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# The Construction of Causal Schemes:
# A Cognitive Analysis with a Dialectical Point

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**Abstract.** This paper sketches a careful analysis of an exceptional classroom event where students develop, without explicit instruction, a model equivalent to Newton's thermal law as a composition of intuitive knowledge elements. Lessons about how social (cultural, discursive, situated, etc.) and cognitive perspectives may interact are put forward.

**Keywords:** Cognitive analysis, intuitive knowledge, dialectical approaches to cognition, thermal equilibration.
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## INTRODUCTION

This paper makes two related points. First, I wish to illustrate a state-of-the-art analysis of a classroom learning event based on a Knowledge in Pieces [1] perspective. This perspective aims to treat knowledge and learning in a very contextualized way, and at a fine grain size. Second, befitting the "multiple perspectives" orientation of the group of presentations of which this was part, I wish to make a brief point about integrating "cognitive" and "social" (or socio-cultural or participatory) perspectives. Concerning the second issue, I take a strong "dialectical approaches to cognition" position: The study of knowledge, as it exists in individuals, is not in any way opposed to or even separable from the study of social interaction, participation, or culture. Cognitive and social (and similar other) perspectives are but starting points in a necessarily integrated study of human intellectual performance and learning.

## THE LEARNING EVENT

In a project we call "Patterns of Change and Control," we are seeking to develop and test strategies aimed at helping late middle school or early high school students learn about dynamical systems theory. Our overall strategy is to understand the intuitive knowledge that students possess about abstract and general phenomena such as oscillation, equilibration, and threshold, and to parlay that into the beginnings of a curriculum on system dynamics more generally. The subject matter is generally familiar to physicists, but we aim at a higher level of abstraction that covers the same kind of phenomena in, for example, biology, chemistry, population dynamics, and even social and psychological behavior.

The learning event described here occurred in an experimental class on equilibration. The equilibration unit had three roughly one-hour classes spread over several days. Contrasting with our general practice, we designed this unit with one phenomenological area in mind, heat equilibration. This particular class was one of four instantiations of our equilibration curriculum. The data here came before any instruction in the normative model, so it is, perforce, mainly a spontaneous student construction.

Before the learning event that I will analyze occurred, students were asked to think about what happens when a cold liquid, like milk, is removed from a refrigerator and left on a kitchen table. All the students involved in any of our classes believed that the glass of milk would come to room temperature, but the question is how and why. After an open discussion, we asked students to draw graphs and continue the discussion focused on what the graph would look like and, again, why. Finally, we had students do an experiment with hot or cold water in a test tube immersed in a larger amount of room-temperature water, taking data with a probe attached to a computer on which graphs of the data could be produced.

The goal conceptualization that we expected to introduce was "Newton's thermal law" which is usually expressed in the differential equation

$$\frac{dT}{dt} = k(T_{ambient} - T).$$

Since the students in this class had not had calculus, we wanted them to come to the idea that "the rate of

change of temperature of an object is proportional to the difference in temperatures between the object and its ambience."

## PREPARATION FOR ANALYSIS

Following a Knowledge in Pieces perspective, I begin by identifying a group of knowledge elements that, it turns out, will be useful to understand the students' construction. These all are described in detail in [2]. First, and most important, the common intuitive schema *Ohm's p-prim* recognizes that an agentive source of effort gets results in proportion to that effort. (In general, I italicize intuitive knowledge elements.) This idea is very "high priority": It is broadly applied to both human and inanimate circumstances. In fact, our goal conceptualization for Newton's thermal law was precisely for students to come to see the differences in temperatures as a kind of "driving force" for a change in temperature.

A cluster of intuitive ideas on balancing phenomena, it turns out, is also important. Students often feel that certain quantities must, as if a law of nature, balance each other out. So, a pan balance stays "in balance" just because that is the nature of balanced situations. We call this phenomenon *abstract balance*. But, in addition, students (and even young children) know that things can get "out of balance," and still seek to return to balance. That state is called *abstract imbalance*, and the resulting return to balance is called *equilibration*. There are two common forms of equilibration. One, *slowing equilibration*, assumes (as a primitive, unexplained pattern) a slowing return to balance. Notice that slowing equilibration is very similar to the normative result, leading to a typical (exponential) equilibration curve, but there is no explanatory substructure. The second and much less used primitive is *overshooting equilibration*, where students expect an overshoot before balance is finally restored. One very important observation about these primitives is that they are *not* agentive. That is, nothing forces the return to equilibrium; it is just a natural pattern. In fact, many physics students refuse to find a force or torque that drives a pan balance back into balance. Forces (agencies) are just not needed.

