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The Variability of Student Reasoning, Lecture 1: Case Studies of Children's Inquiries

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Classroom observations show variability in student reasoning, from young children through adults, even moment-to-moment for the same students in the same class. This varied phenomenology conflicts with views of naïve theories, entrenched conceptions and stages of development as stable attributes. Student knowledge and reasoning is better understood in terms of a manifold ontology of more fine-grained, context sensitive resources. Expectations of variability in student knowledge and reasoning suggest different approaches and objectives in instruction, especially in early science education.

This is the first lecture in a series of three. It introduces the overall agenda and then begins with a series of examples of children's inquiries to reflect on the beginnings of scientific expertise.

1 Introduction

Several years ago a story broke in the newspapers about a grossly unethical experiment conducted in 1939 on the causes of stuttering [1]. Wendall Johnson, a speech pathologist, had developed a "diagnosogenic theory" that a principal cause of stuttering is its diagnosis.[1] That is, he thought, children can become stutterers as a result of caregivers' worries over ordinary flaws of speech. To test this hypothesis, he assigned a graduate student, Mary Tudor, to conduct a study for her masters thesis. She identified 12 normal speakers from children at an orphanage and split them into two groups. The experimental condition, for six children, was to tell them they were at risk of stuttering, that they should monitor their speech carefully, and in a series of sessions provided "therapy" to correct the children when they repeated a word or misspoke. Tudor also identified these children as potential stutterers to their teachers and asked the teachers to help monitor and correct the children's speech.

The experiment, according to Tudor's thesis, was a success: Five of the six children began to show signs of "disfluency." The formal study only lasted for the spring of 1939, but teachers were unaware it had been an experiment and continued to correct the children's speech for more than a year. Whether it was a result of the study or not is in dispute, but several of the children in the experimental group grew up to be lifelong stutterers.[2] The experiment came to be known as the "Monster Study."

We don't need a connection to disfluency in speech to generate our own hypotheses about disfluency in physics. Still, the comparison may provide some perspective. The ethical violations are obvious for the Monster Study, but the analogous "treatment" in physics instruction is simply routine: From early grades through university, science educators attend carefully to the correctness of students' thinking, judging it with respect to the established canon. And disfluency in

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[1] "Diagnosogenic" isn't a word; the accepted term would be "iatrogenic": a iatrogenic disease or symptom is one caused by medical treatment. (Finders fee to Joe Redish.)

[2] The study was never published, although secondary accounts of it have been [2]. Some researchers [3] discount the findings in favor of accounts rooted in genetics and brain structure.

physics—"failing in basic logic or common sense" would be a reasonable definition—is a familiar phenomenon.

It only seems reasonable, to focus on correct understanding, just as it only seems reasonable to focus on correct pronunciation. Even progressive educators assess learning primarily by reference to the canon. There has certainly been progress: Reformed curricula have made important changes that reflect insights into students' prior knowledge and the importance of active engagement for learning.

Still, the objectives remain centered on a traditional view of content, and learning seen as a succession of concept attainments. While there have often been calls for greater attention to teaching science as inquiry[4-6], such objectives and assessments remain subordinate to the traditional ones of content. Moreover, these views of content and learning pose particular challenges for thinking about progress in early grades. In physics, the most "basic" ideas are also the most subtle. The basic concepts of a Newtonian framework—force, mass, acceleration—are not complicated ideas built from a hierarchy of simpler ones. On a traditional view of science as content, it is difficult to frame objectives for children, beyond those of interest and engagement.

My ultimate purpose in these lectures is to propose an approach to conceptualizing progress in physics from children's inquiry to professional science. In that I shall take "inquiry" in physics to be *the pursuit of causal, coherent explanations of physical phenomena*, and I shall frame progress as the cultivation of various "resources" for engaging in that pursuit. In this way, I hope to move beyond correctness by the canon as the sole or overriding concern in instruction.

That approach, however, is founded on a view of student knowledge and reasoning as *variable and manifold.* This represents a shift from the predominant perspectives in science education, of students knowledge and reasoning as generally *coherent and unitary*. For most of these lectures I shall be trying to motivate, support, and develop this shift, with discussion at the level of phenomenology—what sorts of things do we see happen?—and at the level of ontology—what sorts of cognitive structures do we attribute to learners?

I begin with a brief, personal anecdote, which may help motivate this work and give a feel for the perspective.

1.1 "Why did that happen?"

Six years ago I was sitting at the dining room table with my five-year-old son when a drawing of his fell from the wall where it was taped. We laughed, asked each other "why did that happen?" and started to talk about possible explanations. "I think it was Molly," I said—my ideas were mostly silly: Molly is a dog and she was on the other side of the room. He laughed at that: "How could Molly have done it?" And from there we took turns tossing out ideas. Maybe it was the wind? (But the window's not open!) Maybe bugs pushed it off the wall? (Where would the bugs come from?) Maybe worms ate the glue. Maybe the glue soaked into the wall. Maybe the glue dried up. And so on—we never arrived at a conclusion or even tried to frame a testable hypothesis. We were just "messing about," as Hawkins [4,7] put it.

But it's not a big stretch to imagine a connection between our messing about and professional inquiry. To pick an example, Jocelyn Bell was studying chart output from her radio telescope when she stumbled on something that made her wonder "why did that happen." The purpose of the study was to look for variations in source strength ("twinkling") from radio signals passing through solar wind. What she saw was a regular signal with a period of about 1 1/3 seconds, when the antenna was oriented toward one part of the sky. And so she thought through possibilities. Maybe it was a problem with the equipment? (But why that period?) Maybe the antenna was detecting some kind of manmade source? (But why would it come from only that part of the sky?) Maybe it was from a geosynchronous satellite? Maybe it was an astronomical source? (But how could an astronomical source have such a short period?) Thinking about the possible causes of the signal meant a kind of shopping for ideas that seems similar to what my son and I were doing. It even included the silliness: Bell named the source LGM-1, for "Little Green Men," after one of the ideas she and her colleagues jokingly considered.

