Preprint of essay to appear in Amin & Levrini (Eds) *Converging and Complementary Perspectives on Conceptual Change*. New York, Routledge

The interacting dynamics of epistemology and conceptual understanding

The editors ask that I focus on clarifying my position, "rather than trying to be persuasive." It's an unusual assignment, and my sense of the line between clarifying and persuading shifts as I write, and as I get the editors' feedback. My framing shifts, in other words, my sense of what I'm doing, and as it does so do the ideas I express and the ways I try to express them.

That, in brief, is the position I'll try to convey: Thinking involves a complex mix of awarenesses and intentions, personal history and social context. It's dynamic, for me in this moment revising my draft as for students thinking about natural phenomena. For a case in point, I'll borrow data from a paper Jen Radoff, Lama Jaber, and I are writing this summer.

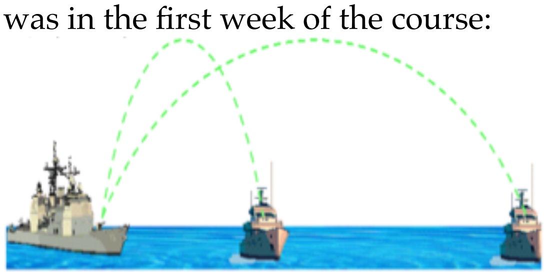
Marya's reasoning and my position

"Marya" was in my "General Physics I," which is a significant departure from traditional expectations, especially in emphasizing students "learning how to learn." Lectures, problem sets, labs and exams all challenged students to think in new ways.[1] Jen was Marya's teaching assistant (TA).

Marya approached both Jen and me early in the semester for help with homework and to express her intense anxiety about the course. She was not doing well, treating physics as equations to memorize, disconnected from tangible experience. Several weeks in, though, she was making progress, and by then end it was dramatic, in how she approached and felt about learning. Jen suggested we study how it happened, using data from the course and an interview. Marya agreed, and Lama, who was not involved in the course, interviewer her the afternoon after the final exam.

The interaction of conceptual reasoning and epistemology

I'll start with Marya's response to one of the "checkpoint questions" students answered online before every lecture, from *smartPhysics* (Gladding, Selen, and Steltzer, 2014). This was in the first week of the course:



[1] For a glimpse into lecture and references for further reading, see http://studentsdoingscience.tufts.edu/sp_cpt/block-and-cylinder/.

A destroyer simultaneously fires two shells with different initial speeds at two different enemy ships. The shells follow the parabolic trajectories shown. Which ship gets hit first?

Marya answered the farther ship, #2, gets hit first:

> I think enemy ship 1 has the greater speed because it parabolic trajectory shows a steeper positive slope than does enemy ship 2. If we were to go back to the two time values at which the projectiles are at zero, the second value (where the projectile hits the ship) is dependent on the initial speed and the gravitational pull [(2 x initial velocity) / g]. The greater the speed in the nominator, the greater the result of the fraction meaning the greater the time. Enemy ship 2 will be hit first because it has the lower speed.

It is an occasion for instructional sense-making.

The hardest part is her inference that the projectile aimed at Ship 1 has a greater speed, because its “trajectory shows a steeper positive slope.” She’d seen that steeper slope means greater speed in a graph of position over time, that week and probably also in high school. Evidently she took “steeper slope means greater speed” and applied it to the projectile’s trajectory. The rest is clear: She used a formula from the *smartPhysics* video “prelecture” for the time a projectile spends in the air, $t = 2v_0/g$: If the first shell has a greater initial speed v_0, it spends more time in the air.

There is a rationality to her response, which is important to appreciate. But what does it indicate about Marya? Accounts of conceptual change have traditionally focused on identifying and addressing students’ misconceptions. To me, though, her response does not indicate she has a misconception.

I see conceptual understanding as involving a complex myriad of resources in many forms, including p-prims (diSessa, 1993), and symbolic forms (Sherin, 2001), remembered facts and simple associations. Some researchers focus on pinning down specific properties of particular forms; I focus on the many-ness of resources and their variable, contextual activation, to think about what that means for learning and teaching. After collaborating with David Brown (Brown & Hammer, 2008), who introduced me to Thelen’s and Smith’s models of dynamic systems, I’ve come to see resources more as recurrent, dynamic stabilities—more like Bartlett’s account of schemas as “active organized settings” (Bartlett, 1932/1995), and less like intact cognitive objects with well-defined properties.

Thelen and Smith (2006) present two themes in applying dynamic systems theory to human development: (1) continuity of *system*, “from the molecular to the cultural,” and (2) continuity of *timescale,* “from milliseconds to years” (p. 258). Patterns appear in moments; some recur and shift and grow, developing greater stability, the pattern formation as ontogenesis. The pattern of infants’ moving legs in alternation, for example, first emerges in particular situations, and over time it becomes a stable part of walking. I take the pattern of connecting speed and displacement as another example, first emerging in moments of childhood and becoming over time, a stable resource.

