Prior Knowledge for the Construction of a Scientific Model of Equilibration

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Abstract: The Next Generation Science Standards charge U.S. teachers with the task of including *patterns*, as a crosscutting concept, in their science curriculum. This study explores prior knowledge that is relevant to students' construction of a scientific model of an equilibration pattern. A *Knowledge in Pieces* lens is applied to video transcript of a class discussion on thermal equilibration in order to identify elements of students' prior knowledge that might be productive for their construction of a scientific model of equilibration. The discussion occurred near the beginning of a unit on equilibration, in the middle of a yearlong pattern-based curriculum. Twenty-one 8th grade students participated in the class. Six previously undocumented knowledge elements are identified, characterized, and considered in terms of their potential productivity for helping students construct a *difference drives rate* model of equilibration. These findings contribute to literature concerned with the productivity of prior knowledge in conceptual change.

Keywords: Conceptual change, Knowledge in Pieces, prior knowledge, Knowledge Analysis

Introduction

The Next Generation Science Standards promote 7 crosscutting concepts as recurring themes throughout the K-12 science curriculum. The first of these is *patterns*. The Framework for K-12 Science Education argues that patterns are important for science and science learning because they are readily observed in nature across dimensions of structure and process; noticing patterns is a first step to asking deeper questions about the mechanisms that drive their emergence; and patterns can be used as rules for categorizing similar phenomena within a unified explanatory framework (Schweingruber, Keller & Quinn, 2012).

This study focuses on one specific process pattern: *equilibration*. Equilibration can be found in a range of contexts across the physical sciences. It can be seen in both the warming to room temperature of a cold liquid and the diffusion of gas across a semipermeable boundary. Both phenomena follow a pattern in which their *rate* of equilibration is directly proportional to the *difference* between their current state and their equilibrium state. For example, a cold liquid's *rate* of temperature change is directly proportional to the *difference* between its temperature and the temperature of the environment with which it is equilibrating. When the temperature *difference* is large, the *rate* of temperature change is large. As the *difference* decreases, the *rate* of change decreases. A *difference drives rate* model of equilibration can be a powerful tool for scientists as it predicts and explains a range of observable phenomena. Despite its power, the *difference drives rate* pattern is usually introduced later in the science curriculum when it is taught in the form of a differential equation, for example as Newton's law of heating.

It is the goal of this study to identify elements of prior knowledge that might serve as a foundation for younger students' construction of a conceptual understanding of the *difference drives rate* model of equilibration. This understanding might in turn help them make sense of phenomena like thermal equilibration before they have the mathematical machinery to interpret Newton's law of heating; it may also serve as a foundation for their construction of related mathematical concepts later on. The research reported here looks at a single class discussion during which students generated explanations for an instance of thermal equilibration and asks the question: "What prior knowledge emerged as a resource for students' construction of a *difference drives rate* model of equilibration?"

By identifying elements of prior knowledge that are potentially fruitful for science learning, this study makes theoretical and empirical contributions to the conceptual change literature. The larger work within which the study is situated makes a practical contribution to classroom science through insights into how instruction can be designed to leverage students' prior knowledge. Such instruction not only supports learning, but positions learners as agents of knowledge construction. This, in turn, may have the power to enhance students' picture of the scientific enterprise, making science a discourse where their voices matter, and to which they might one day make meaningful contributions.

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Theoretical orientation

I align my research with the *Knowledge in Pieces* (*KiP)* perspective (diSessa, 1993). *KiP* models knowledge as a complex system of elements that are cued in response to the sense-making demands of a particular context. Consistent with constructivism, the development of more sophisticated knowledge involves the reorganization and refinement of existing knowledge. This view stands in contrast with perspectives on conceptual change that view knowledge as a unitary theory that is cued consistently across contexts, and learning as a process in which a naïve theory is replaced by a more expert one (Clement, 1982; McClosky, 1983).

Motivated by the *KiP* model of learning, I investigate elements of students' prior knowledge that are potentially productive for their construction of a scientific model of equilibration. I have therefore analyzed student contributions to a relevant class discussion and identified potentially productive knowledge elements, characterized those elements, and considered how they might foster students' construction of a *difference drives rate* model of equilibration. I compare the elements that I identify with a class of intuitive knowledge called *phenomenological primitives*, or *p-prims* (diSessa, 1993). *P-prims* model the smallest units out of which a larger knowledge system may be comprised. They are deeply intuitive elements of explanations, providing a learner with an *intuitive sense of mechanism*. An example of a previously documented *p-prim* that is also identified here is *Ohm's p-prim*: the intuition that *more effort begets more result*.