Of course, there are extensive differences as well. Bell had a much more richly developed body of ideas to consider in her shopping for possibilities, informed by her studies and experience thinking about radio signals and their possible causes. She also had a more richly developed understanding of scientific approaches to checking ideas for consistency, empirical and theoretical. She was systematic in ruling out possibilities. Manmade sources seemed less and less likely as she determined the signal came up once every sidereal day, not solar: "So if it was Joe Bloggs going home from work in a badly suppressed car, he was getting home about four minutes earlier, each night." [8] She ruled out little green men by the appearance of other similar sources in different parts of the sky. Eventually she decided it was an astronomical source and looked to the theoretical literature for help in understanding what that source might be. (She had discovered pulsars.)

Could that messing about with my son have had any value for him as science education? If "scribbling" with crayons can be the beginnings of art, perhaps this kind of play with explaining phenomena can be the beginnings of science. Supposing it did have value, what might the value have been?

One possibility is that by going through all the silly and not-as-silly possibilities we were making a quick scan through various kinds of mechanism. That might have been valuable as practice with the different particular ways of thinking, such as the idea that something would have to happen to the glue, that it wouldn't just disappear. It could also have been valuable as a kind of inventory-taking of the different sorts of mechanisms that are available for explaining things, like rummaging through a tool box to see what sorts of tools are there. Worms eating glue would not really apply here, but the idea of small organisms eating some important substance could certainly come up elsewhere! Trying to figure out the cause of the periodic blips, the first thing Bell did was to brainstorm about possibilities for what might cause it, and no doubt the possibilities that occurred to her included many mechanisms she had considered in other circumstances.

Our messing about could also have had value for my son's forming a sense of what an explanation ought to do. I was glad he thought my idea about the dog was absurd: We didn't know of any mechanism by which she could have affected the poster from the other side of the room. Other ideas did involve mechanism. If there had been worms or bugs on the wall, they could easily have played a role in the poster's fall. Maybe the game contributed to his sense of how a "serious" explanation should provide a tangible mechanism? Maybe, too, it contributed to his sense of this kind of activity, this brainstorming of possibilities. In my college courses I encourage students to go "shopping for ideas" in their knowledge and experience, to try to get them to do this kind of thing; many do not realize how many "wrong" ideas a scientist like Jocelyn Bell will think through in trying to sort out a problem. We didn't name it brainstorming, or anything else, but it is at least worth supposing that the experience of having that sort of conversation (with a science teacher!) would contribute to his forming a sense of it as a way of getting started on a question.

In other words, we might think of the conversation as providing a bit of (1) practice with different pieces of mechanistic knowledge; (2) practice with a kind of activity; and (3) awareness of the knowledge and the activity. In what follows, I'll refer to resources of these various kinds: (1) conceptual resources that make up knowledge about the physical world, (2) resources for reasoning with and building from that knowledge, and (3) epistemological resources for being aware of the first two.

In sum, our conversation could represent an entry into inquiry about physical phenomena. This one involved play with ideas about causal mechanism. Another sort of entry activity could involve play with ideas about coherence—empirical coherence in games that try to identify parameters that reproduce an outcome ("Watch this! If I yank the paper hard it comes out from under the book!") or theoretical coherence in games that explore implications ("This pot is the biggest, and this stick is the biggest, so that should be the loudest."). Still others should involve play with ways of representing ideas, of gathering information, or debating a point from different perspectives.

1.2 The three lectures

The program I am promoting is to identify resources for learning and understanding physics, hopefully toward an organizing scheme to complement the traditional canon for educators planning and assessing science learning from early grades through university. My main objective is to present and argue for a resources-based perspective on student knowledge and reasoning to motivate and explain what it means to understand student thinking as variable and manifold.

The first two lectures are phenomenological, presenting examples of student inquiry from grade school through university introductory physics. In this lecture I focus on children, highlighting what they say and do that looks like the beginnings of scientific expertise. The second lecture focuses on the variability of student reasoning, beginning with examples of college students apparent inexpertise and proceeding to examples of variability in the form of transitions over short time scales. In the third lecture I turn to ontology, to argue for a manifold view of cognitive structure and to consider the implications of that view for early science instruction.

2 Classroom examples of children's inquiries

For the rest of this first lecture, I focus on inquiry among grade school children, to give a general appreciation of the sorts of things children are capable of doing, which go well beyond commonly-held expectations. I present a range of examples, from first grade (6-7 year-old children) through eighth (13-14 year-old students). Individual case studies can be impressive, but they are always vulnerable to the concern that they are not representative, that the children were unusual, and so on. At this early level of theory building, it is difficult to encapsulate data about many children concisely—indeed, one contribution to the systematic underestimation of children's abilities may be premature commitments to particular measures of cognitive development in the interest of large data sets. If, as I contend, we do not yet have a sound theoretical framework for understanding children's abilities in science, it is useful to examine phenomena at varying levels of detail. These lectures are an opportunity to scan through a range of examples, to give a sense of the sorts of behavior and reasoning a theoretical framework should be able to consider.

