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REFINING STUDENT THINKING THROUGH SCIENTIFIC THEORY BUILDING

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Summary

Theory building is a central activity of science. I argue that children can engage in an intellectually honest version of scientific theory building in the classroom. I present a method for helping students build theories of patterns (such as threshold and equilibration) exemplified by phenomena across domains. Through iterative cycles involving both creative and critical thinking, the approach helps students refine their theories in terms of *alignment with scientific conceptions*, *deeper structure*, *explanatory power*, and *abstraction*. Empirical findings suggest the approach helps students construct scientific understanding while also developing communicative competence and qualities of a theoretical turn-of-mind.

Introduction

According to Albert Einstein (1936, p. 349), “The whole of science is nothing more than a refinement of everyday thinking.” This observation conveys the constructivist perspective on learning, where a learner builds formal knowledge by reorganizing and refining their informal knowledge (diSessa, 1993). In this chapter, I describe a theory-building course designed to help students refine their thinking through theory invention, test, and revision.

The course focused students on building theories of patterns in system behaviors (including threshold and equilibration) that can be seen in examples across domains, from physical to psychosocial. Threshold, for example, can be seen in the tipping point of a tower of blocks, and in the limit of a person’s patience. Both phenomena exemplify a pattern of *pre-phase*, *limit*, *reaction*, where a parameter is varied during a *pre-phase* until a *limit* is exceeded and the system *reacts* by making an irreversible transition to a new state. Equilibration can be seen in a glass

of cold milk warming to room temperature, and in the calming of a person's emotions. Both phenomena exemplify a pattern of *difference drives rate*, where a system tends toward equilibrium quickly at first, and then more slowly as it approaches that state. Patterns like threshold and equilibration are concerned with the behavior that underlies phenomena, or their *deeper structure*. They often capture causal relationships between events and therefore have *explanatory power*. They are exemplified by many phenomena and are therefore best articulated in general terms, as *abstract* constructs.

These qualities make patterns a good target for theory building in the science classroom. Scientific theories are meant to convey the deeper structure underlying a class of phenomena (Hempel, 1974; Toulmin, 1958), to explain those phenomena (Hempel & Oppenheim, 1948), and to apply to a broad range of phenomena (Atkins, 2010). Identifying deeper structure and abstraction, however, are commonly considered beyond the capacity of young learners (Chi, Feltovich, & Glaser, 1981; Larkin, 1983).

Because patterns are essentially the abstract deeper structure underlying multiple examples, they can be thought of as the *relational structure* (Gentner, 1983) or *schema* (Gick & Holyoak, 1983) instantiated by analogs (examples that are similar by analogy). Findings from research on analogical reasoning can therefore be leveraged to support students' abstraction and articulation of patterns. As well, patterns can be explored through many different phenomena, so students can generate their own examples and construct their theories in contexts where they have some expertise. Students' pattern theories vary in the degree to which they achieve deeper structure, explanatory power, and abstractness. All students can succeed, however, at generating an initial theory, and all students can improve their theories by thinking about their own and their peers' ideas more carefully (Swanson & Collins, 2018).

Description of the method

In this section, I introduce the key components of my theory-building approach. First, I will provide a sketch of the theory-building course that I developed and researched. The goal of the course was to engage students in an "intellectually honest" (Bruner, 1977) version of scientific theory-building, so that they might cultivate elements of a "theoretical turn-of-mind" (diSessa, 1991). I also expected students might refine their pattern theories to more closely align with scientific conceptions of the patterns they investigated.

The course was implemented over an entire school year and met during a 40-minute elective period on Monday, Tuesday, and Thursday mornings, for a total of 52 hours of instruction. It was offered at a public middle school located in an economically depressed neighborhood of a large city in the United States. I taught the course, having been a high school science teacher for 6 years before transitioning to research. I arranged to teach the course with the intention of cultivating a classroom culture that supported students in sharing, making sense

of, and refining their everyday thinking. Twenty-one 8th-grade students (ages 13–14; 11 girls and 10 boys), participated in the course. Eighteen of the students had immigrated with their families to the United States from Mexico and Central America. Two students identified as African American and one as Bosnian American. The majority of students attending the school were low-income and designated as “English-language learners.”

