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The Variability of Student Reasoning, Lecture 2: Transitions

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This lecture continues the phenomenology of student reasoning from the first, beginning with brief examples of introductory physics students failing to apply basic logic and common sense. These contrast with the examples from the first lecture of children's reasoning, but it would be a mistake to interpret the university students' behavior as evidence that they are not capable of what we saw in elementary students. Rather, students at all ages are capable of reasoning in a variety of ways, and the bulk of this lecture focuses on examples of students shifting in their approaches and ideas over short time scales. Often these shifts follow epistemological prompts from an instructor, suggestions for how students should think about knowledge and learning.

1 Introduction

In the first lecture I presented examples of young children's reasoning, highlighting aspects of what they said and did that might be productive beginnings of scientific thinking. Among those aspects were children's drawing on their own ideas and experience; creating and reasoning with analogies; looking for tangible, mechanistic explanations for new phenomena; identifying and trying to reconcile contradictory lines of reasoning. In all, there were many examples of children approaching science as if it should make sense.

This is not what university physics instructors are accustomed to seeing in students. Rather, it is a familiar complaint among professors that students do not apply common sense to their studies, such as to check the solutions to problems or to understand the meaning of a symbol in an equation. Indeed, the most frequent response among professors to snippets I presented in the first lecture has been to wonder why they can't get their students to do the same things.

I briefly review several examples in the next section, and then I turn to the main purpose of this lecture, which is to discuss the variability of student reasoning. It would be a mistake to suppose that the university students are no longer capable of what we saw the children doing. Rather, students at all ages are capable of reasoning in a variety of ways, and in section, "Productive transitions," I present examples of short time-scale shifts in students' approaches and ideas.

2 University student difficulties

University professors and high school teachers are familiar with the phenomenon of students engaging in rote learning disconnected from their everyday sense of the physical world. Instructors complain about students giving unrealistic and nonsensical answers to questions—calculating a car's mass to be on the order of a kilogram, or in units of density; plugging a value for velocity into a formula concerning volume, and so on. Because the phenomenon is familiar, I shall be brief in reviewing three examples, citing references for more thorough accounts.

2.1 Roger: Setting common sense aside in favor of the calculations

Roger was a student in a calculus-based introductory physics course at the University of California, Berkeley. During one session he worked a problem from an assignment: Find the acceleration of the masses in an Atwood's machine with two masses connected by a cord.

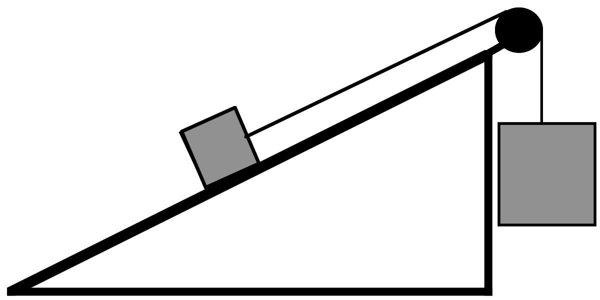

Figure 1: Two masses connected by a cord.

Roger found an expression for the total force on the two blocks, treating it as a one-dimensional system, and then he set that force *F* equal to *ma* for each block in turn. That is, he treated the total force on the system as the total force on each of the blocks separately. In this way, he found that they had different accelerations. He was uncomfortable with that outcome at first, but decided to stay with it.

> Roger: From what I put, I guess that's right . . . . Oh geez, how could one be accelerating faster than the other . . . . That would mean the velocities would have to be different . . . . Yeah, I guess so . . . . Well, I don't know; I'd check and see if I got the right answer. I'm 90% sure.[1]

Roger's behavior in this instance fit a broader pattern in his approach to the physics course and comments about it [1,2]. This pattern could be characterized as reflecting epistemological beliefs consistent within the context of the introductory physics course: Roger acted and spoke as if he believed that physics sometimes simply violates common sense, and when it does there is little to do but trust the formulas. Unlike Tommy, the third grader who struggled to reconcile the conflict he saw between what he felt with his hand and what the thermometer said, and unlike the eighth graders who struggled to reconcile a conflict they found in their account of sedimentary rock being exposed to heat, Roger simply accepted the conflict with common sense and moved on, "90% sure" that he was right.[1]

It is important to note that the evidence supported a consistent characterization of Roger's epistemology *within the context of the introductory physics course*. There was not evidence of his epistemology in other contexts. By the arguments below, it is very likely that in other contexts the characterization of his beliefs would be different.

2.2 Daniel: Setting aside a common sense definition of velocity

Daniel was another student in the same study whose comments and behavior could be characterized by a similar epistemology. During one of his interviews I asked him to solve a problem the professor had presented in lecture:

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[1] Another student in the same study, Tony, happened to make exactly the same mistake. Consistent with approach and comments throughout our interviews, he immediately rejected his calculation and looked for the conceptual error it contained [1,2].