The examples are from *Case Studies of K-8 Student Inquiry in Physical Science*[3] (SIPS), a collaboration among a team of K-8 teachers and university faculty, post-doctoral research assistants, and graduate students. The project was funded to produce case studies of children's inquiry as professional development materials, to help current and prospective teachers learn to recognize and respond to the substance of children's thinking. For three years, we met in three-week summer workshops, part of which we devoted to engaging the teachers in scientific inquiry and discussing what that entails. During the school years, we met every other week in two hour sessions, working in groups to discuss "snippets" of data from the teachers' classes, typically videotapes classroom conversations. The teachers then chose their favorite snippets to expand into case studies, and the second task of summer workshops was to work on revising these into publishable form.

I review three examples of children's inquiry at different ages in modest detail. In each case, I begin by presenting some of the data—excerpts from what the children said and did—and then I turn to reflect on what we might see in that data. To give a further sense of the breadth and richness of possibilities in children's inquiry, I supplement these three main examples with very brief summaries of others.

Some readers will want more details about individual cases, including and maybe especially about the ones I present in more but still not enough detail. The trade-off of trying to scan through many examples is that it is not practical to present them thoroughly, and even the longer descriptions are a compromise. Many of these examples are or will be presented more thoroughly elsewhere, and I provide references when available.[4]

Some readers may find it useful to skim section 3 ("The beginnings of scientific expertise") before proceeding, to have a sense of what sorts of things they might look for in these examples. Readers inclined to skip examples should at least read 2.3 ("Third grade students discuss earthquakes"), which will come up again in the third lecture. For those readers who have not spent much time listening to children's inquiry in science, it may be worth taking the full tour.

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[3] This project is funded by the US National Science Foundation, grant # ESI-9986846, D. Hammer and E. H. van Zee.

[4] We are in the process of choosing and editing case studies for a book that will present them along with video on digital media. There will only be space for a dozen cases, and at present we have not made the final selections which ones to include. Most of the examples I describe here are candidates, and the final set will likely include several of them.

2.1 First graders discuss whether a seed can grow in sand

Jamie Mikeska's first-grade students were conducting experiments in botany, planting seeds in different conditions as part of the school's science curriculum, when a student raised the question of whether a seed can grow in sand. Ms. Mikeska decided it was a good question for a class discussion, and asked the students what they thought.

Maxwell started the discussion with the idea that sand "doesn't have the protein that soil does"; he thought protein is "like the food." Arden said he agreed, adding his idea that the sand could blow away in the wind, then went on to talk about how sand soaks up water.

> Arden: Cause sometimes when I see some stuff come out of my mouth that's wet and it drops on the sand it's a little round dot of water and the sand is like sucks UP the water. It like keeps it to itself like takes the water away from the seed and the seed doesn't have any water but the sand does.
> Teacher: What do you guys think about Arden's idea? He brought up a little bit of a different reason. He said if you put water in the sand, if you put the water in the sand, what's going to happen. What's he saying is going to happen?
> Jeremy: Um, the sand takes it away.
> Teacher: Takes it away. What is it taking it away from?
> Arden: The water – it's like keeping the water to itself.
> Teacher: And so that seed in the sand—?
> Eleanor: Is just left alone without the water that helps it grow in soil. Because the soil is like hard and water is like blocked. Like with all those sticks and stuff – it's real hard so the water won't get through. But in sand so usually sand will be blown away not sticks into the sand – it's easy that it's not blocked so it just goes – shhhhhwwweee (sound effect)
> Teacher: Do you want to call on one of your friends that have their hand raised?
> Arden: Bobby?
> Bobby: I don't think that the seed will grow in sand because, um, it doesn't even hold water that good. It just like goes right out.
> Teacher: So that's similar to Arden's, no, that's different from Arden's idea. Because Arden is saying that when the – you put water in the sand it takes it all but you're saying that the sand can't hold water? What do you mean by that?
> Bobby: Pretend this is the sand and this is the water. It just goes out.
> Teacher: Oh. It'll just go straight through the sand.
> Bobby: Mm-hmm. (Yes)
> Teacher: Which is a little bit different from what Arden thinks.

Several minutes later, Tammy entered with her idea.

> Tammy: There's an idea that I had. Maybe if you, even if you put a seed in the sand, it won't grow because there's not food for the plant.
> Eleanor: You agree with Maxwell?
> Teacher: Eleanor, say that more loudly.
> Eleanor: I think I think that she's agreeing with Maxwell.
> Teacher: What makes you think that?
> Eleanor: Because. Because they're similar. They're similar.
> Teacher: How? How are – how is Tammy's idea similar to Maxwell's
> Eleanor: I don't remember what Maxwell said though.
> Teacher: Do you want to remind her Maxwell?
> Maxwell: Uh. That it won't grow because sand doesn't have the protein. Soil has the protein. That soil has for plants.
> Eleanor: But he added protein and she didn't. But they're still similar – cause she just – even though she just said food he said food too and that's similar. I think she's agreeing. Because they're similar by what I'm hearing with my ears.

Within a few minutes, the students considered several different reasonable ideas about what could affect a seed's growing in sand. The first concerned the presence of "protein," which Maxwell said was "like food" and thought would be in soil but probably not in sand. Perhaps he was applying an idea from earlier in their unit, that sand is made up of tiny rocks; perhaps he had some kind of sense of the difference between organic and inorganic materials. A little later, Tammy expressed a similar idea, as Eleanor noted, but without using the word "protein."