Students created theories for patterns of threshold, equilibration, exponential growth, and oscillation; however, I will only report on threshold and equilibration here. Pattern units were interspersed with smaller units and single lessons focused on the nature of patterns and how building pattern theories related to theory building in science. In order to make the task of building a pattern theory more accessible, I separated it into smaller components and staged their introduction over the course. These included 1) describing a behavior underlying a single phenomenon (i.e., articulating a phenomenon’s *deeper structure*), 2) explaining the cause of the behavior (i.e., giving the theory *explanatory power*), and 3) generalizing the description by articulating the elements of the behavior that could be found in multiple phenomena (i.e., making the theory *abstract*).

For each unit, students constructed theories through an iterative cycle that involved steps of example exploration and theory generation, test, and refinement. For each pattern, they individually produced three theory drafts. They produced the first draft after considering two example phenomena. They tested their theory on a third example and refined their ideas, producing a second draft. They generated a list of examples that followed the pattern and tested how well their theories fit their examples. They refined their ideas and produced a third and final draft of their theory. Table 4.1 outlines this cycle for the first three units of the theory-building course.

Students wrote their theories on their own; however, they were encouraged to share their ideas with their classmates. The 21 students were distributed across six tables, with four groups of four, one group of three, and one group of two

TABLE 4.1 Cycle of example exploration and theory generation, test, and refinement for the first three pattern units

<i>Unit</i>	<i>Example exploration</i>	<i>Theory generation</i>	<i>Theory testing</i>	<i>Theory refinement</i>	<i>Theory testing</i>	<i>Theory refinement</i>
Introductory Unit	Chocolate chip cookie, oatmeal cookie	Draft 1	Graham cracker, Oreo	Draft 2	Student-generated examples	Draft 3
Threshold	Spaghetti bridge, drops-on-a-coin	Draft 1	Salt-water and floating egg	Draft 2	Student-generated examples	Draft 3
Equilibration	Cold milk warming, hot tea cooling	Draft 1	Beans-in-a-box	Draft 2	Student-generated examples	Draft 3

students.¹ I randomly assigned their seats at the beginning of each month. When students investigated examples, they worked in pairs (with one of their tablemates). When they created group artifacts such as posters, they worked with the other students at their table.

The key components of the approach are: 1) introducing new concepts and processes through example and experience, 2) moving back and forth between empirical and theoretical activities, 3) providing a range of familiar examples, 4) eliciting and refining student ideas, 5) moving back and forth between individual and group thinking, and 6) reflecting on products and processes.

Introducing new concepts and processes through example and experience

It can be helpful to introduce students to new ideas, such as abstraction, by giving them concrete examples, and it can be helpful to introduce them to a new process by walking them through it in a familiar context. I introduced my students to ideas related to abstraction at the beginning of the course through two activities. The first activity introduced the ideas *general* and *specific*. I opened class by projecting the results of a Google image search for the word *vampire* and asking students what they saw. Some students named vampire characters while other students replied “vampires.” I pointed out that each of the characters was a *specific* example of a *general* category called vampires. I continued with image searches for zombies, birds, and reptiles, asking students to explain what was general and what was specific in each case. I asked students how they would define general and specific and recorded their ideas on the board. For *general*, they shared “simple” and “huge category.” For *specific*, they shared “not random,” and “focuses on a small topic.”

The second activity gave students practice characterizing a general category and introduced them to the iterative cycle of example exploration and theory generation, test, and refinement. I began the activity by giving each table a chocolate chip cookie and an oatmeal raisin cookie. I asked them to think of a name for the general category to which the two belonged and to brainstorm a list of characteristics they had in common. The students did this individually and then shared their ideas with their tablemates. They created a poster showcasing their category’s name and characteristics, which they presented to their classmates. I then gave them two new objects with which to “test” their “theory”: an Oreo and a graham cracker. Some groups expanded their categories to include the graham cracker (e.g., renaming the category from “cookies” to “snacks”). Some groups narrowed their categories to exclude the graham cracker (e.g., making a circular shape a distinguishing feature of a cookie). They then brainstormed examples that fit into their categories and tested their category names and characteristics against these. They refined their ideas and produced a final draft description of their category. All along, I asked students to identify examples of *general* and *specific* in their work. Understanding how to create a general description is critical for creating an abstract, broadly applicable theory.