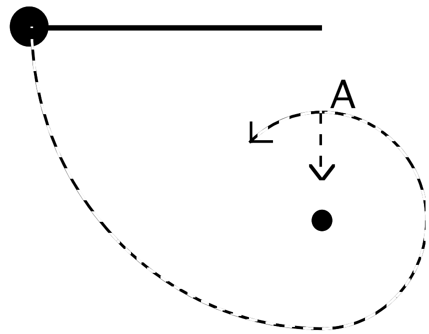

Figure 2: A ball tied to a string swings past a post

A ball is tied to a string of length l *attached to a pivot. A post is placed a distance* h *directly below the pivot. If the ball is released from the position shown, with the string straight and horizontal, how large must* h *be so that the ball will swing in a circle completely around the post?*

Daniel solved the problem by conservation of energy, setting the initial potential energy equal to the kinetic energy at the bottom of the swing and then equal to the *potential* energy at the point of its swing just above the post, labeled A in fig. 1. (His mistake was to omit the kinetic energy at point A.) He then solved the problem to find that $h = l/2$, and from that result concluded that the ball would have "zero velocity" at point A. He explained that "it will have zero velocity, so I'm also assuming that it will drop this way [along a circular path], instead of back down, or, straight down." In his sketch he showed the two options clearly, as shown in fig. 2.

Asking him to clarify, I made an interviewing error, but he corrected me:

> I: So you say it will come up here, gonna fall, and then it stops right there. [tracing the path from release to point A]
> D: It will have zero velocity, I didn't say it was gonna stop.[3]

Daniel continued to work on the problem, maintaining throughout that the ball would have zero velocity but that it would keep moving. Like Roger, Daniel chose to ignore his common sense in this instance, the association of velocity with motion, and this reflected a pattern in his approach and comments throughout our interviews [2,3].

2.3 Jan and Nancy: Devaluing common sense and plain language

For the past three years we have been working on a project, *Learning How to Learn Science*, to study and find ways to address student epistemologies in the setting of a large-enrollment introductory course.[2] Jan was a student in our reformed course who became the subject of an extended individual case study by Lising & Elby [4], having come to the group's attention as a result of her behavior during "tutorials" [5].

The first tutorial in geometric optics has students place various light sources on one side of a board with a hole in it—the hole could be of various sizes and shapes—and looking to see what appeared on a screen placed on the other side. The tutorial guides inquiry from point sources to extended sources, culminating in the phenomenon of a pinhole camera.

At one point, the group was working on a question about what would happen if there were two point-sources of light shining through the single hole. The group was discussing why that would make two spots of light on the screen. One member of the group, Veronica, tried to explain to the others why it made sense that there should be two spots, explaining that the light is just traveling in straight lines from each bulb through the hole to the screen. Nancy asked for help from the graduate student teaching assistant (TA), but when Veronica responded to the question, the TA decided to let the students work it out for themselves.

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[2] This project is funded by the US National Science Foundation, grant REC 0087519, E.F. Redish and D. Hammer.

Nancy: [addressing the TA] How is it possible for the things to, like when we have the two bulbs, for one little circle to create the two —
Veronica: Because they are two different directions. One's going in like that and one is going in like that.
Jan: So you are saying that —
Nancy: But what's the normal direction of the light? Cause that's what I'm asking.
Veronica: It, it spans out, and whatever part goes through that circle is the part we're going to see.
Jan: [drawing as she talks] So the light is like that and these are the rays, and the vector points that way will go through the hole.
Nancy: Okay, so then if you move it [a light bulb] up, then it's going to be?
Carl: So if here is the hole and the light is down here, the light is going to go in the direction —
Jan: Right, so like it has [Nancy, Jan, and Carl talking, unintelligible]
Veronica: Really, it's just normal.
Jan: All the rays are going like this. So, it's kind of like polarized.
Veronica: Mmm, not really.
Veronica: It's just, well, it's just, guys you're making it, you're trying to make it more difficult. It's just, the light goes out. It only goes through that one circle. So, obviously, if it is down here, and I'm looking through that circle. Look, you're sitting down here. You're looking at this big cardboard. You're looking through that little circle. All you're going to see is what's up there. It's a direct line.
Jan: Look, I see what you're saying, alright. But, I'm just trying to make it like physics-physics-oriented. [laughs]
Veronica: It is, it is physics-oriented. That's just the way it is. [4]

Nancy wanted to ask the instructor for the answer to the question. Unlike the children in the examples from the first lecture, she was more inclined here to ask the instructor than she was to persist in reasoning with her group. For Jan, the question was a physics question, and she did not seem to trust either Veronica's common sense reasoning or that the answer could be expressed in plain language. Unlike so many of the children, she was not interested to draw on everyday reasoning about causal mechanism. In their analysis, Lising and Elby document how this reflects a pattern in the data concerning Jan's approach to the course.