My research generally focuses on dynamics from the scale of minutes, such as in classroom episodes, to scales of weeks and months. And I see theoretical continuity of system, from an individual to an "ensemble" (Conlin & Hammer, 2016).

So, in making sense of Marya's response, I consider the dynamics of the moment. They involve resources I can attribute to Marya, including her sense of *slope*: I'm sure she sees slope easily, in terrain, in images, across many contexts. She has a sense of time as a duration, which she applies in reasoning that larger t for #1 means #2 hits first. There's also evidence she has the symbolic form "prop+" (Sherin, 2001), by which she reads the expression $t = 2v_0/g$ as saying that larger v_0 means larger t.

But her response as a whole is a local "soft-assembly" (Thelen and Smith, 2006) of a system that extends beyond Marya herself. The set of activations and connections nests within and involves features of the situation: She's responding to checkpoint questions after watching a formula-intensive prelecture within a required course she finds intimidating. It is part of that soft-assembly that Marya *misconceives* an association of slope with speed, but only a part: It would be a mistake to attribute that to her as a misconception she *has* as an individual. In just about any other situation involving motion, Marya would think differently. It's hard to imagine her on a tennis court explaining that she'd need to hit the ball more slowly to lob it a greater distance.

Attributing reasoning to Marya ought to mean it is stable *in her*, easily recurrent and persistent across diverse situations. I'm confident in supposing that in many many situations, Marya easily and persistently expects that moving a greater distance or at a lesser speed takes a longer time. That's why her answer to the checkpoint is a moment for instructional sense-making: It's idiosyncratic. How does it last long enough for her to write it down as her answer without activating resources that are robust parts of her everyday thinking?

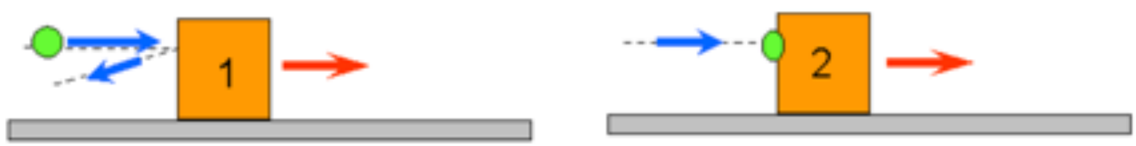
I've started to explain my answer to that question: Marya's reasoning holds together because it's nested within the physics course. That matters in part because of her epistemology. Across her work early in the course, Marya framed (Hammer, *et al*, 2005) what was taking place with respect to knowledge in ways I and others have described at length: She saw the relevant knowledge as the facts and formulas delivered by the instructor and materials, and her role was to use them: Greater slope means greater velocity, $t = 2v_0/g$. Her framing excluded her own experience in the physical world, much as someone playing chess excludes their knowledge of actual knights, kings and queens (*cf* Ford, 2005). In that respect, she did show stability, across contexts of this course and, by her account, other courses as well.

Following through on my little thought experiment—suppose she were talking about hitting balls on the tennis court—she would automatically, easily expect knowledge comes from her experience, and she would apply her more stable patterns of reasoning about distance, speed, and time. In this way, the dynamics of Marya's thinking about physical phenomena involve both conceptual and epistemological resources. They also involve affect—that's what Jen, Lama and I are writing about—and a great deal more, including her history in other courses, the *smartPhysics* graphics, the institutional role of grades.

This all contrasts with traditional accounts of individuals' stable cognitive structures. From a dynamic systems perspective, the stability is often of a system larger than the individual, much as described in accounts of situated and distributed cognition (e.g. Greeno, 1997), and it can be momentary or long-lasting.

Progress in learning physics

This was from Thursday of the seventh week:

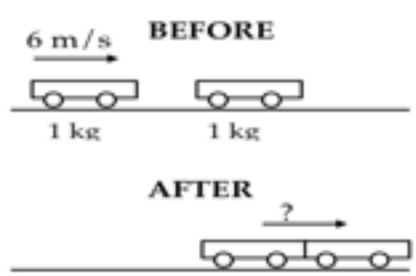


Two balls of equal mass are thrown horizontally with the same initial velocity. They hit identical stationary boxes resting on a frictionless horizontal surface. The ball hitting box 1 bounces back, while the ball hitting box 2 gets stuck. Which box ends up moving faster?

Marya answers that Box 1 moves faster because the "the interaction in situation 1 would not take away as much of the kinetic energy as the situation in 2." That makes her wonder, "is there loss in kinetic energy in the box 1 scenario?"

> I can imagine the ball slowing down after the hit but I also feel that it would speed up. Actually, I take that back. I just watched a video of billiard balls being hit and the ball that does the hitting changes directions and slows down. [...] I just hit a ball against the wall and I varied the speeds. It seemed to me that the ball bounced back with the same speed that I hit it with. I tried but I couldn't make it go faster that it's original speed no matter how hard I hit. At least, it looked that way to me.