Moving back and forth between empirical and theoretical activities

Teachers can engage students in a theory-building process that loosely mirrors that of scientists by having them generate theories and then test them against empirical observations. In the theory-building course, students refined their theories through an iterative process that moved back and forth between empirical and theoretical activities. During the empirical activities, students investigated pattern exemplars to seed their initial theory or to guide their refinement of an existing theory. During the theoretical activities, students articulated and revised their theories in response to the examples they had investigated.

Students were introduced to the task of describing a *deeper structure* behavior in the threshold unit. They began by investigating two phenomena that exemplified the threshold pattern. First, they added coins to a cup hanging from a spaghetti bridge. With the addition of coins, the bridge collapsed and crashed to the floor. In the second example, they added drops of water to the surface of a coin until the water flowed onto the table. For both investigations, they took notes on the behavior that they observed. Following the investigations, they wrote initial theories for the pattern (i.e., the behavior the two examples had in common). When students named their patterns, some focused on the *pre-phase* (“Getting More”), some on the *limit* (“Maximum Capacity”), and some on the *reaction* (“The Break”). Students’ theories ranged in focus from common surface features (“Both used pennies and had to have a special technique”) to common deeper structure (“Both had to carry something until it couldn’t hold more”).

The students tested their theories on a third example, adding salt to a glass of water until a submerged egg floated to the surface. The students then wrote about how this example was similar to, and different from, the previous examples. I presented PowerPoint slides featuring a representative sample of students’ initial pattern theories (which I left anonymous). I then facilitated a brief group reflection on students’ initial pattern theories, during which an aesthetic for generality emerged. One student raised his hand and noted that calling the pattern “The Break” was problematic, because: “Actually, not everything [had to do with] something breaking. Because you know the one where we squirted the drop of water onto the pennies? It didn’t break, it spilled...” I used this student’s comment as an opportunity to highlight the appropriate level of abstraction and acknowledged that “break” might be too *specific* a word, and that students might want to choose a more *general* word.

Following the discussion, students wrote second drafts of their theories. They then generated their own examples that exhibited the pattern. They worked with others at their table to create posters to showcase their examples and then conducted a gallery walk (Kolodner et al., 2003), sticking notes on each other’s posters to indicate where they agreed or disagreed with examples. I used two contentious examples (“bothering someone until they burst” and “getting your hair cut”) as the basis of a whole-class debate. Following the debate, I reviewed

students' earlier theories and invited them to revise their drafts a final time. Most students characterized the pattern as either *pre-phase, limit, reaction* ("We added something till something happened"), or *pre-phase, limit* ("We put something until it couldn't hold it anymore").

Students were introduced to the task of explaining a pattern's *cause* in the next unit on equilibration. They began by investigating two phenomena that exemplified the equilibration pattern. For the first example, they used computer software to collect data for temperature over time as ice water (simulating cold milk) warmed to room temperature. Following the investigation, students interpreted the data (shown in both graph and table), arriving at a description of the general pattern they found in the rate of temperature change over time as "fast and then slow."

They individually generated explanations for this pattern, which served as the basis of a whole-class theory-building discussion. Students began the discussion with idiosyncratic ideas about the temperature of the milk "slowing to a stop" like a runner slowing to avoid crashing into a wall, and the temperature increasing quickly at the start because it was far away from the wall and therefore safe to go fast. Gradually, through guided discussion, the students refined their ideas into a *difference drives rate* explanation reflective of Newton's law of heating (Swanson & Collins, 2018).