2.4 Abilities lost?

All of these students, in these moments (and evidence shows more generally in their physics courses) failed in one way or another to connect the formal material they were learning with their everyday sense of physical mechanism. Other problems we have observed include a reluctance in many students to use analogies, and an open distrust of analogies in instructors' explanations, such as in one conversation in which a roomful of students lambasted two teaching assistants for talking only about models and not about how electricity *really* works. I expect the reader's experience supports my claim that these students were not unusual; there is more formal evidence in the literature [6,7]. Note too that the university students, unlike the young students in lecture 1, had been selected for their abilities through the university admission process.

The natural question is how this could happen: If we can see so many nice beginnings of scientific practices in elementary school students, shouldn't university students be further along? What happened to those nice beginnings? It doesn't seem plausible that these students "lost" the various abilities we could see in the younger students, that they are no longer (or were never) capable of drawing on everyday ideas, trying to reconcile inconsistencies, expressing themselves in clear language, or using and understanding analogies.

More plausible is the possibility that the university students are able to engage in more scientific sorts of inquiry, but that the contexts of their introductory physics courses do not bring those abilities out. In this respect, the university students may be very much like the younger students who, as I noted, engaged in the sorts of proto-scientific behavior in some moments but not in others. The university students may be similar, in that they could engage in many different ways, although it seems many have become more systematic in how they approach learning in familiar course settings.

In some cases, students have expressed their perception of a pressure against meaningful thought. Elby [8] has discussed students' expectations regarding what sorts of performance are valued by their professors. Tobias's study [9] revealed how sophisticated students acting as informants experienced introductory physics instruction. As one of Tobias's informants put it, the course was measuring her "Obedience Quotient" rather than her IQ; a student in another case study similarly complained that the course pressured her to follow procedures rather than try to understand [10]. The same conditions that led these students to complain about may tip other more susceptible students into counter-productive reasoning. If the pressure is systematic, the effect on how students approach learning in science may be to move students away from the productive beginnings that would otherwise come naturally.

That is, it would not be surprising for university students to have adapted to the environment of school science, to the extent that environment has been consistent. Still, in other environments they may behave differently, and in the following section I continue the phenomenology with instances of shifts in student thinking.

3 Productive transitions

At the end of the first lecture I commented that the children's productive reasoning was episodic, although I did not present evidence. I have also noted that the university students' counter-productive approaches (for Roger, Daniel, and Jan) were more than episodic, reflecting patterns in how they approached and discussed their respective physics courses. With the assumption that the university students still have in some form the same understandings and abilities we observed episodically in the younger children, the collected observations are consistent with a view of student reasoning as sensitive to context. We should expect to see, then, changes in context producing changes in reasoning.

That is, if we expect that the university students still have those abilities, then in some sense they are making a choice when they take the approaches they do to learning introductory physics. In some instances, the choice may be deliberate. Here I review examples of students shifting in their ideas and approaches, at a range of ages from children to adult, focusing on four examples of shifts that seemed to result from an epistemological prompt, a suggestion by an interviewer or instructor for how to think about knowledge and learning. More often the choice seems tacit, and I also review examples of shifts that seem to occur spontaneously.

3.1 "K": A momentary shift

I interviewed "K," a student in an algebra-based introductory course, as part of a project in local conceptual change [11] At one point during her first interview, I held my watch in the air and dropped it, asking K whether it speeds up as it falls or falls at a constant speed. K said she was not sure and offered her uncertain memory that it falls at a constant rate while she flipped through her textbook looking for help. After a moment I suggested, "Forget you've ever taken physics." At first, K answered, "I can't!" but I pressed her to try. She then answered without further hesitation, and in a tone of voice that conveyed obviousness, that the watch speeds up as it falls: "It isn't moving when you first let it go, so it must be speeding up." Shortly later she commented, "But you never really know in physics."

This quick example from a clinical interview illustrates what the next three examples from physics courses all have in common: The student showed a substantial shift in her reasoning after a prompt with no conceptual content. My suggestion said nothing about velocity or acceleration; it spoke only to K's sense of how to approach reasoning about the question. For K, the shift did not last in our interviews, not without further prompting.

3.2 Louis: A lasting, deliberate shift

Louis was a student in my section of our reformed algebra-based introductory course, , part of the project *Learning How to Learn Science*. It was the second semester of a year-long sequence, but Louis had been in a traditionally taught version of the course for first semester.