This study is embedded in a larger program of design-based research (Collins, Joseph & Bielaczyc, 2004). The present analysis considers data from a class discussion that occurred during an iteration of a yearlong course in which students practiced identifying and articulating models of process patterns including equilibration. The fundamental assumption of *KiP* that guided my design of instruction is that prior knowledge can play a productive role in students' construction of scientific knowledge. Designing instruction is therefore about creating opportunities for the learner to activate productive elements of their prior knowledge and engage those elements in their construction of new knowledge (Hammer, 2000). This stands in contrast with instruction designed from the *misconceptions* perspective, which focuses on identifying incorrect knowledge and replacing it with correct knowledge (McClosky, 1983). Instruction was therefore designed to elicit and engage students' prior knowledge in their construction of more sophisticated pattern models.

To identify productive elements of students' prior knowledge, I drew on a set of strategies for qualitative analysis connected with the *Knowledge in Pieces* framework and organized under the name *Knowledge Analysis* (*KA*). *KA* is characteristically focused on knowledge, analyzing the *ideas* that learners internalize, rather than the means or modes through which they communicate those ideas. *Knowledge in Pieces* is firmly committed to the complexity and idiosyncratic nature of individual knowledge systems. *Knowledge Analysis*, therefore, begins with a grounded characterization of the data. It then compares emergent knowledge with the existing KiP model in order to contribute to its expansion and refinement.

Methodological approach

This study investigates the prior knowledge of a group of 8th grade students that is potentially productive for their construction of a scientific model of equilibration. It considers data taken from a class discussion that occurred during an iteration of design-based research. The instructional design under test was a middle school science course called Patterns Class. Patterns Class met for 40 minutes on Monday, Tuesday, and Thursday mornings. The class met both fall and spring semesters, totaling approximately 60 hours of instruction over the course of the school year. The researcher was the primary instructor and undergraduate research assistants doubled as teaching assistants, attending class about one morning a week with moderate consistency over the school year.

Patterns Class curriculum was designed to guide students through the systematic exploration of four patterns: threshold, equilibration, exponential growth and oscillation (though these names were never formally introduced to the class participants). The results presented here are taken from analysis of data from the equilibration unit. The target model of the equilibration pattern can be characterized as *difference drives rate*, in which the rate of a system's equilibration is directly proportional to the difference between its current state and its equilibrium state. An example that is explored by students during the unit is the equilibration of a glass of cold milk with a warm room. At the start, the temperature of the milk is farthest from the temperature of the room and it is observed to warm at the greatest rate. As it warms, the difference between the milk's temperature and the temperature of the room decreases and the milk is observed to warm at a progressively slower rate until it reaches the temperature of the room.

In each of the units, instruction was designed to support students in modeling the pattern by activating and engaging their prior knowledge in a general sequence of activities that alternated between exploring prototypical examples and generating and refining models of the patterns those examples followed. The equilibration unit was comprised of 7 core activities and ran for approximately 20 instructional hours. The sequence of core activities consisted of: 1) investigating the thermal equilibration of a glass of cold milk, 2) investigating the thermal equilibration of a glass of hot tea, 3) constructing a model of the general pattern of behavior common to both examples, 4) investigating the equilibration of beans in a partitioned box through a simulation of diffusion, 5) revising pattern models, 6) generating additional examples that followed the pattern of behavior exhibited by the three examples , and 7) revising pattern models.

Participants

Twenty-one 8th grade students participated in the focal iteration of the Patterns Class. The majority of the students were children of families that had immigrated to the U.S. from Mexico and Central America. Several students identified as African American and European American. English was a second language for most, Spanish being the primary language spoken at home. The majority of students attending the school were designated as English Language Learners, and the majority qualified for free and reduced lunch. The group of students participating in Patterns Class was selected on the basis of availability and willingness to participate. The particular school was selected because the science teacher there was amenable to sharing her elective period students with our group for both fall and spring semesters. Her elective period had traditionally been used as a science enrichment period for students that had scored proficient or higher on tests of basic skills in English and math.