For the second example, they used the software to collect temperature data as boiled water (simulating hot tea) cooled to room temperature. They engaged in another theory-building discussion to create a causal explanation for why the tea cooled fast and then slow. Following these investigations, students wrote down their initial pattern theories. They named their patterns versions of "fast and then slow" and described the pattern similarly.

The students tested their theories on a third example, particle diffusion, which they simulated with a partitioned box filled on one side with two tablespoons of dried beans. They shook the box back and forth, and beans moved in both directions through a small gap in the middle of the partition. The students recorded the number of beans on the initially empty side of the box every ten shakes and then graphed the total number of beans on that side over 100 shakes. Their resulting graphs, which they drew on the front board to analyze, showed a similar shape (here representing number of beans over total shakes) as the warming and cooling investigations. In this example, the *difference* between the number of beans on either side of the box could be inferred as *driving the rate* of the redistribution of beans on either side of the box.

The students engaged in a theory-building discussion to collaboratively create a causal explanation for why the beans diffused fast and then slow. They wrote about how this example was similar to and different from the previous examples. I presented a sample of students' initial pattern theories and their thoughts about how the third example compared to the first two. Students then wrote second drafts of their theories. About 40% of the students included the idea of *difference drives rate* in their pattern theories, though most of these students also included the

nonnormative idea that the final state also drove the rate (e.g., “Slows down to reach equilibrium, goes fast in the beginning because it has more room to cover”).

Students then generated their own examples that exhibited the pattern. As in the threshold unit, they worked with the others at their table to create posters to showcase their examples and participated in a gallery walk to view and comment on each other's examples. Again, I used contentious examples (e.g., emotions calming down) as the basis of a whole-class debate. I then reviewed students' earlier theories and invited them to revise their drafts a final time. By the final draft, over half the theories were solely *difference drives rate* (e.g., “Fast because there is more space to cover and it slows down because every time less space is available and with less space it can slow down”).

Providing a range of familiar examples

Teachers can help students find deeper structure and create abstract theories by giving them a range of examples. Research on analogical reasoning has shown that it is quite difficult for people to identify an abstract deeper structure with just one example, but given two examples, it is possible (Gick & Holyoak, 1983). Research has further shown that it is easier for people to find a deeper structure in two examples that are similar on the surface (Loewenstein & Gentner, 2001). It is therefore helpful to provide students with examples that are closely related. Once they have identified a common deeper structure, they can see it in more distant examples. Giving them examples that are distantly related is also beneficial, as it helps them generalize their theory so that it is more broadly applicable. In the theory-building course, students began their exploration of the threshold pattern by investigating two similar examples: the spaghetti bridge and drops-on-a-coin. In both cases, a discrete amount of something is “added” to an object that “holds” it (e.g., a stick of spaghetti, a bead of water) until it reaches capacity and “breaks” (the spaghetti breaks, the bead of water bursts). These examples helped students notice a deeper pattern in behavior where “we had to keep on putting something until it broke.” The third example that they explored was more distantly related, as it did not show something breaking. Instead, it showed that after they had added enough salt to a cup of water, a submerged egg floated to the surface. This example helped students further generalize their language, by replacing “break” with a more general reaction as in: “Adding something to something until it changes.”

For the equilibration unit, students worked in a similar way with closely related (heating and cooling of liquids) and then more distantly related (particle diffusion) examples. The closely related thermal examples helped students find a common pattern in behavior, for example, “Both go fast then slow. Goes slow to reach maximum room temperature.” The more distantly related diffusion example helped students generalize their language, for example, “Fast because there is more space to cover and it slows down because every time less space is available and with less space it can slow down.”

It is also important to give students familiar examples. All examples students considered were either from their investigations or generated by the students. Generating their own examples allowed students to think carefully about the pattern in a context in which they had some expertise. In this way, students created their own on-ramps to engaging in the complex task of theory building in a rich and meaningful way.