The students other ideas were of physical mechanisms. Arden first thought of sand blowing away but quickly turned to the more interesting idea that the sand would "suck up" water, based on what he had noticed happens to his spittle, dry sand absorbing the moisture. The seed wouldn't get any water because the sand would "keep it." Eleanor described a different mechanism, although it was not clear whether she thought it was different. She explained that soil is "hard" and "blocks" the water, "so the water won't get through." She went from there to agree with Arden's first idea about the sand being blown away, which she might have been elaborating: If the sand blows away, it isn't there to hold the water. She might also have meant what Bobby went on to say—he probably got the idea from her—that sand doesn't "hold water that good," so the water "just like goes right out." That is, the seed won't get water because sand doesn't contain (block) the water the way soil does.

It is also worth noting (because there will be examples otherwise with older students in lecture 2) that these children were thinking about the question in ways that drew on their other knowledge and experience, about living things needing food, about experiences with sand. They were explaining their ideas well, at least with Ms. Mikeska's help. In several places she asked students to explain their meaning—Maxwell about protein, Jeremy about "taking it away," Bobby about "can't hold water"—and the students responded helpfully.

The children needed the help Ms. Mikeska was providing to recognize similarities and differences among their ideas. Eleanor and Bobby had not acknowledged that they were describing a different idea from Arden's. Neither did Tammy notice that she was agreeing with Maxwell, although in that case it was Eleanor who pointed out the similarity, a point Ms. Mikeska highlighted in her case study and during class.

2.2 Other examples, grades 1-2

The concern often arises that the children in any given case are exceptional.[5] One way to respond is to note that these were students in a socially diverse public school, with no tracking for ability. We have other evidence in our project in the breadth of examples we find of children's expertise.

Ms. Mikesaka was the only teacher in the project working in third grade. The previous year, one of her snippets presented first-graders discussing the question of which would hit the ground first, a piece of paper or a book, if they are dropped at the same time. The class all predicted that the book would hit first, because "it has more strength", as one student explained: "Because if you put it on, um, the things that you weigh yourself on, the paper is going to weigh nothing but the book is gonna weigh like one or three pounds." In another line of reasoning they said that the paper would "float" because "the air is blowing it. Then they went to try it, and in some cases some students reported they had seen the paper fall first, other students reported "the book and the paper tied—twice." The students' reasoning centered on two different senses of mechanism, the "strength" or "force" causing the fall and the "blowing" air resisting. They showed a variety of stances toward reproducibility, with

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[5] Another that often arises is that not all of the children are actively engaged. This is certainly a valid concern in an assessment of instructional practices, for all of the children to be engaged, but there are several reasons to set it aside here. First, it simply does not make sense over intervals of time as small as these excerpts represent. It can take several conversational turns to understand an idea; for young children who are learning to be articulate it can take more. Moment-by-moment there must be a trade-off between engaging all students and genuinely attending to the substance of their thinking—and modeling for them what this entails. Second, it is a mistake to expect that participation means speaking. Someone observing the first segment of Ms. Mikeska's class would likely have included Eleanor among the students "excluded" by the teacher's focus on Maxwell's thinking. (On the video, she is not looking at Maxwell; her eyes are wandering in other directions and she has her fingers in her mouth). In this instance we have evidence of her participation in that moment. Third and last, this lecture is not an assessment of instructional practices, and I am not providing enough information for that purpose.

one group emphasizing that they had repeated their experiment and others willing to accept that different students' results need not agree, and they showed abilities to keep track of each others' perspectives, to the point that students would restate other students' points of view.

Kathy Swire's second graders had a discussion about magnets that surprised us in the project—we had come to think of the topic as a dead end for small children. Playing with fairly strong button magnets, Ms. Swire's students noticed that one magnet could stick to one side of someone's hand if there was a magnet on the other side. This sparked a discussion about how that could happen. One student thought it was because there is metal in our bodies, and another agreed, saying he'd seen metal on people's bodies in an x-ray. Others disagreed, arguing that if we had metal in our bodies, a magnet would stick by itself, and the person in the x-ray "was probably wearing something" metal. A student suggested that the magnetism was "like electricity," but was careful to clarify that it was only similar. The students expressed but did not resolve their puzzlement about how "power" could pass through someone's hand without hurting it. We were impressed by their persistence in trying to connect the phenomenon of magnetism to other experiences, in looking for familiar, tangible explanations for what they were seeing, and in their abilities to hear and respond to each others' reasoning.

2.3 Third grade students discuss earthquakes

In this case study, Pat Roy's third-grade students explored their first ideas for what might cause an earthquake.[6] Children had offered various ideas, mostly in a brainstorming mode, of what might cause an earthquake. Many of their ideas involved cracks in the ground and "disturbances" of some kind either causing the cracks or resulting from them. At one point late in the discussion, Skander was thinking of a disturbance that could cause the ground to "crack open and then squeeze out the lava." Ms. Roy checked with him to be sure he was talking about an earthquake and not a volcano. Skander then had a particular idea.

> Skander: That, um, that there might, you know if the ground is closed and there's lava like a giant rock, er a giant rock, might fall into the lava and which would cause the lava to go up because it's pressing it to go up.

A couple of other students spoke about their sense of what the disturbance could be, and then Skander elaborated on his.

> Skander: Another thing that can, you know how if you fill your water up and you put like too many ice cubes in it, it can flood.
> Teacher: Mm hm. [Yes]
> Skander: That's what I mean. A rock could, like, the volcano is this big [motions with hands] and you're on this side of the ground, a rock could go in, and pretend like, pretend the lava is water and the giant rock is a cube it goes up and since it's blocked the ground has to shake which causes it to crack open so it it'll actually like go up farther.
> Teacher: Okay, so you're—
> Skander: So it's like you're actually flooding the cup of the water.
> Teacher: And so the rock acting as the ice cube is flooding the lava so it has to come up and go out?
> Skander: It doesn't have to, it just makes the ground come, it just needs space to go up. It's just causing it to shake and crack open.