Data collection

Data relevant to the present report were collected in three different forms: 1) video footage, 2) field notes, and 3) teacher reflections. Two digital video cameras recorded the activities of every Patterns Class. One camera was positioned at the middle of one side of the room and pointed at an angle out across the classroom toward the front board. This camera captured the activity of the teacher and/or student(s) speaking at the front of the room and the artifacts recorded on the front board. A second camera was positioned at the front of the room just to the side of the front board. It was pointed out across the tables at which the students sat and captured the activity of the students as they attended to the front of the room or engaged in small group work. Field notes taken by research assistants and reflections written by the teacher were used to identify segments of video for more careful analysis. Video footage of a whole-class discussion was selected as data for the present study, as it was particularly generative of prior knowledge. The discussion was transcribed and investigated through a Knowledge in Pieces lens. Potential knowledge elements were identified, characterized and compared with previously documented phenomenological primitives, and considered in terms of their potential productivity for students' construction of a *difference drive rate* model of equilibration.

Certain conventions were used to transcribe students' verbal utterances captured on videotape. The names of students contributing to the class discussion have been replaced with pseudonyms. I omit certain contributions that are interruptions or part of productive conversations that are not temporally linked to the contributions that are immediately relevant to my analysis. I use the symbols defined below to indicate the flow of speech and gesture:

- // - break in speech
- /…/ - interruption or parallel speech
- <…> - gesture

Major findings

My analysis addresses the research question: "What prior knowledge emerged as a resource for students' construction of a *difference drives rate* model of equilibration?" I will present elements of prior knowledge invoked by the students during a class discussion to explain the *changing* rate of temperature change exemplified by the results (Figure 1, below) of a thermal equilibration investigation. Facilitated by the teacher, students shared their explanations for why the temperature of a glass of cold milk would warm up quickly at first and then slow down as the milk reached room temperature. Below, I present the knowledge elements in their order of appearance and describe their context of emergence, character, and potential productivity for students' construction of a *difference drives rate* model of equilibration.

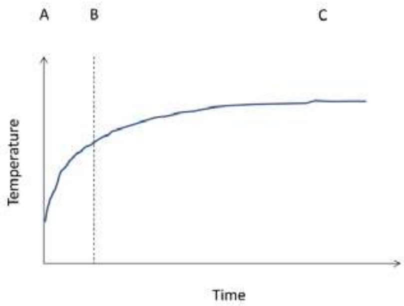

Figure 1. Approximate graph of temperature over time for cold milk equilibrating with a warm room.

Knowledge element 1: *Slowing Down to Stop*

This element emerged near the beginning of the whole class discussion. The teacher had asked students to respond to an explanation for the milk's changing rate of temperature change written by one student at the end of the previous lesson: "Because it was getting to room temperature at the end so it was slowing down. It's like a race, when you're getting to the destination you start to slow down."

Leo:	um//why would you slow down when you're about to finish a race? It doesn't make sense
Alvaro:	say there's a wall// are you going to run straight into it Leo?
Leo:	well I'm not gonna go slower though// because then I'll lose
Alvaro:	like no no no no no like// say you're winning cause you're going as fast as you can// then when you're gonna reach the wall// don't you start to like <stomps feet on the ground> kinda/
Michelle:	/is there a wall?
Alvaro:	yes there's a wall
Michelle:	there is no wall
Alvaro:	there is a wall
Michelle:	where?
Alvaro:	the room temperature// huh? huh Michelle what? This time when you're running// you're racing// you run as fast as you can// but then you're gonna go// you're going to hit a wall so you start to like slow down// *you have to slow down to stop*

The discussion begins when one student, Leo, challenges the internal consistency of the race analogy by questioning the sensibility of slowing down at the end of a race. Alvaro responds to Leo by explaining that this is a special case in which the race ends at a wall. Michelle challenges Alvaro's wall, questioning the mapping between the wall and the milk. Alvaro connects the wall with room temperature and presents his idea once more. His explanation for the decreasing rate of change is: "*you have to slow down to stop*."

Slowing down to stop appears to be a notion that belongs to Alvaro's *intuitive sense of mechanism*. The wall, in Alvaro's analogy, serves to reinforce the sense that there is a hard line beyond which neither the runner, nor the temperature, can go. Trying to stop after moving quickly is a common experience of many middle school-aged students (and many people, in general). Attempting an abrupt stop after activities like running, skating or driving are several possible origins of this intuition. If one attempts to stop abruptly, inertia causes one to overshoot and continue beyond the intended stopping point. An abstraction of the experience of inertial overshooting may be the previously documented p-prim *overcoming* – the sense that one influence wins over another (diSessa, 1993). One may intuitively know that they can avoid this overshooting by slowing down before they stop. It is reasonable to conjecture that this is an intuitive element of knowledge that Alvaro is drawing on when he says: "you have to slow down to stop."