He had done very poorly on the first hour exam; his score of 36/100 was one of the lowest in the class of 120 students. A week and a half later, he took the make-up exam[3], and his score jumped to 84/100, the highest score on the make-up exam, near the top of the original distribution, and by far the highest gain. Rachel Scherr interviewed him to ask what he thought was the reason for his dramatic improvement. She assured him that the interview was confidential, and that she would not share any of it with me until after the course was over and grades submitted, and she recorded the conversation on videotape.

Louis begin by explaining what he had been doing to prepare for the first exam.

> Louis: I studied a lot for the first test. I studied every word of those homework solutions. And I studied a lot more for the first test than I did for the retest. And um then so I went into the first test thinking I would do really well.

He went on to explain why he had improved, and his explanation centered on a brief conversation with me during office hours. He had come to ask what he should do differently in the course, and I had suggested a change in his approach. During his interview, Louis recounted our conversation.

> Louis: I said I was looking at the homework solutions and I was, I was memorizing the book too, the Cutnell and Johnson book [12]? And um the advice that he gave me he said, 'When you study, try to explain it, try to explain it to a ten-year-old.' So I said okay. [But] I still was confident I knew the stuff and then he goes, 'okay then what's voltage?' I was like 'voltage, V=IR?' I gave him a formula he's like, 'okay what's voltage?' I was like 'I don't know [laughs].'

As a result of that conversation, Louis explained, he decided to change his approach to the course.

> Louis: I went back and I actually wrote down, I wrote down like an explanation to a ten-year-old. I used an analogy, I used like dump trucks? And the dump trucks were the voltage carrying across the highway the little line you draw in the circuit, and uh the a resistor was like a traffic accident. Like a resistor would like stop sign so it'd be harder to get through. And […] if the circuits are parallel it'd be like the highway is splitting. So more current would get through.[…] Then I went back to the homework solutions again but instead of like memorizing them I would try and relate my analogy with the dump trucks to the answers in the solutions. The dump truck analogy was like common sense to me. If there's a traffic accident less traffic's going to get through it.

He said that he would continue with this approach for the remainder of the course.

> I: Are you do you think you'll still be memorizing them, or do you think that those days are over, or what?

> L: Yeah what I plan to do is to make to do the same exact thing I did for the retest. And just think of analogy instead of memorizing the answers. Relate the analogies to how, to why something happens.

Louis explained that he'd heard me give this advice before, but that he "didn't trust" it.

[3] Our practice in these courses is to give students the opportunity to take a make-up exam, and we average the scores. As much as we can manage, the make-up exams are of equivalent difficulty.

> L: He was saying in the beginning before the first test […] 'think of an analogy.' Exactly what I did before the retest. But when he was saying it the first time, he said it and I was like, 'Whatever.' Because in all, especially in my like chemistry classes, the way I did well on the exam is like flash cards of different reactions and memorize it and the better I memorized it the better I did on those exams. I guess physics is a little bit different. You really need to know the concepts.

The "dump truck" analogy was his own. Explaining it during the interview, he confused current with voltage—it would make more sense if dump trucks were units of charge—the evidence does not show he had a formed a fully expert conceptual understanding. It does show, however, that he was substantially further along toward an expert understanding, based on his performance on exams. Louis went on to do well in the course, ending in the top quarter of the class with an overall grade of B+.

Louis alluded to advice he had heard all along in lecture. In fact, the whole of the course was designed to help student move in the direction he did, epistemologically, to prompt this shift.[4] There is no reason to believe that our brief conversation, absent the design of the rest of the course, would have made a difference. Rather, for Louis it seemed to have been the tipping point, what pushed him to give this other approach a try. On his account and the available evidence, he went through an overall, qualitative shift in his approach to the course, and he made this transition deliberately and on a relatively short time-scale.

In contrast to K, Louis mostly maintained this shift in his approach for the remainder of the course. One likely explanation for this is that Louis was working in this context of a reformed physics course, with many explicit and tacit prompts for him to approach learning as a "refinement of everyday thinking." [13] K was taking a conventional physics course that, in all probability, was prompting in the other direction.

3.3 8th grade students shift from gathering information to reasoning from what they know

One of the brief examples I mentioned in the first lecture was of Jessica Phelan's eighth grade students working on the rock cycle. The assignment had been for them to work as a group to come up with a model of the rock cycle. In the first lecture I mentioned how the students identified and worked to solve the puzzle of how layers of sedimentary rock become exposed to heat.[5]

Several minutes earlier, however, the students had been behaving in a very different way. When they first sat down to begin work on the assignment, they approached it as a matter of assembling information, in the form of technical vocabulary, from a set of worksheets they had used in their study of igneous, sedimentary, and metamorphic rock. One student was taking notes, and her summary of their progress after a couple of minutes illustrates what they were doing nicely:

> "So the Teutonic plates move and create rock, and then I have the igneous rock forms. Is that wrong?"