At this, other students spoke up to challenge Skander's idea. Hugo disagreed because "the lava will make it [the rock] melt," because it was "like acid." Louis elaborated on Hugo's objection, saying the rock would melt "automatically melt, melt right when it touches the lava." Ms. Roy helped Louis clarify that he saw a difference between the lava and the ice cube in that the rock would melt before it had a chance to push the lava up, unlike the ice cube which would melt more slowly. After a bit, Skander had a response to this reasoning.

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[6] A more thorough treatment is forthcoming.[9].

Skander: I kinda agree with Hugo and Louis, but I also agree with myself because if the lava's right here and the ground was right here, the rock would actually go into the lava but melt but cause more lava because when it melts, it's like, it's like you're adding more lava and it'll cause, it still crack to make an earthquake—
Teacher: Okay, very interesting.
Skander: —because it's a solid.
Teacher: Because it's a solid?
Skander: It could melt and make more lava.

Some educators will immediately recognize and want to address the common misconceptions about earthquakes that the ground cracks open and lava comes out; the children were not making much progress toward a geologist's understanding. I shall return to this concern in lecture 3. Here, I continue the approach of considering what aspects of the children's reasoning might reflect productive beginnings of scientific expertise.

At the core of this exchange were ideas about physical mechanism that would be useful in many other contexts. First was the reasoning that an object pressing down on a fluid (lava or water) in one spot will cause the fluid to rise in another. At that point Skander was talking about forces, how the rock would be "pressing the lava to go up," the way one might talk about a lever, pressing down on one end making the other end rise. Second was reasoning about how the heat of the lava, or its intensity in some more general sense that would also include "acid," would cause the rock to melt. This included a sense of the time scale involved—Louis thought the rock would melt immediately on contact with the lava, probably thinking of the lava as especially potent. Louis was also reasoning about relative time scales: The rock would have to remain a rock for a moment in order to press down on the lava as Skander had suggested. Finally there was a notion of conservation in Skander's reasoning that a melted rock would produce more lava, which would still "take up space." Tacit in his reasoning are more ideas about matter and phases, including that fluids take up space. On this way of thinking, the time scale is no longer important; all that matters is that the melted rock still takes up space.

There is more to appreciate about what is happening. The students in this exchange are considering the situation based on their sense of physical mechanism, rather than, for example, anthropomorphic thinking about the earth "shaking with anger" or "snoring." Such ideas are valuable as poetic metaphors, but they are further away from scientific thinking than the ideas about physical mechanism the students were expressing here. Part of scientific expertise is learning to differentiate mechanistic explanations from others.

This is also another instance of a student drawing on everyday knowledge and experience, the ice cube in a glass of water, to help him think about his idea or perhaps just to help him explain it. Skander was explicit that he was making an analogy — "pretend the lava is water…"—and his classmates recognize this is a legitimate, appropriate move in the conversation. When Hugo and Louis object, they do so with specific reasons: The rock will melt, and it will melt too quickly to be able to press down on the fluid. They might, instead, have objected in general to the analogy, that knowledge from the dinner table can't be useful for thinking about what happens underground. (Again, this is worth noting because of what happens later, college students resisting the use of analogies to familiar situations.)

2.4 Other examples, grade 3

The previous year, one of Ms. Roy's snippets was of her third-graders talking about whether star-shaped, square, or triangular wands will produce bubbles in those shapes. Zoë tried to explain why she thought they wouldn't: "Because it can't get all the sides it's supposed to get. If it was blown in that, it would just be, it would be like it is flat." Several boys talk about having tried it, two reporting the bubbles came out as circles, one that they came out as rectangles from a rectangular wand. Samantha expressed the strength of her conviction by saying that even if she "tried it and it came out the shape" of the wand, she still "wouldn't believe it." She too had trouble articulating exactly why, but she thought it had something to do with "the corners. . . it'd be silly… if you tried to touch the corners, it'd pop." Samuel later suggested trying an oval wand, to have something that is not a circle but that doesn't have corners. Like Ms. Swire's second graders talking about magnets, Zoë and Samantha were trying to explain a mechanism for why bubbles would come out round; Samuel proposed an experiment that would isolate corners as a factor.

Trisha Kagey's had shown her third-grade class how the petals of a white carnation turn red if the stem of the flower sits for a long time in water colored with a red dye. She started them thinking about possible "models" for how that happens, explaining what a model is and priming the discussion with two possibilities: The stem acts like a straw, sucking up the water, or it acts like a sponge. Working in small groups, the students came up with their own ideas and questions. Some thought about what would do the sucking, if the stem is like a straw, and their ideas included the petals themselves or a breeze blowing across the flowers. Some wondered why the *stem* doesn't turn red, too. During presentations, Lauren explained her group's modification of the sponge model. She showed a diagram of many little sponges, stacked along the stem, and explained how each would soak up the red water and then squeeze it out to the next sponge. Like Skander, they were comfortable with using everyday knowledge and experience as a basis for generating ideas about something unfamiliar.

Cynthia Cicmansky's third-graders were thinking and experimenting with the question of whether hot water would cool more quickly in a tall, thin container or a short, wide one. After a time interval of cooling, they found that the water in the tall container was at 115 degrees (Fahrenheit) and in the short container 110 degrees F. They had various ideas about why—like other classes who worked on this question they talked about cool air touching or mixing with the water and about hot air coming out. Tommy noticed, though, that if he put his hand over the short wide container it felt *warmer* than if he put his hand over the tall thin one, although the thermometers said the tall cylinder was hotter. The class was persistent in trying to reconcile this inconsistency, and they had several new experiments to suggest. (They did not, however, complain that Ms. Cicmansky should tell them the answer.) Like Ms. Swire's students thinking about magnets, they expected there must be some *reason* for what they were observing and they wanted to figure it out. That, in itself, is an aspect of thinking to recognize and support.