Eliciting and refining student ideas

At the heart of theory building lies the refinement of everyday thinking. Students can refine their thinking by articulating and making sense of their ideas. The teacher can facilitate this process by eliciting, showcasing, and engaging students in making sense of their own and their classmates' ideas. Eliciting and showcasing student ideas created the raw material for the class to refine through collaborative sense-making. When engaging students in making sense of ideas, it is important to get students to think critically about their own and their peers' ideas. It is through careful consideration of these ideas that students will refine their own thinking.

Throughout the theory-building course, I employed strategies to elicit, showcase, and engage students in making sense of ideas. I elicited students' ideas by asking them to share their pattern theories (e.g., for threshold or equilibration), or their theory for a particular phenomenon (e.g., why cold milk warmed fast and then slow). I showcased students' ideas by presenting screenshots of their pattern theories to the whole class via PowerPoint and displaying posters of their pattern exemplars. I revoiced and wrote student contributions on the board during class discussions. I engaged students in collaborative sense-making during whole-class theory-building discussions and pattern-example debates.

One activity structure that facilitated students' articulation and refinement of ideas was the theory-building discussion, where students worked to build a causal explanation for an everyday phenomenon. A teacher can facilitate a theory-building discussion by using moves that elicit, showcase, and engage students in making sense of ideas. I illustrate this with a discussion where students developed an explanation for why a glass of cold milk warmed fast at first and then slowed as it approached room temperature (for more details see Swanson & Collins, 2018).

Moves that elicit student ideas

These moves draw out students' knowledge by asking them to articulate their ideas and unpack their reasoning. Such eliciting moves spark creative thinking and guide students to generate the raw material they will refine into more formal knowledge. Specific moves that elicit students' ideas include: 1) asking students to explain a phenomenon, 2) asking students to restate their contribution, 3) asking students to elaborate their contribution, and 4) checking with a student to clarify their contribution.

To begin the discussion, I read aloud students' (anonymous) explanations for why cold milk warmed fast and then slow, then asked for additional explanations. When students' responses were hard to hear or follow, I asked them to repeat their contribution. When students gave minimal explanations, I asked them to elaborate, and when I wasn't sure I had understood, I checked with them to clarify. These moves had the effect of eliciting *more* student ideas. Even when a student restated their contribution, they tended to add new ideas, because they tried to justify it for others.

Moves that showcase student ideas

These moves create shared artifacts on which the community can reflect and refine their explanation. Some of the moves create momentary artifacts (e.g., verbal restatements) while others create more permanent artifacts (e.g., writing ideas on the board). Specific moves that showcase students' ideas include: 1) repeating a contribution, 2) restating a contribution, 3) characterizing the nature of a contribution, 4) recording a contribution on the board, 5) distinguishing contributions, and 6) connecting contributions.

During the theory-building discussion, I either repeated or restated virtually every contribution made by a student (both spoken and written), in part, to give them a chance to correct me if I had misheard them, and in part, to amplify each student's thinking for the class to hear. When students contributed explanations that were clearly distinct from those that were previously given, I showcased their ideas by writing them on the board for later consideration. Sometimes when I showcased students' explanations, I characterized them as belonging to a more general category (e.g., as an explanation focused on stopping at room temperature). Other times, I explicitly distinguished or connected their ideas with those given by other students. All of these moves had the effect of bringing attention to particular ideas and reifying those ideas for the duration of the period. Often, I brought their attention to a particular idea as an object of inquiry, to see if they understood it and, if so, whether the logic made sense.

Moves that engage students in making sense of ideas

These moves help students consider their classmates' ideas more carefully. They sometimes lead to the production of new ideas, but their main function is the modification of existing ideas by facilitating critical thinking. Specific moves that engage students in making sense of ideas include: 1) asking students to evaluate another's contribution, 2) asking students to restate another's contribution, 3) asking students to justify another's contribution, and 4) mediating students' interactions. I often fell into a pattern with students, asking them to take a position on an idea that I had just showcased, and if they agreed with it, asking them to restate it in their own words and explain why they thought it made sense. In some cases, students argued among themselves and critiqued each other's ideas.

Occasionally their critiques were unproductive and I intervened to mediate their interactions to help them understand their classmate's idea, instead of just dismissing it.