When others in the group raised concerns, it was not over the meaning of that sentence:

> Johanna: No, there's something. There was like de-desa-whatever.
> Lisa: Deposit[inaudible]
> Johanna: Yeah, Deposition.
> Tracy: We're not there yet.
> Louis: The deposit comes after that.

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[4] There is evidence that other students in the course shifted in their approach and views about knowledge and learning, in measured gains on the Maryland Physics Expectation Survey. For those familiar with MPEX scoring (see [7] and Redish, this volume), changes for the course as a whole were as follows: Concepts cluster scores improved from (35% unfavorable, 40% favorable) to (10%, 70%), Coherence from (25%,54%) to (14%,68%), and Independence from (34%,48%) to (31%,52%).

[5] An extended analysis of the shifts in student reasoning during this discussion is forthcoming [14].

It was at this point that the teacher intervened, telling the students they were "looking at a lot of papers and using a lot of words" they did not really understand.

> Ms. Phelan: And if you're doing that, for your model, it's not going to be very good. So I want to start with what you know, not with what the paper says.

Her advice brought them up short—Lisa exclaimed "but we don't know anything!" And then they began to work in a different way, nicely encapsulated by what Lisa called out next: "So, a volcano erupts." When Bethany next read a summary of their progress, it was much more reasonable.

> Bethany: OK, the volcano erupts, and lava comes out. Lava cools and makes igneous rock. Rain and wind cause small pieces of rock to break off. Sediments form, and rain and wind carry it away, and rain and wind slow down and deposit sediments and this happens over and over again to form layers.

It was shortly after the summary that the group encountered the problem of how the layers of sedimentary rock are exposed to heat.

As with Louis, it would not be appropriate to think of Ms. Phelan's suggestion as an isolated intervention. To the contrary, she had worked with the students for months; her suggestion here was on top of a general background of class expectations. Still, the moment reflects students, this time as a group, shifting quickly from one approach to another following an epistemological prompt.

3.4 3rd grade students shift from thinking about why *to* how

Trisha Kagey wanted her third grade class to talk about what might cause leaves to change color, the proximal mechanism of what occurs in the leaves themselves.[6] She tried to pose the question specifically, asking "What is happening inside the leaf?" and she explicitly contrasted that question with the more general "Why do leaves change color?" The children, however, did not seem to understand what she was after. At one point, Ms. Kagey tried to clarify the difference between the two questions by answering them with respect to hunger:

> Teacher: You say I'm hungry because I haven't eaten since eight o'clock in the morning or six o'clock in the morning. And the second question says how - what is going on inside of your body that's making you hungry? You can say the food already went into my stomach, my stomach already digested it, and now my stomach is empty and that's why I'm hungry. So, you are talking about what's going on. What things are going on inside of the leaf – what things are going on inside of your body to make you hungry.

Most of the students' thinking, however, remained teleological or anthropomorphic.

> Morgan: I think, inside the leaf, um, to make it change colors it's a lifecycle […] I think it just sorta means like growing up […] when it changes colors it's like telling that it's growing up, and it's telling that it's Fall. And, like, in Fall it like, it might be like the leaves' birthday. And, it's telling that it will have to fall off soon. […]
>
> Teacher: *How* is it happening? *How* is it happening?
>
> Morgan: It's happening because, I think because of the weather, and because of the sun and water and because— For some reason I think of the seasons. I don't know why, but—
>
> Teacher: That's a "why" question. What's going on inside the leaf? Pass to someone if you're not prepared to answer? What's going on inside of the leaf that is making it change color? What's going on *inside of* the leaf that's making it change color? A lot of good hands up right here.

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[6] See [15] for further analysis of this discussion.

> Camille: I think that it's, it's um, it's getting food from the trees, so it, so it's like— I agree with Morgan because it's kinda like a life cycle of a caterpillar having, only changing colors.

Eventually Ms. Kagey tried another comparison, this time to baking cookies.

> Teacher: Think about it this way. Say I'm making cookies for my birthday […] and the question was why am I making cookies? What's the answer? Because it's my birthday. *How* am I going to make these cookies? Well, I'm going to put together a bunch of ingredients, put them inside of a bowl, mix it all up, put into the oven, take it out of the oven, lay it out to cool off. They are two different questions. We talked about the "why" question. People said it gets cold, it's getting old, it's drying up, the wind is happening. Now I'm asking you the "how" question. How are the leaves changing color? *How* are the leaves changing colors? What process is it going through? What steps are happening inside of the leaf?

That seemed to do it: The students started to talk about what they thought might be happening inside the leaf.