Though it has not been previously documented, *slowing down to stop* is a candidate for intuitive knowledge roughly the grain size of a *p-prim*. The connection between *slowing to a stop* and the experience of overshooting suggests that the knowledge element may in some cases be cognitively linked (and have high cuing priority) with the p-prim *overcoming*. *Slowing to a stop* seems close, in character, to the *p-prim slowing equilibration* – the notion that things slow as they approach equilibrium (diSessa, 1993). I would argue, however, that it is different in three important ways. The first difference is the *degree of urgency*. While *slowing equilibration* is described by a natural and gradual easing to a stop, the slowing described by Alvaro is marked by an urgent need to stop. The second difference is in the location of the *impetus* for slowing. In the case of *slowing equilibration* the object slows because that is its natural internal tendency. In the case of Alvaro's slowing, the object is pressured to stop by an external entity or demarcation. The third difference is related to the *stopping point*. In the case of *slowing equilibration* the object is returning to its natural state or state of balance. In the case of Alvaro's slowing, the object is moving to a new destination.

Slowing to a stop is potentially very productive for the construction of a scientific model of equilibration. While it only explains the latter half of the equilibration curve (Figure 1, segment BC), *slowing to a stop* maps well to that part of the curve and, moreover, it is analogous with *difference drives rate*, though in a spatial incarnation as *distance drives rate*. As the distance to the endpoint decreases, so does the speed of the equilibrating entity, until, at the endpoint, the rate of change is zero. The productivity of the element is limited in that it cannot be generalized to explain the decrease in speed at any distance from the endpoint. Instead it only explains the change in speed at a point where the entity is near enough to the endpoint that it needs to begin to slow down. This limitation will be clear in the way Alvaro thinks about the first half of the equilibration curve (Figure 1, segment AB).

Knowledge elements 2 and 3: *Energy Drives Rate* and *Energy is Greatest at the Start*

Noticing that the students have focused on the second half of the equilibration curve (Figure 1, segment BC), the teacher turns their attention to the task of constructing an explanation for the first half (Figure 1, segment AB).

Teacher: let me ask you this: what if we need to do the other half of that// going really fast at the start? Why would the water start warming up really fast at the start?

Leo: because *at the start you have a lot of energy to run so you run*/

Continuing to reason within the general context of the race analogy but shifting from the *end* of the race to its *beginning*, Leo offers an idea that is completely unrelated to the "wall" at the finish line. He suggests: "at the start you have a lot of energy to run." Because it is given in response to the teacher's question, Leo's idea could be interpreted as meaning "at the start you have a lot of energy to run, *so you run fast*." At the beginning of the race the runner's speed is the greatest because they have the most energy. As the race unfolds, the runner uses up energy and slows down as a result. It seems as though there are two underlying intuitions here. The first is *energy drives rate*. This is a potential abstraction of the experience of moving with greater speed when one feels energized and moving more slowly when one feels less energized. The second intuition is that *energy is greatest at the start* of an activity. This implies that one has a fixed amount of energy to devote toward activity, and as one is active, one depletes that fixed amount of energy. The second intuition is potentially fruitful for constructing a scientific understanding of conservation of energy. It is probably grounded on the very common physical experience of moving quickly at the beginning of an activity (such as a race) when one is fresh and has not yet exerted oneself. As one goes along, one experiences increasing fatigue (which one might attribute to the expenditure of energy). Really, a person uses up chemical potential energy as their body converts it into the kinetic energy of their movement, so the explanation that Leo suggests is not unscientific in the context of the race.

Leo's ideas might also be connected with the impetus conception of force, documented by early *misconceptions* researchers (Clement, 1982; McClosky, 1983). The conception explained a moving object as being driven forward by an internal impetus *force* that perpetuated its motion until it gradually died out. Here Leo is calling the impetus force *energy* as opposed to *force,* but the idea appears to be much the same. At the beginning, the object (the runner in the case of his analogy) could be said to have a lot of force, but the force dies away over time and results in the slowing and eventual stop of movement. An important distinction between Leo's idea and the impetus force conception is that Leo's idea is invoked to explain human motion (though ultimately he may have meant it to explain the warming of the milk, as he shared the idea in response to the teacher's question about the milk). Impetus force is a documented explanation for the slowing of inanimate objects. While it is not scientific to explain an object's slowing as the result of running out of impetus force, it *is* scientific to explain the slowing of a human runner as the result of running out of energy.