Moving back and forth between individual and group thinking

In facilitating students' articulation and refinement of ideas, it is important to give them time to think on their own and together. This gives them space to access intuitive knowledge that may be difficult to articulate quickly or under pressure (diSessa & Minstrell, 1998). It also supports their critical thinking by working collaboratively with their peers to make sense of ideas. The elicit-showcase-sense-make sequence naturally structures the integration of individual thinking with group sense-making. In the theory-building course, pattern units began by eliciting students' individual thoughts in response to example phenomena. Students then shared their ideas with their classmates through presentations and poster gallery walks and engaged in collaboratively making sense of their ideas through whole-class discussions and debates. In the theory-building discussions, students first wrote their own explanations for phenomena (e.g., why the cold milk warmed fast and then slow), and then engaged in collaboratively making sense of their ideas.

Reflecting on products and processes

The teacher can help students improve the products and processes of their theory building by facilitating reflection and peer-critique activities. Throughout the theory-building course, students shared the products of their work with each other, and engaged in reflecting on their products and how they could be improved. These reflections occurred in the context of PowerPoint presentations of student work, poster gallery walks, and whole-class discussions. This gave the students a sense for the ideals toward which they should strive. Finally, I led the students in several reflections on how their activities (in particular, example exploration and theory invention, test, and refinement) related to the activities of professional scientists.

Evidence of effectiveness

I argue that the theory-building approach to science instruction promotes deeper learning, competence with elements of communication that are essential to science, and thinking skills that belong to a theoretical turn-of-mind. As evidence, I summarize results from my analysis of student work. The analysis is based on a qualitative coding of students' three theory drafts with respect to four aspects of scientific thinking. Another researcher and I independently coded the theories and then met to compare results and reach consensus. Through a social

moderation process (Frederiksen, Sipusic, Sherin, & Wolfe, 1998), we reached 100% agreement for all codes for all drafts.

Deeper learning occurs when students construct new knowledge on the basis of their prior knowledge (Smith, diSessa, & Roschelle, 1994). In the case of the theory-building course, students refined their ideas into pattern theories that aligned with scientific conceptualizations.

Alignment with scientific conceptualizations

Students wrote three drafts of their theories over each pattern unit. I developed coding schemes to determine the structure of students' pattern theories according to the elements of the canonical scientific conceptualization that they had included. For the threshold unit, a comparison of pattern structures across drafts (shown in Figure 4.1) suggests students refined their theories over time to include more elements (i.e., *pre-phase*, *limit*, *reaction*) of a scientific threshold structure. Many students began with theories that were either focused on surface features (e.g., "Both used pennies") or included only one of the elements of the scientific threshold structure (e.g., "Both had something that had been broken, destroyed in the process"). By the end of the unit, half of the class had constructed theories that included all three elements (e.g., "Adding something to something until it changes"). A third of the class constructed theories that approached the scientific conceptualization, missing only the *reaction* (e.g., "Adding or taking something away till it reaches the maximum").

Rank scores (ranging from 0–3) were assigned to the theories based on the number of elements they included. Students' rank scores for first and final drafts

FIGURE 4.1 Proportion of theories featuring one, two or three elements of the scientific conception of the threshold pattern.

FIGURE 4.2 Proportion of theories featuring one or two elements of the scientific conception of the equilibration pattern.

were compared using the Wilcoxon signed-rank test with continuity corrections. Results showed that improvements in students' theories were statistically significant ($p = .02$).

The same method was used to analyze students' work from the equilibration unit. Comparison of pattern structures across drafts (shown in Figure 4.2) suggests students developed their theories over time to include more elements of the scientific equilibration structure (i.e., *rate* and *difference*). The class trajectory moved from theories that merely described a change in *rate* (e.g., "Starts off fast then it starts to slow down"), to ones that explained the change in *rate* as driven by a *difference* (e.g., "In large distance it goes fast, then when the space gets smaller it goes slow, then when there's no more space it stops"). By the end of the unit, 55% of the class constructed *difference drives rate* theories of the equilibration pattern. Students' rank scores for first and final drafts were compared using the Wilcoxon signed-rank test with continuity corrections. Results showed that improvements in students' theories were statistically significant ($p = .003$).