> John: I think it, like us, I think it has special cells in it that change color inside of their, inside of the leaf.
> Teacher: Talk about that.
> John: Like how?
> Teacher: Yeah, but why do you think that?
> John: Cause I don't think there's like a special type of warmth, there's like, I think there are basically cells in every type of living thing.
> Christian: I think when you see colors with like veins inside of it, they change, and like, it depends on how, when it's like gets really cold, like the veins, like, make it change all kinds of colors.

The discussion continue from there, with students turning their attention to the make-up of leaves.

This example contrasts with the previous ones in several interesting respects. First, it was more difficult to achieve: Ms. Kagey was perseverant through several attempts to shift the focus of conversation. One possibility for the difficulty is simply that reasoning about proximal mechanism is difficult, and a small tentative start in that direction would not be sufficient. The 8th graders, in contrast, did not have any trouble finding generative material to 'start from what they knew.' (It's easy to think of an explicit analogue: Given the instruction to "climb through that hole," and seeing a very small hole, it would be natural for someone to doubt the literal instruction and find another interpretation.)

A second difference between this example and the earlier ones is that it was more targeted to a particular aspect of the children's epistemology. The students were already starting from what they knew; that wasn't the issue. Rather, Ms. Kagey was trying to get them to reason in a particular way, toward thinking about proximal mechanism, within a more general mode of starting from what they knew. That is, Ms. Kagey's intervention depended on a more precise diagnosis of student difficulty.

Finally, Ms. Kagey's intervention involved a more deliberate search for particular knowledge she expected students had available. She believed them capable of making this distinction between knowledge of "why" and knowledge of "how"; the challenge she took on was somehow to tap that capability. Her various attempts included the original contrast, in how she framed the question, her emphasis on asking what happens "*inside* the leaf," her illustration of the difference with respect to hunger, and finally her illustration with respect to baking cookies.

Still, the example is similar to the others in that Ms. Kagey only spoke to the children's understanding of different kinds of knowledge. She never said anything about leaves or what might cause them to change color. In the end, her analogy to answering the questions of why and how in the situation of baking cookies prompted students to shift in their reasoning.

3.5 Brief examples of spontaneous shifts

Similar shifts happen without any such prompting, "on their own" or triggered by other aspects of the situation.

One example is the 5th/6th grade discussion about the dropped pendulum [16], a portion of which I described in the first lecture. Earlier in the discussion, the students had not been engaged in the sort of argumentation evident in the excerpt I presented. Rather, they were mostly asserting answers they each believed, endorsing or disagreeing with Chris's idea that the released pendulum bob would go out and down or Ike's idea that it would go up and out. Ms. Bell had been prompting for students to explain their reasoning, and to think of connections to everyday experience, but the transition point seemed to have been Victoria's new idea, that the pendulum bob would fall straight down. Then the class as a whole seemed to shift into a different conversational mode, in which students defended their reasoning and responded to others'—many more student utterances took the form of "I think it will [answer] (or I dis/agree with ___) because [argument]." Loucas Louca [15] suggested that the transition came about because Victoria's idea brought a contrasting but tangible possibility; students became more aware of multiple, conflicting ways of thinking.

Similarly, most of Ms. Roy's 3rd graders' talk about earthquakes [17] was comprised of students taking turns giving their ideas, rather than attending and responding to each others' reasoning. Ms. Roy modeled the sort of careful attention she was trying to engender, and she prompted students, but a noticeable shift in the discussion came after Skander's analogy to adding an ice cube to a full glass of water. Here, too, the students' entrance into a different mode of conversation may have been triggered by the tangible ideas students connected to Skander's analogy.

Turning back to older students, an analysis of "J"'s epistemology during a series of interviews with Andy diSessa [18] showed patterns in her behavior that reflected what we could characterize as an epistemological stance throughout the interviews. Those patterns could not have been characterized by any of the existing frameworks, including mine [1]. In the absence of direct data on J's approach to learning within her course, Andy Elby argued that the patterns in the data from interviews probably did not reflect her approach to the course, given her relatively successful performance (she got a B). He argued that this difference may have reflected the difference in context between the interviews and the course.

Working with Laura Lising, Elby has pursued this conjecture in the case study of Jan, the student I discussed above who wanted the explanation about light to be more "physics-oriented." Elby conducted a series of interviews in which, like diSessa, he posed physics questions in a different form and tone from those of her physics course. Lising's and Elby's [4] analysis shows different patterns emerging in Jan's approach during interviews from her approach during the physics course.

