

Instructional explanations as an interface - the role of explanatory primitives

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Abstract. What makes an instructional sequence in physics meaningful to students? Why do some explanations seem more plausible than others? Why is it that an explanation can appear plausible to one student but not to another? We present a model that addresses these questions. Elaborating diSessa's (1993) concept of p-prims, we develop a model of explanatory primitives and argue that different individuals have different sets of explanatory primitives, or they assign different priorities to the same explanatory primitives. Individual differences in explanatory primitives can account for differences in reactions to an instructional explanation, and we present empirical data to support this claim. We then use the model to analyze Jim Minsrell's (1982) instructional sequence about normal forces to illustrate how an effective learning sequence addresses differences between individuals by evoking a rich set of explanatory primitives.

Keywords: Explanations, intuitive knowledge, preconceptions, prior knowledge, epistemology, sense making.

PACS: 01.40.Fk

INTRODUCTION

Good teaching is often described as an art. Expert teachers know how to tailor instructional sequences and explanations to address students' particular needs. Teachers use a large repertoire of explanations [1]. The variety of strategies used has direct effect on students' understanding [2]. Teachers' pedagogical content knowledge [3] thus also includes anticipating how their explanations will be received by students.

Gilbert, Boulter, and Rutherford [4] suggested that learners evaluate an explanation according to four criteria: plausibility, parsimony, generalization, and fruitfulness. We believe that plausibility is a crucial factor in students' evaluation of explanations presented to them.

Master teachers and experienced curriculum developers often know intuitively what will work for their students, and this knowledge shows up in effective interventions. We take Jim Minsrell's [5] instructional sequence on the existence of normal forces as a canonical example of such intervention.

In this paper we suggest a theoretical model that can explain why some instructional sequences are more successful than others, focusing specifically on student judgments of plausibility. Our model makes three contributions. First, it can provide explanation for why certain strategies work. Pedagogical prescriptions often do not cleanly separate their

scientific claims and validation from their suggested actions [6]. The fact that something works does not mean we know why it works. Second, our model provides fine-grained detail needed to understand instructional sequences. In Minstrell's instructional sequence, for instance, we want to know why the demonstration of a beam of light that is reflected at a low angle off the table top to the wall had a dramatic influence on the students' belief that the table can exert a force, yet other elements in the sequence had a much more muted effect. Third, our model also aims to explain how students differ, and how these differences lead to different judgments of plausibility.

Our prime assumption in developing the model is that differing behaviors, in terms of the individual assessment of the plausibility of an explanation, are determined by prior knowledge. This idea is, of course, not new. A large body of research shows that learners' background knowledge determines how well they comprehend, learn, and use new information [7, 8]. Our model, however, identifies a specific type of prior knowledge that plays a central role in an individual's assessment of the plausibility of an explanation. In the following sections we describe the model, explain how it can be empirically tested, and present a sample of empirical work. The empirical work suggests how the model can enhance our understanding of instructional sequences specifically with respect to the three above-mentioned goals:

understanding how they work; adding detail to our understanding of elements of instruction, and understanding and predicting individual differences in effectiveness.

EXPLANATORY PRIMITIVES

We consider explanations to be a reduction of a phenomenon to a selected set of *explanatory primitives*. Explanatory primitives, then, are unquestioned units of explanation. “Unquestioned” must be understood in a relative sense. Under probing by a skillful teacher, or even through the passage of time, students may begin to question what they take to be more or less certain or even indubitable. However, in the time-span of evaluating an explanation, explanatory primitives are likely relatively stable. Explanatory primitives also include assessment of degree of certainty. Some may seem indubitable, but some may appear “pretty certain” or “good enough” for present consideration.

The notion of explanatory primitive is a generalization of the theoretical construct of p-prim [9], and we use p-prims as a reference model. The construct “p-prim” (phenomenological primitive) is central to the Knowledge in Pieces (KiP) perspective on conceptual change. P-prims are a basic constituent of intuitive knowledge that people develop, for example, as they interact with the physical world. P-prims (a) act by being recognized in a situation, (b) are evoked as a unit, and (c), central to present aims, account for people’s comfort with certain situations and surprise in others. Students treat p-prims as “just the way the world works”; they are a type of explanatory primitives. For instance Ohm’s p-prim schematizes the phenomenological experience that more effort leads to more effect, and more resistance leads to less effect. There is an extensive corpus of work empirically identifying p-prims and their effects in student learning [9].

Epistemological assumptions that are based on personal experience, but not necessarily on a *physical* interaction with the world, might be another type of explanatory primitives. Examples are the belief that some changes occur even if they are invisible, or the proposition that “gravity pulls things downward” (as opposed to a p-prim that released objects fall downward).