2.5 Fifth/sixth grade students discuss a dropped pendulum

Mary Bell, in her first try at having a more open discussion on a topic in science with her students, presented her combined fifth/sixth grade class with a question we had discussed during the summer workshop at the start of the project. She had a string with a metal washer on the end, swung it back and forth as a pendulum, and she asked the students what would happen to the washer if she let go of the string when the washer was at the highest point of the swing.

We have presented more of this discussion elsewhere [10]; here I begin at a point several minutes in, after Victoria presented her answer. Chris and Ike had drawn their ideas for what would happen on the board. Chris thought the washer would go out from the point it was released and then turn downward in a smooth arc; Ike thought it would move *up* and out from that point, and again turn downward in an arc. Students in the class took one side or the other, choosing from these two options, until Victoria spoke up with a third.

> Victoria: I disagree with all of them because I think that if you cut it at the top, then it's like gonna kind of curve and then come straight back down.

Ms. Bell asked Victoria to draw her idea on the board, and while she did Amber spoke.

> Amber: I agree with her because if it's going fast or something, and you cut it, it might curve around because it was going so fast the speed allows and the speed allows it to come back up so forceful.

Victoria had drawn a vertical line down from the endpoint of the swing.

> Teacher: Okay well Victoria, and correct me if I'm wrong Victoria, you're showing that you think that once we cut it, it's going to come straight down.

Victoria: Yes, because I think, that it's gonna, like the string, gravity is gonna push it down and the string is gonna kind of curve and then just come straight down to the bottom.

Teacher. Okay, so the string might curve a little bit but the washer is going to come straight down. [Several student voices.] Wait, we haven't heard Jeff.

Jeff: I agree with Victoria because the washer is a lot heavier than the string, and the washer will come straight down.

Brandon: I disagree with Victoria because, and I kind of agree with Ike because if the washer, and if you swing it, and it's at the top point, it's gonna go flying up some and then it's going to drop down.

Shadawn: I kind of agree with Amber because like, it depends on how fast, how fast it's going. Because I think like if you, if it's going really fast and you cut it, it's gonna fly somewhere and do all the curves and stuff but if you, if it's going really slow and you cut it, I think it's just gonna go straight down.

Teacher: Shadawn can you tell us why you think that? Is there is something that you know of that maybe makes you think that?

Mathew: Can I say something? I agree with um Shadawn because it's kind of like, you, you have a little, like you know how some times on movies and things and real life like that, they have lakes or swimming pools and you have a little rope and you run and grab on to the rope and then fly and then let go and you go flying over to the side? That's just like that, the washer. It depends on how much force is on it.

Vanice: Not exactly Mathew, because the pendulum is, I mean the washer is tied to the string so it won't go to the other side.

Mathew: But she is cutting it, or she'll let it go.

Vanice: I know but it still not gonna go to the other side because it's hooked together, if there wasn't hooked together then yea it might go to the other side, like the string would still be in your hand and the pendulum, I mean the washer will go somewhere else.

Mathew: I know that. It's kind like, it's kind like, um, the person flying off of it, letting go and going into the water.

Vanice: I know but it's not connected I mean it's connected so that wouldn't work.

Grace: Well um, I agree with Chris because it can't really go up more because like gravity doesn't go up. And like I don't think it can just go straight down because I think you were swinging it.

Mathew [over other voices]: Well, I disagree because um, I disagree with Grace because, because it's kind of like you throw a bucket or a ball up in the air, gravity is coming down, forcing it to come down but you still, it's still going up.

Depo [over other voices]: I disagree with Mathew because like gravity always pulls you down. Like if you throw it up, like that's, that's your force, but if you just leave it alone, it will just come down.

Mathew: That's what I'm trying to say, that it's the person who pushes it, how fast they goes, that it determines how high it goes. Like if it goes [sound effect and gesture showing a fast swing] fast, it's going to go flying out [gesture showing bob flying out].

In all the students spent about 45 minutes on the question. Writing her case study, Ms. Bell was impressed by how much more quickly the students came up with this range of ideas than had the teachers during our summer workshop.

Again, we can recognize aspects of mechanistic reasoning. Several students thought in ways McCloskey[11] and others have described, associating motion with force—a sense that the motion of the pendulum on its way up comprises a force that will continue to move the pendulum if the restraint of the string is released. Shadawn and Depo argued that the higher the speed, the greater the effect, an insight that later would support Victoria's argument, as students came see that the washer slows down toward the end of the swing. Several students, too, speak of gravity as acting downward. Some may also have had a sense of a kind of tug-of-war at the end of the swing, between that outward force of motion and the inward tension of the string, so that if the string is released the outward force wins. In general, as in other discussions above, the students seemed to struggle with explaining ideas that are difficult to articulate. As in other examples, the elements of physical mechanism they were considering are all useful in some situations.

And again, there is more to notice about what they were doing. For much of the discussion they continued with a high level of energy and enthusiasm, drawing on their own various ideas for what will happen. They did not, as adults often anticipate, turn to the teacher for the right answer. Victoria was willing to speak up against the general consensus in the room. Shadawn and Depo were considering the role of a specific factor. Mathew was the first to draw explicitly on everyday knowledge and experience, in his comparison to rope swings.

