properties along a link mutually activate one another, whereas those with different properties inhibit each other. Dimensional links can have different weights.

reliability mechanism similar to diSessa's is plausible. Talmy's dimensions suggest slots which would simplify and facilitate access to a particular FD patter. In contrast, diSessa's network of primitives settles down relatively slowly.

Physical Intuitions vs. Physics Concepts

When people apply their intuitions to physical situations, their reasoning can either support or conflict with formal physics. For example, instructors can build upon the nearly identical *Force as Mover* and Engage patterns to teach a qualitative version of Newton's Second Law (a force causes a mass to accelerate). In the *Force as Mover* p-prim, "a directed impetus acts in a burst on an object," resulting in "displacement and/or speed in the same direction" (diSessa, 1993, p.217), whereas Engage represents "a stronger Antagonist that comes into position against a [Protagonist] with an intrinsic tendency toward rest, and thus causes it to change from a state of rest to one of action" (Talmy, 1988, p.57).

However, intuitions can also interfere with formal domain knowledge at both the primitive and systemic levels. Primitives such as the *Dying Away* p-prim and the Permit FD pattern conflict with formal physics. Frequently cued in situations involving deceleration, *Dying Away* probably accounts for the impetus misconception: "all motion, especially impulsively or violently caused, gradually dies away" (diSessa, 1993, p.219). Again, this violates the Newtonian concept of momentum. Similarly, Permit[10] also conflicts with formal physics, wherein all phenomena are causal. For instance, water does not leak from a tank because a hole allows it; gravity and water pressure push it through the opening.

Systemic conflicts with formal physics. Unlike p-prims, force dynamics's dimensions embody systemic conflicts with physics. For example, the intrinsic tendency, relative strength and result dimensions in force dynamics contribute to misconceptions about physical force interactions. The intrinsic tendency dimension violates the law of inertia and contradicts the existence of normal forces. In FD patterns, force entities seek to assert their intrinsic tendencies. A river tries to move. A table tries to remain still. Consequently, when a person stops pushing a table, it asserts its intrinsic tendency and stops. According to Newton however, an object has constant momentum unless a net force acts upon it (the table would continue moving in space). In physics, objects have no intrinsic tendency toward rest or motion, but rather an intrinsic tendency toward constant velocity. diSessa incorporates intrinsic tendency in a generalized account of successful and unsuccessful resistance. However, he only encodes this "resistance" in a few p-prims, such as *Ohm's Law*, *Intrinsic Resistance*[11] and *Supporting* (see diSessa, 1993, pp. 126-129).

Novices also believe that objects with an intrinsic tendency toward rest cannot exert forces (see sentence (1)). For instance, large, inanimate entities such as floors, walls and shelves cannot exert forces on other objects. Compare sentence (6) to its awkward counterpart (7):

(6) This cabinet can accommodate/store/hold fifteen dishes.

(7) ! This cabinet can lift/push up/hold up fifteen dishes.

Sentence (6) describes the cabinet's storage space in a conventional manner. The sentence fulfills our expectations of large, heavy objects by attributing a rest tendency to the cabinet. When sentence (7) assigns an active verb however, the cabinet acquires a counter-intuitive tendency toward action. Consequently, sentence (7) sounds awkward. Whereas novices believe that only animate entities exert forces, experts believe that *all* entities can. diSessa concedes that an underdeveloped sense of agency (e.g., tables cannot push) may cause this error, but he locates this naive conception within particular p-prims (such as *Supporting* and *Intrinsic Resistance*).

The FD dimension of relative strength contradicts the physics principle of net forces. Focusing on the relative strengths of two opposing actors suggests that the stronger actor wins and manifests its effect. In physics however, there is no "stronger" actor. The sum of *all* forces acting on an object determines its resulting motion. Employing relative strength induces holistic intuitive reasoning about the interaction of two entities as one phenomenon. In contrast, the expert view focuses on each object *separately* and analyzes the sum of all forces acting on each one. This misleading notion appears in the *Overcoming* p-prim, which requires an analysis of the relative strengths of the forceful actors: "one force or influence overpowers another" (diSessa, 1993, p.222). As with novices' limited agency, diSessa localizes relative strength in a few primitives.

Finally, the FD result's focus on one force entity contradicts Newton's Third Law of action/reaction. In all FD patterns, two entities are in conflict, but the result of only one entity (Protagonist) is highlighted. In the Engage pattern for instance, one is primarily concerned with the outcome of the Protagonist (will it be forced to move?), paying little attention to the Antagonist. However, the law of action/reaction states that two interacting entities always exert equal and opposite forces on each other. Unlike novices, physics experts are concerned with the results of *both* entities. diSessa (1980, 1993) recognizes this mismatch in his description of causal syntax in which an agent acts upon a patient to produce a result. The syntax imputes an agent/patient relationship, highlighting the patient's outcome, again in conflict with Newton's Third Law.

To summarize, both Talmy and diSessa describe several intuitive primitives that conflict with formal physics concepts. Furthermore, both discuss common properties across

[10] "A stronger Antagonist that has been blocking a [Protagonist] with tendency toward motion now disengages and releases the [Protagonist] to manifest its tendency" (Talmy, 1988, p.58)

[11] *Intrinsic Resistance*: "Especially heavy or large things resist motion" (diSessa, 1993, p.218).

intuitions. However, Talmy argues that these properties exist system-wide in the form of dimensions, whereas diSessa typically locates them in particular primitives.