## THE FOCAL EXPLANATION

In this limited space, analysis will have to be much abbreviated. See [3] for details. Just after the experiment where students graphed data from cooling and heating, a student, W, produced the following explanation of why the graphs start changing quickly at first, and then slows gradually toward equilibrium. We number lines for reference:

**1.** I think that the liquids like to be in an equilibrium,
**2.** so when one is way off, they sort of freak out and work harder to reach equilibrium.
**3.** And when it's closer to equilibrium, they're more calm. So they sort of drift slowly towards equilibrium.
**4.** So maybe that's why it moves fast at first, because it's like freaking out, but then it slows down because it's approaching the right temperature.

In line 1, W reiterates the claim that objects like to be "in balance" as far as temperature is concerned. He had previously produced a normative graph, just like *slowing equilibration*, including *not* providing any explanation—which is consistent with *slowing equilibration* as a primitive phenomenon. In line 2, however, W introduces a strong agency that is attributed to the liquids. They "freak out" (that is, react strongly to the size of the "out of balance" gap, which he productively interprets as the temperature difference). The result of freaking out is "working harder" to re-obtain balance. Typical of *Ohm's p-prim*, a greater effort begets a greater result, which W interprets as rate of change of temperature. Line 3 cites the comparative "smaller imbalance" case, and line 4 reviews the logic of the overall explanation.

All in all, W produced the following chain of causes: (In the following, "→" means "causes.")

Difference in temperature (amount of imbalance)
→ freaking out (agency)
→ trying harder
→ greater result (interpreted as rate of temperature change).

Looking from first to last in the chain, we see, overall, Newton's thermal law. Indeed, during successive use of this idea, students gradually pruned all the agentive talk to cite their law, finally, as "a greater difference in temperature means a faster rate of temperature change toward 'balance'." In the end, all of the students in the class agreed with this idea and most were documented using it, without help, to explain heating and cooling phenomena in a number of different situations. Thus, we see a remarkably successful case of learning with very little instruction. Even more remarkably, video data showed that another student, R, independently invented nearly the same idea during the lab, before W's presentation, when she and W could not hear each other.

W's model is an excellent construction. It uses a combination of p-prims, starting from the idea of *slowing equilibration*, but filling in a detailed chain of causality, which uses *Ohm's p-prim* as a key link to the focal effect, rate of change of temperature. The causal chain, itself, contains some apparently naïve

and metaphorical elements ("freaking out" and "trying harder"), but those elements died away in the course of use of the model without any teacher intervention.

Important parts of W's contribution included the following: W started with the intuitive idea of *slowing equilibration*. While an insufficient scientific explanation, it has the top-level pattern correct. In other classes, more typical expected patterns were linear change in time, or an S-shaped "logistic" curve. W then introduced agency strongly into the normally non-agentive schema. He talked about "freaking out" and "trying harder," which allowed *Ohm's p-prim* to connect a "driving force" (agency or effort due to the "balancing gap") to a "result," the rate of temperature change. Overall, W cleverly chose temperature difference, on one end, and temperature change at the other end of his causal chain, which perfectly aligns with Newton's law.

Our analysis of W's production and the class's appropriation of it is notable for the following reasons. (a) This is one of only a few cases of classroom data analyzed relatively thoroughly from the micro Knowledge in Pieces perspective. Most such work comes from one-on-one clinical interviews. (b) This is a case where naïve elements are seen clearly to be productive, on the road to normative understanding. They are not misconceptions, but rather resources that can be recombined into normative thinking. (c) The essential insight was to add agency to a non-agentive schema, *slowing equilibration*. Many researchers have described agentive and other forms of direct causality as primitive and non-scientific. In this case, the first intuitive take, *slowing equilibration*, was both non-agentive and insufficient. Introducing agency was precisely the important bridge to more normative understanding.

## DIALECTICAL APPROACHES TO COGNITION

### A Mini-Essay On Complementary Perspectives

The early days of the "cognitive revolution" in the 1970s and 1980s could well be faulted for a lack of concern for socio-cultural matters. The Pittsburgh School of cognitive science, advanced mainly by Allen Newell and Herbert Simon, attended to supposedly universal mechanisms of mind, did not consider human-interactive issues, and treated culture as if it might be simply a reflection of problem solving over a long time scale. I am unaware of any cross-cultural studies at all in this paradigm.

On the other hand, the reaction to this blind spot has been far overdone. "Situated cognition" in the 1990s was touted as a revolutionary *replacement* for studies of knowledge and mind processes. Whether intended by advocates or not, many researchers thought that considerations of what happens in the mind were dead. My own work was criticized for methods that were not ecologically valid, and for confusing "knowledge" with social events and forms of discourse [4].