Like Hugo's and Louis's objections to Skander's analogy, Vanice's concern about Mathew's analogy was specific: Someone on a rope swing lets go of the rope at the bottom, but in the case they were considering the string is connected to the washer and released at the top. Vanice may have had a sense that the falling washer will move differently trailing the string than if it were not.[7] Grace argued that the washer could not go up "because gravity doesn't go up," possibly intending to say that the washer would not go up *further* than the end point, because there would be nothing to make it do that. Mathew, taking her literally, drew on common sense again to respond that if "you throw a bucket or a ball in the air," it does go up for a time, although gravity "is forcing it to come down."

As the conversation proceeded, more students became convinced that the washer would fall straight down, and at the end of class Ms. Bell helped this by demonstrating with the string and washer. More important to this analysis, however, are the ways they were thinking along the way. They were discussing different ideas of physical mechanism, drawing on everyday knowledge and experience, trying to be specific and precise in their reasoning, identifying and trying to reconcile inconsistencies.

2.6 Other examples, grades 5/6 and 8

Ms. Bell had a similar experience at the start of each year we worked with her in the project. Last year she posed another question from our summer workshop: If you're running with a set of keys and you want to drop them in a basket, should you let go of the keys before you reach the basket, when your hand is right over it, or after you've passed it? Again, the students quickly produced a range of arguments. In an early exchange, one student said that you'd need to release the keys after passing the basket, because that was his experience running—things go backwards if you drop them. Hannah felt it should be before, because "the force of when you were running when you let go of the keys" would make them "travel a little forwards before they landed." Abdela supported that reasoning with an example from something he'd seen on television game show. Casey answered the first argument to say that "it's not going to go back…you just think it will go back because you're running [forward]."

We have many other examples at grade five, but I turn to eighth graders for the last two quick examples. Steve Longenecker's class was starting a unit on chemical and physical changes. He used a sodium bicarbonate tablet in water as a prototypical chemical change and glass beads in water as a prototypical physical change. The class talked about whether salt dissolving in water was more like the bicarbonate tablet or more like the glass beads. Most thought it was like the bicarbonate, because "it actually mixes with the water," as Alex put it. Lincoln elaborated that the added salt does not take up "space" the way glass beads do. Christine gave another reason, that with the beads "you can just put your hand in and take them out," while you can't with the salt or the bicarbonate. Mr. Longenecker identified her reasoning as "reversibility," and later in the conversation Sam used Christine's reasoning to come to the other conclusion. He thought the salt would be more like the beads because "you can evaporate the water and get the salt back," but the bicarbonate tablet "turns into a gas… and you can never get them back."

Jessica Phelan had asked her eighth graders to work without her to come up with models of the "rock cycle." One group was making good progress: Lava cools to make igneous rock, weathering erodes that rock and layers of sediment accumulate at the bottom of the sea where it gets "cemented" into sedimentary rock. At that point they wanted to understand how the sedimentary rock turned into metamorphic rock, which they knew involved heat and pressure. Pressure was easy: The bottom layers would be underneath many other layers. But why would it get hot? The bottom layers weren't any closer to the heat from the Earth's core, because the sedimentary layers build up, not down. And

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[7] If the mass and aerodynamics of the string aren't negligible, then Vanice is right.

even if the bottom layer is heated, how would the layers above it get hot? One student suggested they move on, so they could finish the project, but others in the group wanted to work on the question. Keren came up with an answer that Lisa demonstrated with her hands and shoe: Plates of rock underneath the sedimentary layers could separate, and the sedimentary rock could fall in between.[8]

3 The beginnings of scientific expertise

To take a constructivist view of knowledge and reasoning is to believe that children construct new understandings and abilities from the understandings and abilities they already have. It means seeing children's minds as fertile and generative, rich with raw material from which to construct. If we want children to make progress in science, we should study their reasoning for that productive raw material. What can we see them doing that could be the beginnings of the expertise we hope them to develop?

A look across this set of examples gives a sense of the extent and variety of those beginnings. Consider, first, aspects of their sense of physical mechanism, and the signs of some children's ideas about:

- *sucking*, in 3rd grade ideas about carnations—there needs to be an agent doing the sucking;
- *absorbing*, which doesn't need an agent, coming up in the 1st grade discussion about seeds and again in the 3rd grade one about carnations;
- *forces causing motion*, in 1st or 5th/6th graders dropping objects;
- *forces resisting motion*, in the 1st or 5th/6th graders thinking about the effect of air blowing on paper or keys;
- *blocking* or *transmission* through material, the 1st grade ideas that soil blocks water but sand lets it flow, or the 2nd graders thinking about how magnetic "power" can travel through hands, or 8th graders thinking about heat blocked or transmitted by rock;
- *conservation of matter/volume*, in 3rd graders thinking about ice melting into water and rock melting into lava, or in 8th graders thinking about how glass beads take up volume in water but salt does not;

That's a partial list, all aspects of children's sense of the physical world they could build from and refine toward expert understanding. Conversations such as these give children opportunities to explore the different ways they have of thinking about physical causes and effects, to become aware of ideas that are usually tacit—about *sucking* or *blocking* or *conserving*. Given the chance to explain and defend his view of what causes an earthquake, Skander had to think through his sense of what happens when a solid melts, to see a connection between rock melting into lava and ice melting into water, and then to articulate that reasoning to others.

At the opening of the paper I gave the example of my son and me playing with ideas for what could make a poster fall from the wall, and I gave the example of Jocelyn Bell's more serious work thinking through ideas for what could cause a periodic signal she observed. One of the differences I noted was her far more richly developed set of possibilities—she was aware of many kinds of mechanisms, had thought about them in many situations, and was familiar with their attributes. It is at least plausible that conversations such as these can help children make progress toward that kind of familiarity with different physical causes and effects. Having thought through an idea in trying to solve one problem, even if the idea does not end up being useful in solving that problem, may help a student use that idea in other situations.