In science, it is important to communicate ideas through theories that attend to deeper structure (Hempel, 1974; Toulmin, 1958), possess explanatory power (Hempel & Oppenheim, 1948), and are abstract (Atkins, 2010). I analyzed students' theory drafts for both threshold and equilibration units using coding schemes designed to evaluate them along each of these dimensions.

Deeper structure

I operationalized this as articulating a *behavior* exemplified by multiple phenomena, rather than *surface feature* matches between their objects. Students

showed a statistically significant ($p < .002$) decrease in their inclusion of surface features (e.g., “Both involved household items”), and a statistically significant ($p = .03$) increase in attention to deeper structure (e.g., “The space is greater at first which makes it go fast”). This suggests that the course helped students shift attention from surface features to deeper-structure patterns in behavior.

Explanatory power

I operationalized this as going beyond *describing* a behavior to *providing a potential cause* for it. For equilibration, all students merely described the pattern for their first drafts (e.g., “They both start out fast and then slow down”) while over half offered a cause conceptually similar to Newton’s law of heating for their third drafts (e.g., “The space is greater at first which makes it go fast, then it slows down as the amount of space decreases”). The increase in the number of students explaining the equilibration behavior was statistically significant ($p < .0001$). The theory-building discussion, which was introduced for the first time in this unit, may have played an important role in this shift.

Abstraction

I operationalized this as using general language to describe the pattern in behavior, rather than describing it in a specific example. Over the course of both units, students improved their theories by decreasing their use of specific examples and increasing their use of general language. The decrease in specific examples was statistically significant ($p = .03$), meaning that fewer students described the pattern in the context of a particular phenomenon (e.g., “We used pennies, we put the pennies in a container, we counted, we did it again”). The increase in general language was statistically significant ($p = .02$), meaning that by the equilibration unit, students described the pattern without referencing particular phenomena (e.g., “In large distance it goes fast, then when the space gets smaller it goes slow. Then when there’s no more space stops.”). These changes suggest that the course helped students learn to craft more abstract theories.

Discussion

The results of the study suggest that given appropriate instructional support, young learners are capable of engaging in, and developing skills for, activities that are commonly considered beyond their developmental capacity. In particular, the course supported their refinement of theories in terms of *alignment with scientific conceptualizations, deeper structure, explanatory power, and abstraction*. Below, I speculate on the features of the theory-building course that may have promoted refinement along each of these dimensions.

Alignment with scientific conceptualizations

Eliciting and refining student ideas

Students constructed pattern theories that aligned with scientific conceptualizations by refining their everyday thinking. The features of the instructional approach that supported this were the activities and teacher moves that elicited students' ideas and engaged them in collaboratively making sense of those ideas. This approach is based on a theory of learning called Knowledge in Pieces (KiP; diSessa, 1993). On the KiP view, knowledge is seen as a complex system of elements. People draw on their knowledge elements to explain the events they experience. Sometimes they use one element, sometimes many. Professional scientists have been trained to draw on elements that work well together to explain their observations. Their knowledge consists of a network of elements that are reliably connected together. Nonscientists have a knowledge network that is less stable than that of the expert. From a KiP perspective, scientific thinking develops through the reorganization and refinement of the learner's existing knowledge network. A nonscientist's prior knowledge is viewed as a resource for the construction of more expert understanding. KiP instruction is therefore designed to elicit and refine student thinking.

Deeper structure

Providing examples that are closely related

For both threshold and equilibration units, students began by exploring two examples that were quite similar. They identified the pattern based on the first two examples and then tested their theory on a third example, which was more distantly related. It is possible that looking at the similar examples helped students identify the pattern, and that knowing the pattern helped them see it in the third example and the later ones they invented. In her research on analogy, Gentner found that giving novices two near-analogy examples (examples that matched both in terms of relational structure *and* surface features) helped them identify relational structure in those examples. Novices were then more likely to notice the relational structure in a more distant example (Loewenstein & Gentner, 2001). She gave the name *progressive alignment* to the process of helping students find relational structure in more distant analogies by having them first identify the relational structure in near examples.