Leo's intuition about having more energy to run fast at the start may in fact produce a curve that matches the equilibration curve and therefore provide a working explanation (possibly even one with predictive power) for the changing rate of temperature change. Its productivity is ultimately limited, however, because it does not map to *difference drives rate*, which is the target model of equilibration. While a race of a particular length might afford a run that begins as a sprint and slows as the runner loses energy, it is possible to imagine that a shorter race would yield a sprint of a consistent rate, or that a longer race would yield a run of variable pace, or one in which the runner stopped entirely before reaching the finish line. A main limitation of Leo's reasoning is that rate is not dependent on the amount the entity has to change (position or temperature). It therefore does not map to the scientific model of equilibration as *difference drives rate*.

Knowledge elements 4 and 5: *Space Allows Speed* and *Ohm's P-prim*

Leo has hardly shared his idea when Alvaro interjects to voice his disagreement and provide an alternative explanation.

Alvaro: /no// I disagree// Because *you have more space* <gestures spreading hands apart>// you're not going to crash into a wall <moves whole body forward> so *that's why you run faster*/

Leo: /that's not really true/

Alvaro: /you *try to win*//So you can try to like// win// *that's why you're running faster*// but then// when you're like approaching the wall// you're gonna start to like slow down// so you don't want to like crash into it

Continuing to reason in the context of the analogy of a race to a wall, Alvaro produces an alternative explanation for the high speed of the runner at the beginning of the race. This is that, unlike the end of the race where the wall constrains the runner's speed, at the start, the runner can safely run as fast as they want. His final contribution suggests that the runner will go as fast as possible at the start because they are trying to win the race. The goal of winning, together with the safety of the large space, drives the high speed of the runner at the start of the race. It is possible that Alvaro's conception of *space* is invoked as a result of the way he is thinking about the race with respect to the wall: with both the start of the race and the wall in mind *the space between the starting line and wall is made salient*. At the start, there is a great deal of space between the two and it is therefore *safe to run fast*. Near the finish there is less space and the runner is in *danger of crashing into the wall* and must therefore slow to a stop.

Both driving factors - space and effort – appear to be separate intuitions. Alvaro's explanation has nice internal consistency and it is likely that his intuition that *space allows speed* is cognitively connected with *slowing to a stop*. When there is space to run quickly, one runs quickly, as the space decreases one must slow to a stop. Both knowledge elements are connected with, and probably mediated by, a perception of safety. The experience of running to a wall is a possible origin of the intuition that *space allows speed*. Alvaro's intuition that effort drives rate is essentially an instantiation of the previously documented intuition *Ohm's p-prim*: greater effort begets greater result. *Ohm's p-prim* has previously been shown to be highly productive in students' construction of a *difference drives rate* model of equilibration (diSessa 2014). As well, Alvaro's idea of *space allows speed* might be useful for constructing a *difference drives rate* model of equilibration. It does map to *difference drives rate*, if the entity is motivated to go as fast as it is allowed *and* responds proportionally to the decrease in space. This conceptualization of the relationship between space and rate is limited, however, in that it is possible to imagine that the entity would not have a proportional relationship with the distance. Rather, it may go fast at a constant rate until it needs to slow down to avoid crashing into the wall.

Knowledge element 6: *Difference Drives Desire to Eliminate Difference*

The teacher summarizes the ideas shared by Leo and Alvaro and frames them as competing explanations. She adds another explanation to these two, one that had been written by a student the previous day: "Because when it first goes in, the temperature is so different so it changes faster." She invites the students in the class to respond to any of the ideas put forth by their classmates thus far. She pulls Sofia's name at random and asks her which of the ideas make sense to her.

Sofia: they all make sense// because// the last one// because the temperature is super different// it wants// I guess it warms up faster

Teacher: why does it go fast and slow// based on what you said?

Sofia: I guess// It wants to get warmer? I don't know

Teacher: <writes on board> because it wants to/

Sofia: /get warmer and reach room temperature

The original idea read by the teacher maps directly to *difference drives rate*, however it is not clear what intuition, if any, underlies it. In explaining why this idea makes sense to her, Sofia invokes an intuition about the relationship between the difference in temperatures and the *desire* of the cold milk to reach room temperature. She appears to be suggesting that the milk wants to be at the same temperature as the room. The temperature difference sparks that desire in the milk, to "get warmer" and "reach room temperature." Though her explanation is fragmented, it seems that for Sofia, the milk's desire to eliminate the difference in temperature drives the rate at which it warms. It is plausible that she is invoking *Ohm's p-prim*, connecting desire and rate through effort. In this case, a more complete version of her explanation would be comprised of three elements of intuitive knowledge: *difference drives desire to eliminate difference, desire drives effort, and effort drives rate (Ohm's p-prim)*.