Beyond the physical range: Social and psychological realms

People also apply their physical intuitions in the social and psychological arenas. Physical influences (pushes) and their results (motion) are easily recognized, but their social counterparts (compliments and social acceptance) are less conspicuous. Nevertheless, people offer intuitive explanations for social situations as well. Talmy (1988) suggests that social intuitions are derived from physical intuitions. Consider an argument in which Melina convinces Juan of a particular viewpoint. Melina may employ the Propelling pattern to make sense of her interaction with Juan. She views herself as an agent with a tendency towards action, trying to *move* Juan to her *point of view*. Juan's tendency, on the other hand, is to *stay* at his current *position*, thus hindering Melina's *progress*. If Melina is to persuade him, she must provide sufficiently *strong* arguments. From diSessa's perspective, Melina may similarly employ the *Ohm's Law* p-prim to guide her actions. By arguing more vehemently (providing more evidence, drawing better conclusions and so on), Melina is more likely to convince Juan of her views. On the other hand, if Juan has strong, opposing opinions, he is less likely to change his views. By applying physical intuitions to social situations, people can make sense of social relations (cf. Johnson, 1987; Lakoff & Johnson, 1980).

The psychological realm presents even greater obstacles to comprehension. Unlike explaining physical and social phenomena, understanding the psyche requires identification of unseen influences within one person (cf. Lakoff, 1993). Several folk theories of psychology split an individual into different entities, e.g., reason and emotion. Consider the following sentences:

(8) My fear of heights overwhelmed me and drove me from the airplane.

(9) I prevailed over my fear of heights and stepped onto the airplane.

Two conflicting entities (reason and emotion) exist within the same person. Although the emotion of fear exists is a part of us, people frequently refer to it as a separate entity. These sentences, then, describe situations in which one psychological influence overpowers another. The *Overcoming* p-prim or the Overcome FD pattern may underlie this view which pits the intellect against the emotions.[12] If a person's emotions overpowers his rationality (8), he loses control. He resumes control when his intellect regains the dominant position (9). *Overcoming*/Overcome structures both the problem and the solution.[13] In short, people also interpret social and psychological phenomena through physical intuitions.

Conclusion

diSessa and Talmy, working independently in different fields (physics education and linguistics), have formulated strikingly similar views of intuition. Both argue that intuition consists of pieces of knowledge organized as primitives. Although Talmy's force dynamics describes more system-wide connections than diSessa's p-prims, both lack internal consistency in comparison to McCloskey's tightly-woven impetus theory. Moreover, both FD patterns and p-prims explain students' intuitive reasoning about social and psychological situations as well as physical phenomena. Table 1 contrasts p-prims and FD patterns.

The pieces view of intuition suggests that primitives remain resilient to instruction because they are relatively unaffected by changes to other parts of the formal knowledge structure. Consequently, misconceptions may still lurk behind newly learned and applied concepts. Novice reasoning that vacillates between different explanations highlights the co-existence of these inconsistent perspectives. Students may hold contradictory views simultaneously (Clement, 1982; Karmiloff-Smith & Inhelder, 1974-5) because their epistemology does not demand system-wide coherence. As novices become experts, they may build systematic links among their knowledge pieces. Teachers, then, should encourage students to value connections among their knowledge pieces and help them develop appropriate metacognitive tools.

Instructional design may be improved by building metaphors on universal intuitions. Some physical intuitions (*Force as Mover*, Engage) are the best candidates for universality, because people share many of the physical experiences from which these primitives originate (moving). As a result, these physical primitives can provide common starting points for students and teachers to negotiate comprehension of a new topic. After a metaphorical introduction to the subject matter, students can then critique the metaphorical mapping in detail. Developing this type of metaknowledge would enable students to generate and critique mappings, thereby finding both the insights and the pitfalls inherent in any metaphor.

The current theoretical view of intuition can benefit from research into the application mechanisms of physical primitives. Researchers must ascertain how sensory data cue primitives and how students modify them during the learning process to form larger and more coherent knowledge organizations. Further research must answer questions about the order in which primitives are created or abstracted, about the mechanisms for cueing primitives, and about the way in which learning affects the architecture of intuition.

[12] Overcome: "Instead of a stronger Antagonist's arriving or leaving, to thus begin or end its overpowering effect, an Antagonist already in place can become stronger or weaker with the same results" (Talmy, 1988, p.58).

[13] For an extended discussion of understanding emotions (e.g., Anger) in terms of mechanical interactions (e.g., explosions), see Lakoff (1987). Also see Talmy (1988) and diSessa (1993) for further examples.

Table 1. Comparison of diSessa's p-prims and Talmy's FD patterns

Property	Phenomenological Primitives	Force Dynamic patterns
Similar		
Size	Small	Small
Function	Explain & predict	Explain & predict
Level of explanation	Fundamental (for novices)	Fundamental (for novices)
Organization	Heterarchical pieces	Heterarchical pieces
Primitives conflict with physics?	Yes	Yes
Physics built on primitives?	Yes	Not specified, but possible
Range of application	Physical, social, & psychological	Physical, social & psychological
Different		
Evidence	Student interviews	Linguistic patterns
Internal structure	None	Dimensions
Perspective	Objective	Subjective
Systematicity	Loosely connected	Dimensionally linked
Application mechanism	Cueing & reliability priorities	Not specified, probably slots
Systemic conflicts with physics?	No, but common conflicts across some p-prims	Yes, some dimensions conflict

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