Explanatory power

Attending to causal relationships

In the theory-building course, students were first introduced to the task of articulating a causal explanation in the context of the equilibration unit. The activity that supported this was the theory-building discussion, during which students

worked collaboratively to build a causal explanation for a particular pattern phenomenon. Their first discussion focused on a glass of cold milk that warmed to room temperature “fast and then slow.” They engaged in similar discussions for the second (hot tea cooling) and third (beans diffusing) examples, as well. The theory-building discussion brought students’ attention to the *causal* elements of the underlying relational structure of each example. According to Gentner and Colhoun (2010), looking for causal relationships (or *higher-order* relational structures) is a natural thing for people to do. The theory-building discussion therefore supports students’ natural tendency to look for causal relationships and build explanations.

Abstraction

Introducing new concepts and processes through example and experience

The students were first introduced to abstraction through an activity on vampires. In a second activity, they characterized a general category that included chocolate chip and oatmeal cookies, and possibly graham crackers and Oreos. Through this activity, they practiced writing abstract definitions of their category by using general language. Practice, when given proper guidance and feedback, leads to learning because it affords opportunities to gain a felt-sense for how to do something the appropriate way, through a process that is both guided and exploratory (Trninic, 2018).

Providing more than one example

The students were always asked to find the pattern exemplified by more than one phenomenon. Gick and Holyoak (1983) called the process of abstracting a common “core idea” from multiple analogs “schema induction.” They conjectured that schema induction involved “deleting the differences between the analogs while preserving their commonalities” (Gick & Holyoak, 1983, p. 8). In their research, they found that subjects struggled to derive schemas given a single analog, but given two, they succeeded.

Providing examples that are more distantly related

Presenting students with examples that were analogically distant helped students create theories that were abstract. As their theory had to be expanded to include more and more distant examples, elements of surface-features common to earlier, more similar examples had to be removed. This can be seen in threshold, where one student’s initial pattern theory (that was general to the spaghetti bridge and drops-on-a-coin example) had to be revised from featuring a *reaction* of “breaks” to one of “changed,” in order to include the third example, where the egg is not destroyed but rather floats.

Conclusion

The theory-building approach fosters deeper learning, communicative competence, and thinking skills. By engaging students in articulating, making sense of, and refining their ideas, theory building facilitates a knowledge-construction process that yields deep understanding of scientific patterns. By guiding students to refine their theories along dimensions that are germane to the expression of scientific knowledge, it develops their competence with scientific communication practices. By focusing on these particular dimensions, it develops thinking skills that reflect a theoretical turn-of-mind, including: 1) articulating consequential and empirically valid aspects of phenomena, 2) articulating deeper structure, 3) articulating causal relationships, and 4) abstraction.

The development of deeper learning, communicative competence, and thinking skills is interconnected. As students make sense of and refine their thinking, they get a clearer picture of a pattern's deeper structure and its possible cause. They begin to understand what aspects of the pattern are general to multiple phenomena. Their improved clarity in thinking allows them to articulate their theories more precisely along these dimensions, thereby enhancing their communicative competence. The increased precision of their theories, in turn, allows them to consider their ideas more carefully, and further refine them.

In this way, deeper learning and communicative competence are mutually supportive – the development of each leads to the development of the other. Focusing on the development of both deeper learning and communicative competence by engaging in knowledge refinement, in turn fosters the development of thinking skills that reflect a theoretical turn-of-mind. The development of these skills, in turn, supports students' construction of pattern theories that align with canonical scientific conceptualizations and are more theoretically sophisticated in their articulation. In this way, the development of thinking skills is synergistic with deeper learning and communicative competence.

Note

- 1 I chose this grouping to facilitate students' movement between pair work and small group work. Had there been an even number of students in the class, I would have used groups of four (with one group of two, if necessary).

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