Rebecca Lippmann's dissertation [19] shows different patterns in students' approaches to reasoning in introductory laboratories, again evidence of context dependence. Within each of the settings as well, she analyzed instances of students monitoring their progress and making choices to enter different modes, such as to resolve a conceptual difficulty they discovered. Jonathan Tuminaro analyzed an episode of group problem solving among students working on a question in electrostatics [20]. During one segment of the conversation, the students were conversing in qualitative terms of their sense of mechanism. Then, with one student's recalling an equation, they moved to a more formal mode of speaking and reasoning in terms of algebraic expressions. These students were, like Louis, working in the context of a reformed physics course largely focused on helping students shift toward more productive approaches to learning, but the shifts in this episode were not related to any specific suggestions from an instructor.

3.6 Abilities found!

In section 2 of this lecture I reviewed examples of university students failing to apply basic logic and common sense. The examples in this section support what one might expect: The students are capable of more productive approaches to reasoning in physics, but they have learned not to take them.

It would not be appropriate to think of these as instances of "conceptual change," for two reasons. First, the time scale in these examples is quite different than people generally associate with conceptual change. Several of these examples, including three of those prompted by suggestions, happened on a time scale of minutes. Others, including Louis, took place on a time scale of no more than days. The abruptness suggests that the students were not developing new abilities but starting to draw on different abilities in their already established repertoire. It is not plausible that K formed a new "conception" about motion in the few seconds she paused after the suggestion to "forget you've ever taken physics." Even for Louis, it is hard to believe that he developed fully new conceptions and abilities over the days between our conversation and the make-up exam.

Second, the evidence of change is not only conceptual, in the substance of the students' thinking about some particular idea or phenomenon. Rather, the evidence across these examples is of net changes in approach to reasoning: from looking up information in a textbook or worksheets to starting from common sense; from memorizing specific problem solutions to re-explaining with a personally constructed analogy; from trying to explain purpose to trying to explain mechanism.

The instances in which the shifts occurred as a result of explicit prompts implicate a role for student epistemologies in selecting what knowledge and reasoning to apply. None of the prompts—Ms. Kagey's cookies, Ms. Phelan's "start from what you know," my suggestions to Louis and to K—contained any conceptual content. Rather, they referred directly and explicitly to the students' sense of the different kinds of knowledge and reasoning they could use. Students could only understand and follow through on the suggestions if they had a sense of the epistemological distinctions to which the suggestions referred. Ms. Phelan's students, for example, would not have been able to do what she asked if they did not have a sense of the difference between "starting from what you know" and using words they did not understand. Ms. Kagey's students, too, needed to understand the difference she was explaining between a how and why question. That the distinction was not clear to them until the cookies example suggests that comparison gave them access to aspects of their knowledge they had not yet invoked.

4 Questions for further research

Watching and listening to children, we find—episodically—aspects of knowledge and reasoning that look like nascent forms of mature scientific practices. Watching and listening to university students, we find familiar occurrences of students failing to apply basic logic and common sense. Finally, at all ages, we find non-incremental transitions in students' thinking over short time scales, some prompted by explicit suggestions, others "spontaneous."

Of course, I chose these examples from a theoretical orientation, the focus of the next lecture, by which I expect to see nascent versions of mature science in children, and I expect university students are capable of other approaches than they are taking. The instructors in our projects shared much of this orientation, and they too expected to find productive aspects of student' knowledge and reasoning. In the third lecture I shall argue that this is an important role for theory: Teachers who don't expect to find productive thinking will not listen for it or make appropriate opportunities. What these first two lectures illustrate, then, is what we are able to find when we do look and make opportunities.

Comparing between the examples of children's thinking in the first lecture and of university students' in section 2 above, it is tempting to recite the colloquialisms that 'children are natural scientists' and bemoan the loss of curiosity and interest in older students. If the children in examples from the first lecture did look like better scientists than the university students, however, there is little support here for making that assessment in any general sense. As the examples in section 3 of this lecture illustrate, the abilities we saw in the children were not systematic. For every instance I presented in the first lecture, I could have chosen another segment within the same class period that would have given a very different impression.

Taken as a whole, the phenomenology in these lectures does not suggest that children are generally better scientists, only that they can be in moments: Children are capable of a range of ideas and approaches to learning, including many that are valuable for science. It would be important progress for the children to become more consistent in these ways of thinking, somehow learning to enter them systematically when "doing science." The university students, meanwhile, are capable of the same or a greater range. They may have become systematic, in the familiar contexts of science instruction, but for many it is not a productive systematicity.

In the next lecture I shall turn to ontology. Research in science education, including physics, has mostly adopted unitary models of student thinking as reflecting naïve theoretical frameworks, robust misconceptions, and stages of development in reasoning abilities. As models of cognitive structure, these fit well with a phenomenology of consistency over time and coherence among ideas. The phenomenology I have sketched in these lectures has been more variegated and complex, and it confutes attributions of consistency and coherence to student reasoning. I shall argue that student knowledge and reasoning is better modeled in terms of a manifold ontology of more fine-grained, context sensitive resources.