We also want children to understand physics as involving this sort of reasoning and conversation, of brainstorming through ideas, arguing different points of view, thinking in ways connected to their everyday sense of the physical world. On the whole, research in physics education has devoted far more attention to the level of conceptual knowledge, on science as a body of knowledge explored by inquiry—inquiry as a pedagogical choice. But inquiry is more than a pedagogical choice for teaching "content"; it is, itself, part of what we are hoping students to learn. To that end, we need better conceptualizations of learning science *as* inquiry [4,5,7,13].

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[8] An extended account of this discussion is forthcoming. [12]

What could we see in these examples about how children are able to participate in "the pursuit of causal, coherent explanations of physical phenomena," my working definition of "inquiry"? I have already listed some examples from the children's sense of mechanism; here I list some examples of what we could see in how children approached reasoning about the questions.

- Drawing on familiar knowledge and experience. There were a variety of examples at different ages, from a 1st grader thinking of what happens when you spit on sand, a 3rd grader's thinking about a glass of water, fifth graders thinking about swinging on ropes, 8th graders thinking about what they know about salt in water.
- Seeking articulate explanations. In various places, the primary challenge to the children seemed to be to put in clear terms what they were thinking. This was evident in the transcript, such as in the 1st graders trying to articulate their different ideas for how sand could suck water away from the seed, block water from getting to it, or allow water to flow. It is even more evident in the videotapes, where we can hear the sound effects and watch the gestures or bodily enactments, such as 5th graders waving their hands to show what the pendulum would do or 1st graders jumping and twisting to show how the paper and book would fall.
- Seeking causal factors. Children working on different questions made progress by trying to identify the factors that would affect the outcome— 1st graders thinking of different ways placement in sand could affect whether a seed could grow; 3rd graders coming up with factors that could affect heat flow; 5th graders looking at the speed and weight of projectiles.
- Making and using analogies and models. Examples included the 3rd graders discussing models of how red dye moves through a carnation stem; Skander's ice and water was a deliberate analogy ("pretend the lava is water"); 8th grader Lisa used her shoe on her hands to represent sedimentary rock resting on plates.
- Seeking mechanistic explanations. There were many examples throughout; possibly most impressive was the evident commitment to identifying a tangible cause even when the students were finding it difficult: 3rd graders Zoë and Samantha were confident that bubbles only come out round, but they struggled to articulate a mechanism—"it can't get all the sides," "the corners" would make it pop. 8th graders Keren and Lisa struggled to find a mechanism for the sedimentary rock to get hot, over another student's suggesting to forget about it.
- Seeking consistency in sense of mechanism. Again, it may be most impressive to consider examples in which students could not find the consistency. The 2nd graders were concerned that magnetic power was passing through someone's hand but without hurting in anyway. Ms. Cicmansky's 3rd graders were concerned about the inconsistency between the tall, thin cylinder feeling cooler but measuring hotter on a thermometer, compared to the short, wide cylinder.
- Reconciling contradictory arguments. There were a number of examples in which students showed their commitment to consistency by responding to a conflicting argument. A 2nd grader responded to an argument that people have metal in their bodies by saying that the x-ray someone saw probably showed something the patient was wearing, rather than metal inside the body. A 5th grader argued that someone could think an object falls backwards because they are running forwards.
- Persistence and enjoyment of the game. Discussing these sorts of conversations in the abstract, adults often anticipate that children will have little patience for participating, that they will get frustrated quickly by not knowing and press the adult for the answer. Those concerns do indeed hold, but in our experience they hold more for older students and adults. In general, the children in project teachers' classes seemed especially to relish the opportunities to talk about physical phenomena, provided only that they could think of ways to engage the topic.

Again, this is not an exhaustive list of what we could see in these examples; certainly it is not of what we might see more generally. Still, it is a start at identifying aspects of children's inquiry they could build from and refine toward professional scientific practices. Participating in conversations and explorations such as these give students opportunities to reason in these different ways, to become familiar with what it is like, as would engaging in any other sort of activity.

I've given so many examples here for two reasons. The first is to support the claim that these are not unusual children. I've repeated examples from the same teachers, but only across different years: Every example involves different children. There are many more examples in the research literature, in accounts of children's reasoning in science [14]. The second reason I've given so many examples is to give a sense of the richness and variety of the relevant knowledge and abilities, both with respect to children's sense of mechanism and with respect to the various ways they approached thinking about physical phenomena — children's scientific (or proto-scientific) inquiry.

It might be useful to think of an analogy to the richness and variety of abilities that comprise some other activity. Watching artists paint, I am sure we could identify a rich variety of abilities and techniques that contribute to expertise—ways of seeing shapes in the world, ways of holding the brush, different approaches to making initial sketches. Watching athletes we could do the same, identifying for a basketball player different kinds of shots, ways of running, ways of thinking about positions on the court. If we were art or sports educators, we would be thinking about trying to recognize nascent versions of these various abilities in children: What can they do now that we can help them develop and refine toward professional expertise? The game here has been to do that with science, and in these moments we can see various nascent aspects of scientific inquiry.

These were moments only, though, and this is important. I could very easily have chosen to present other moments, from the same classes, in which the children's participation would not have seemed productive or precursive to expertise. Evidence that children have abilities and use them in one moment does not imply that they will use them systematically. In fact, it seems use of these abilities is sensitive to context, and this may explain why, so often, we find older students apparently lacking in the abilities evident here. In the next lecture, I begin with college students apparent inexpertise.

Here is a link to part 2

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