Explanatory primitives are a function of the individual’s knowledge and experience. Thus, a scientific law could become an explanatory primitive for a scientist. Conservation of energy or Newton’s laws are examples; they are taken for granted by experts, but not by novices. In fact, they may be regarded as implausible by novices.

Similar to the p-prim model, explanatory primitives arise from individual experience. This implies that different individuals may have different sets of explanatory primitives, or assign different priorities (degree of plausibility) to the same explanatory primitives, which reflect a different explanatory hierarchy. This does not imply that each individual has a completely different set of explanatory primitives. On the contrary, the common experiences that humans share suggest that there will be significant similarities across individuals. However, a careful examination should reveal differences.

Individual differences in explanatory primitives may account for different reactions to an instructional explanation. Thus, a successful learning sequence may need to be rich enough to address the range of explanatory primitives present in the classroom. That is, the instruction may evoke and address a large set of explanatory primitives, and therefore serves as an interface between the instructor’s scientific content goals and students’ (potentially diverse) cognition.

EMPIRICAL VALIDATION

This model leads to several hypotheses:

1. Explanatory primitives other than p-prims exist.
2. Different individuals can present either different sets of explanatory primitives, or different priorities for their explanatory primitives.
3. Explanatory primitives can be empirically linked to acceptance or rejection of an instructional explanation. Differential acceptance across individuals can be explained by their particular repertoire of primitives (or their priorities).

Clinical interviews [10] are a particularly important methodology for our purposes. They are specifically designed to capture the interviewee’s reasoning (e.g., explanatory primitives) and not to test his/her knowledge in science (e.g. whether they have expert primitives). Regardless of whether interviewees give scientifically correct or incorrect answers, they are constantly asked to judge and clarify propositions, and to defend them against counter arguments. We designed our interviews around a rich tutoring sequence that has the potential to evoke a variety of explanatory primitives. A fine-grained analysis of transcripts of such interviews was employed to discover and calibrate students’ primitives. The research was strongly informed by the Knowledge in Pieces perspective on conceptual change. In particular, merely giving an answer is an insufficient criterion to determine a student’s attitude toward it. The level of confidence and comparative evaluation in the face of other primitives is a much more reliable measure.

Empirical Study

We cannot give a full empirical account of the model in this paper. However, we provide an example empirical analysis of the effect of individuals' explanatory primitives on their judgment of an instructional explanation. We present three short excerpts from interviews with high school students who had not yet taken a course in physics. The interviews employed a bridging analogy tutoring sequence on the existence of a normal force [11, 12]. We enriched and elaborated the original sequence to afford a better view of the students' reasoning and knowledge state. All three excerpts deal with the explanatory primitive of springiness. Springiness is an empirically identified p-prim [9]. It imputes a causal connection between a deformation and the consequent development of a restoring force (not necessarily understood as a Newtonian force). The intuitive notion of springiness develops through our physical experience with springy entities such as trampolines, mattresses, etc., and is only somewhat similar to the understanding of physical springs acquired in a physics class. As a p-prim, springiness is often not verbally elaborated. The first excerpt is an example of cases where we identified springiness as an explanatory primitive employed by a student:

Inter: But do you see any resemblance between this [flexible board] and that [spring]?

Stud1: They both bounce back, *springy* stuff [gestures bouncing].

.....

Inter: But the attribute of springiness, could you somehow describe it to me? What makes something springy?

Stud1: [laughs, and gestures "I do not know" with her hands] I don't know. Like that [points to the spring].

The following two excerpts demonstrate that not all students regard springiness as an explanatory primitive. We present the reaction of two students to the same stimulus: Stud2, for whom springiness is a valid explanatory primitive, and Stud3, for whom springiness is not an explanatory primitive. Both students responded to the question, "Once a small child told me that the spring wants - of course it doesn't have a will - but it 'wants' to go back to its original length. Does this make sense to you?"

Stud2: Yeah. It wants to return to its original - I'm trying to think of a word to explain that [pause] - state, I guess. It wants to return to the way it was.

Stud3: It kind of does in a way. But I guess I don't think it [points to the spring] really knows what its natural length is. It [compresses the spring] just has an equal reaction to what you put in.

Stud3 understands some version of action and reaction, but does not see a springy object as one that necessarily returns to its natural length.