The following Tuesday she handed in a problem set. It included a question about two carts colliding inelastically, asking for their speeds and kinetic energies, before and after colliding, and then for those quantities with a 2 kg stationary cart. Marya finished the problem and continued:



> Interesting! So it seems that when the cart collides with an object with the same mass, half the initial kinetic energy is lost. When it collides with an object twice its mass, two thirds of the KE energy will be lost. So there's a

> relationship between the KE lost and the fraction of the mass of the stationary object and the total mass of the system. Specifically $KE_{lost} = KE_i \times (m_{stationary\ object}/m_{totalsystem})$.

She checks it for a stationary cart of mass 4 kg: "So the relationship holds true!!" She then reflects on its meaning, for inelastic collisions and the conservation of energy.

Marya's responses again illustrate the interacting dynamics between epistemology and conceptual understanding.

On the checkpoint question, she looked for coherence with her experience and intuition, considering what she could visualize and what she could observe, both in video data and in her own informal experiments. She didn't use any formulas from the prelecture or even mention its topic, the conservation of momentum, in clear contrast with her response to the ships question earlier. On the carts problem, she looked for the conceptual implications of her mathematical calculations and thought to generalize from them; she *composed* a formula of her own. In each, she explored her own questions beyond the assignment, and her responses involve explicit metacognition, as she narrates the flow of her reasoning.

In her interview, Marya contrasted what she had been doing, "throwing symbols all over the place" with trying to "honestly have a good grasp of what was going on."

> Rather than depending on a teacher to give you the right answer or a professor to tell you that's right, […] we were approaching physics as if we were just discovering physics.

It was a shift of epistemological framing, evidenced by and supporting her tapping into her knowledge and experience, such as of bouncing or of finding new patterns and relationships. I believe the influence goes the other way as well: Thinking about her experience of bouncing, for example, helps maintain her sense of what she's doing.[2]

There's also evidence of her interest and excitement ("So the relationship holds true!!"); Marya told Lama about how she "got so excited" to have found that relationship. That's the focus of the article we're writing (Radoff, Jaber, and Hammer, in preparation). But the focus here is conceptual change, as the editors remind me.

Energy is the salient concept in Marya's responses above, and the evidence shows local dynamics. On the checkpoint question, Marya considered the possibility of the ball speeding up when it bounces, which would mean a gain in kinetic energy. Watching a video of billiard balls and bouncing a ball off a wall dissuaded her from that idea, but she ended her response not quite sure the ball can't speed up. She didn't consider that possibility on the carts problem, which did not involve bouncing, nor on the next problem in the set, which did. I believe her presuming conservation on those problems reflects their organization around mathematical expressions that do not afford adding

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[2] An analogy: Having the ingredients for my salad out on the table helps maintain my sense of what I'm doing.

energy. It is also possible she had become convinced energy is conserved, but she did not mention coming to that conclusion.

There are continuities in Marya's understanding of energy across these problems: that there is such a thing, that it can be "lost," that it is associated with speed. So it may be reasonable to say "Marya understands moving objects have energy." In other respects, the substance seems to be a soft-assembly involving features of the situation. She participates in that assembly, but from one situation to another the assemblies only partially align, so it would be a mistake to attribute them to her as an individual. Over time, as she participates in these assemblies, patterns of her thinking in them will recur and shift and develop stability, in her. And, I believe, that stability will involve epistemology, in her sense of *energy* as a concept with consistent meaning, serving physics as a pursuit of understanding.

Attributing a concept of energy to Marya, again, ought to mean stability in her, easily recurrent and persistent across situations. There is evidence from her later work that Marya made progress in that direction, although obviously it was all within the context of the course. In the end, though, I can't say "Marya understands energy," at the level of introductory mechanics.

I can say Marya frames learning differently. There is evidence of new stability in how she approaches and feels about learning, easily recurrent and persistent across situations, both within the course and, we have evidence, beyond it: In her interview with Lama, Marya said she was "doing the same things" now in Calculus. And, in a followup interview with Jen two years later, Marya said what she learned in physics transformed how she approached and felt about learning across her program.

More than conceptions

Science educators have generally seen conceptual change as the main objective, assessing learning mainly by gains on conceptual inventories, designing learning progressions to arrive at canonical concepts. But when I think of what happened for Marya in my course, I see her progress *as a learner* as far more important. I would like to understand how to help that happen more often—it's the reason for our case study (Radoff, Jaber, and Hammer, in preparation).

Some of that, we argue, was in how Marya experienced conceptual change, supporting and supported by her shift of epistemology and, entangled with that, her feelings about uncertainty. Some, it is clear, had to do with our emphasis in the course, prioritizing students' learning how to learn, at times over their arriving at correct understandings.

Looking forward, I think it's important to engage further with the complexity the dynamics—what Amir, Smith, and Wiser (2014) called the "third phase" of research. That may include reconsidering conventional practices of aggregating data, on the possibility of chaotic dynamics in learning (Hammer & Sikorski, 2015).

Finally, for me it includes examining the messy complexity of knowledge and reasoning as I experience it in myself. I'm not suggesting anyone rely on introspection, any more than I would suggest physics students should rely on their experience of physical phenomena. But I do think our theories and our experiences should speak to each other.

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