With so little data, it is difficult to say for certain what knowledge Sofia invokes. If she is in fact thinking that the milk's desire to warm is directly proportional to its difference with room temperature and invoking *Ohm's p-prim*, this would be highly productive. On this view, when the temperatures are very different, the milk has a very strong desire to decrease that difference, and, as a result of that strong desire works harder and decreases the difference more quickly. As the difference decreased, so would the desire and effort of the milk, causing the difference to decrease more slowly. In this way, logic relating the difference in temperature to the rate of temperature change is highly productive for constructing a *difference drives rate* model of equilibration.

Knowledge element 7: *Difference Drives Rate*

The teacher turns to the class to invite the other students to respond to the ideas that have come up during the class discussion. She draws Mateo's name at random and asks him to explain the ideas that have made sense to him during the discussion.

Mateo: there's a big difference in the temperature// um like it has a lot to cover so it wants to do it fast

Teacher: what about this from here to here? <points to the second half of the warming curve>

Mateo: like Alvaro said// it slows down 'cause there's a wall

Mateo's intuition that "it has a lot to cover so it wants to do it fast" appears to map directly to *difference drives rate*. It is a sensible instinctive reaction to having a great distance to cover, or a great amount of difference to decrease. Mateo's intuition seems to be the symmetric reflection of *Ohm's p-prim*. If we interpret "has a lot to cover" as implicating a large result to produce and "wants to do it fast" as implicating a desire to put forth a great amount of effort, "it has a lot to cover so it wants to do it fast" can be interpreted as "greater result motivates greater effort." It is important to note that this is only meant to explain the beginning of the equilibration curve and Mateo invokes Alvaro's notion of *slowing to a wall* to explain the rate at the end of the equilibration process. The knowledge element introduced by Mateo is very powerful. It can be used to both explain and predict the equilibration curve and maps smoothly to the idea of *difference drives rate*. His explanation in fact precedes the emergence of an articulation of *difference drives rate* that is free of anthropomorphic language and independent of Alvaro's "slowing down to stop" explanation.

Discussion

Seven elements of prior knowledge were identified as potential *resources* for students' construction of a *difference drives rate* model of equilibration. Six of these elements were previously undocumented. The first element appeared to be connected with the previously documented p-prim *overcoming*. Several elements appeared to be connected with a previously documented phenomenological primitive, *Ohm's p-prim*. These results verify existing elements of the *Knowledge in Pieces* model and suggest possible extensions to it.

The broader study in which this work is situated makes a practical contribution through the design of classroom instruction that supports students' construction of a *difference drives rate* model of equilibration. In addition to pattern knowledge and science practices (such as explanation and modeling) outlined by the Next Generation Science Standards, Patterns Class presents students with a novel picture of the scientific enterprise. Much of the science curriculum that has been designed to emulate the practices of professional science has focused on empirical activities, such as inquiry-based learning. While certain versions of inquiry have focused on the theoretical side (White, Frederiksen, Collins, 2009; Lehrer, Schauble & Lucas, 2008), much inquiry curriculum is focused on engaging students in practices of observation, data collection, and representation. Patterns Class includes empirical investigations but the theoretical half of the inquiry process is more heavily weighted.

Moreover, the theoretical half is not focused on engaging students in activities concerned with *existing theories*; rather, it is focused on scaffolding students' construction of *their own theories*. Much instructional time is devoted to theory building activities (such as the whole class discussion that was the focus of this report).

Patterns Class features a strength-based curriculum that values and leverages the prior knowledge that individual students bring to their learning. The responsive nature of the instructional design does not privilege *formal knowledge* over *everyday knowledge*. It supports students in the task of knowledge construction by building on their strengths. Though instruction has been designed with target scientific models in mind (e.g., equilibration as *difference drives rate*), it is meant to support students' construction of their *own* pattern models and strives to treat students as autonomous agents of knowledge construction. The general nature of patterns makes them accessible to students from a variety of backgrounds. Equilibration, for example, can be explored in physical phenomena such as the warming of a glass of cold milk, or psychosocial phenomena such as the dissipation of a strong emotion over time. Students can think carefully about an example with which they personally resonate and construct their model of equilibration on the basis of that example. Because they afford a multitude of diverse entry-points to their exploration, patterns are an excellent object of thought with which to engage students from different backgrounds and levels of academic preparation in abstract thinking and authentic practices of science.

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