In the later stages of the bridging sequence, the molecular model of solids, where molecular bonds are modeled as springs, was suggested to the students. Stud1 and Stud2 developed the entire model with almost no support from the interviewer. Later, when explicitly instructed in the model, they used it immediately to explain a variety of phenomena. Stud3 on the other hand, who rejected the idea of a springy table all along, understood the model but did not have confidence in it. The model had a low explanatory priority. Stud3 never used it voluntarily. However, when explicitly asked to explain via this model, he was able to do so fluently and correctly. Stud3 explicitly announced his doubts. For instance, just after the model was suggested to him, his immediate reaction was, "This isn't a solid we're still talking about?" That is, the springy model did not appear plausible as reflecting the reality of a solid table. About 15 minutes later he became more detailed in his rejection: "Like, I can see that we all obviously accept gravity. But I don't quite... I guess I still don't quite understand why it would return to its normal state [stated while compressing a spring with a weight]. I don't quite understand, like [presses the spring between his hands] how the atoms would know that they would return to that shape." This student explicitly states that springiness (returning to rest length) is not an explanatory primitive for him, and he contrasts it with an unquestioned belief in gravity. In his view, the molecular model should explain how a spring behaves, not the other way around.

Stud1 and Stud2 had a form of springiness (return to natural shape) with high enough explanatory priority so that they accepted the springy molecular model of a table easily and confidently. Stud3 did not have this primitive, or did not have it with sufficient priority so that he would autonomously and confidently use the springy molecular model. Together, these demonstrate one of our main contentions, that observable differences in an individual's explanatory primitive repertoire lead to observable differences in the effectiveness of instruction.

EXPLANATORY POWER

In this section we briefly review Jim Minstrell's [5] well-known instructional sequence for the existence of normal forces, using our model to explain how the sequence serves as an interface between the scientific content and student cognition. In particular, parts of the sequence cue and "work on" a variety of explanatory primitives. Minstrell's sequence is as follows: a book is placed (1) on a table; (2) on the outstretched hand of a student; (3) on the outstretched hand of a student, using more books; (4) the book is hung from a spring; (5) a beam of light is reflected at a low angle off the table top, and the beam is observed to move up and down on the wall as the instructor stands on and off the table; (6) A plastic ruler is hung from a spring with an imperceptible extension of the spring; (7) the book is simply placed on the table.

A significant portion of Minstrell's students needed step 3 (more books placed on the hand) to conclude that the hand exerts a force on the book. They needed to feel that the hand exerts force in order to conclude that there is force. Yet only a few concluded, from that alone, that the table exerts a force. We can explain this in terms of two competing explanatory primitives. One is that forces (in static situations) require agency; therefore an inanimate table cannot exert a force. The other primitive is the dynamic balance p-prim [9], that if the book is at rest but we know that a force is exerted on it (gravity), there must be an opposite force to compensate and cancel its effect. The student's reaction depends on which explanatory primitive is cued. If "forces require agency" is evoked, then some mechanism for the agency of the table must be supplied in order to conclude that the table exerts a force. This is precisely what the next steps do, suggesting a mechanism by which the table exerts a force.

Hanging the book from the spring may evoke the springiness p-prim. But the students may not perceive springiness as a valid explanatory primitive in the context of the table. In fact, very few of Minstrell's students changed their view about the book on the table after this demonstration. The competing p-prim of rigidity (solid objects are not deformable [9]) stands in the way. If the table is seen as rigid in this sense, the spring is simply not similar¹.

The demonstration with the beam significantly decreases the priority of the rigidity p-prim. It suggests that tables can deform, addressing the strong tendency to believe what one sees. Hanging the plastic ruler from the spring cues the epistemic explanatory

primitive: "some changes are invisible".² Although the beam does not appear to move when the book is placed on the table, the beam motion, when the heavy instructor steps on the table, suggests that the deformation is there, even if very small. At this point most of Minstrell's class was convinced that the table exerts a force on the book.

CONCLUSION

Explanatory primitives are a type of prior knowledge that plays a central role in an individual's assessment of the plausibility of explanations. Hence, a successful learning sequence serves as an interface between the scientific content and student's cognition by cueing and "working on" a variety of explanatory primitives. The variety is needed, in part, to address individual differences in students' repertoire of explanatory primitives and their priorities.

ACKNOWLEDGMENTS

We thank the members of the Patterns and Knowledge Analysis research groups at UC Berkeley for the helpful discussions. The first author is thankful for the support of the European Commission, Marie Curie Actions, project number 236215.

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¹ Brown and Clement [11] suggest a bridging analogy, where they tell students to think of a flexible table. We can explain this within our model as trying to cue springiness in the context of the table.

² In a similar manner, some teachers who use the bridging analogy technique ask the students first to think about a table made of flexible board, and then a table made of a series of flexible boards placed one on top of another.