There was, in my view, a rush to externalize cognition, to push it into social interactions and practices, and into (thoughtless?) manipulations of external symbols. Bruno Latour [5] famously proposed a 10-year moratorium on considering the mental aspects of scientific competence (in favor of, for example, considering the power of external representations alone). Jean Lave and Etienne Wenger [6] proposed to view learning as a matter of "trajectories of participation" in explicit opposition to the idea of expert knowledge.

In my view, oppositional thinking across the cognitive/socio-cultural divide has done great damage to our capacity to understand fundamental phenomena of learning. It bred knee-jerk rejection of "other paradigm" results, critiques that pot-shot rather than illuminate, and it forced young researchers to make a false choice in terms of their own orientation and in terms of the literature they read and seek to build on.

Dialectical approaches are not a matter of "live and let live." I believe in a strong mutual accountability between social and cognitive explanations. Knowledge analysis is, in my view, not optional. Social and cultural phenomena are driven by mind-state in individuals. How the mind works may not, by itself, explain social and cultural phenomena, but eventually, if not now, we shall just have to account for what goes on in a person's head when acculturation, social exchange, or discourse takes place. To put a point on the claim, participation is based on knowledge, albeit knowledge that includes cultural values and practices in addition to technical knowledge that is usually the focus of expertise. I fully agree that older conceptions of knowledge need to be updated for this program to proceed. Contextual and reactive knowledge is often far more important than codified and propositional knowledge. However, I personally feel I learned that lesson in the 1980s, and my sketch of intuitive knowledge as highly contextual and reactive [1, 2] was a first step, for me, in adapting to minds that work in ways inconsistent with the philosopher's adage that knowledge is "justified, true belief." In my prototype model of intuitive knowledge, p-prims [2] are not justified (lack of justification is a principal property of them). True and false simply do not apply. (P-prims *work*…sometimes, and the ultimate proof is

*productivity in learning* rather than a priori judgment of validity; look at what happened to the "misconception" that more effort begets more speed here, in contrast to how that principle contradicts $F = ma$ in mechanical situations.) And these intuitive schemata are not beliefs in the usual sense. I conjecture that these new assumptions are far better grounds for understanding social action as it involves knowledge than propositions or production rules.

## A Suggestive Lesson On Complementarity of Perspectives

The best proof of the power of proposed directions, such as dialectical approaches to cognition, is in their accomplishments. However, if convincing proof existed, there would be much less point to advocacy of the perspective. Dialectical approaches are important because they are far underestimated, and they are practiced rarely.

I would also prefer to be able to supply a knowledge-based analysis of the social and interactive aspects of the classroom described above. But, that was not the intended point of our work: We aimed to study not knowledge of and in interaction with people, but knowledge concerning physical equilibration. What is left of the dialectical agenda is to suggest how the analysis, above, might be useful to an interactive account of what happened.

Suppose we took a "pure" social view of the situation and asked how it was that all the students converged on a single explanation, which they each used confidently. One might be tempted to claim that W was a charismatic individual who just convinced others that he had a good idea. Indeed, W was a charismatic individual, but almost everything he said about equilibration (many prior attempts at explaining equilibration, not documented here) did *not* contribute to a consensus view! Most of his suggestions met with no social uptake.

Adding a knowledge-based perspective provides critical insight. W's "freaking out" explanation is sensible to students because it involves widely shared and easily evoked elements, like *Ohm's p-prim*.

W's construction and its path to consensus is not the only phenomenon here that resists pure interactive analysis. Recall that another student, R, independently took some of the same steps that W did, with no direct interaction with him (nor guidance from the teacher).

To sum up, understanding the phenomena of consensus and independent construction is greatly undermined unless we know in some detail the content and form of students' intuitive knowledge of the physical world. We know that students widely have the ideas necessary for the "freaking out" consensus because those ideas showed up systematically in clinical interviews with students. Without understanding students' prior knowledge, we might easily mistake legitimate interactive issues, such as social positioning and charisma, as sole causes. Painstaking empirical work on students' knowledge of real-world phenomena was necessary to understand their prior knowledge.

My work has frequently been met with claims that p-prims must be discursive, socially produced, and involve learning through social reproduction. That may all be true, but it has not been demonstrated, and the fact remains that discursive/interactive approaches did not discover the relevant intuitive knowledge.

The point of this thought experiment on complementary perspectives is not blame or anyone's failure. There is a failure only if social and interactional perspectives refuse to accept knowledge as a legitimate pursuit that can offer important help in understanding interactive phenomena. The symmetrical acknowledgment, that in some cases interactive issues dominate and content knowledge may be irrelevant, must also be granted. In this case, W was convincing, in part, because he appealed to knowledge that everyone has. Other students, like R, could and did do very similar work without W's leadership or panache.

## ACKNOWLEDGMENTS

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