Part of the reason for the difference in views has been the difference in approach to documenting phenomena. Research on misconceptions and on stages of development has typically drawn on data from studies in clinical contexts, using questionnaires, interviews, and specialized tasks. The data I have presented in these lectures is mostly from classroom observations of students in contexts of reformed science instruction, and this has much to do with the difference of theoretical perspectives. If student knowledge and reasoning is variable, and if we think of modeling it in terms of context-sensitive resources, then it is a mistake to draw general conclusions about stable conceptions or abilities from data gathered in specific, controlled contexts.

Progress in ontology, of course, is linked to progress in phenomenology, and there are many questions that bear exploring.

1) What sorts of abilities can we distinguish in children's thinking?

A standard approach to sorting would be to look for general developmental stages, but the richness and complexity of the different aspects of children's thinking evident in these two lectures makes it difficult to suppose any single dimension of developmental progression. (It is much easier to imagine many micro-developmental progressions [21].)

As one instance of another approach, Lising and Elby [4] sorted data from Jan's interview in several ways:

- "when she used formal, classroom-taught reasoning resources versus "everyday" and intuitive informal reasoning resources;
- when she was sense-making versus just trying to remember stuff or throwing out ideas with little thought; and
- when she attempted to reconcile different lines of reasoning."

There are other examples in the literature of research of studies that sort, not *individuals*, but instances of reasoning across or within individuals or groups; these studies are often framed as discourse analyses [19,22] or as phenomenography [23]. Identifying these schemes may facilitate identifying modes of reasoning and transitions between modes.

2) What sorts of shifts can we distinguish?

Some of the examples of shifts from one mode of reasoning to another involved students who were deliberately choosing to reason in a different way. That would apply to the cases in which students shifted in response to an explicit suggestion. Louis, for example, described making a decision to take a different approach to his studies; Ms. Phelan's students took her instruction to start from what they knew; Ms. Kagey's students followed her request to talk about "how" rather than "why."

It would also apply to other moments. When Ms. Phelan's students encountered the inconsistency in their account over how layers of sedimentary rock were exposed to heat, they wrestled for a moment with whether it was a problem they needed to solve; they were aware of the decision point and in the end chose to solve it. The mode of thinking they were in, solving the problem, contrasted with the mode they had been in, telling the unproblematic story of the rock cycle to that point [14]. Having solved the problem, they returned to the story. Like Schoenfeld's [24]more sophisticated mathematical problem solvers, and Lippmann's [19] more sophisticated laboratory groups, the 8^{th} graders were monitoring the sense of their account, identified a discrepancy, and chose to shift to a different mode of thinking to resolve it.

There is no indication, however, that the same students chose to reason as they did at the start of the class, to assemble facts from their worksheets rather than reason from what they knew. Similarly, the students in Ms. Bell's class did not choose to shift in their approach to discussing the pendulum question. Nor was Jan likely deliberate in choosing to reason differently during interviews than she did in the physics course, and the students in Tuminaro's [20]excerpt did not appear to choose to enter or exit different approaches to the question.

One distinction perhaps then to draw among these shifts is *active* or *passive*—whether or not the student are deliberate in changing their approach to reasoning. Another may be *coordinated* or *uncoordinated*: Does the shift in reasoning occur within a larger organizing structure?

3) What sorts of modes can we identify?

The complement of asking what sorts of shifts is to ask what sorts of modes we can identify. Students and subjects in the examples above recognized and responded to large-grained differences between using the formal knowledge taught in class and starting from common sense reasoning—that distinction, articulated in several ways, played a role in several examples. But once Ms. Phelan's students had made that choice, to start from what they knew, they had other choices to make, of whether and how to resolve problems [14]. Similarly, Ms. Kagey's students were starting from what they knew in reasoning about the leaves; they were responding to a finer-grained distinction in how to interpret what the question was asking. What different sizes and dependencies can we identify among modes of thinking? [15]

As it may be possible to draw phenomenological distinctions among types of transitions, it may also be possible to draw phenomenological distinctions among types of stability. The stability of Louis's transition to a different approach derived, evidently, from his deliberate choice to implement it; the stability of the 3rd graders' thinking about purpose rather than mechanism probably derived in part from the limited conceptual possibilities for thinking about mechanism for leaves changing color. Several university students showed stabilities in their approach to reasoning across several interviews; these stabilities may have derived in part from the contexts of the interviews [1,4,18]. One finding from work in our two projects, for example, is that authority/vocabulary-based approaches, such as at the outset of the rock cycle discussion or in the snippet of Jan's and Nancy's work, are both more common and more robust for older students.

Here is a link to part 3

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