Implications of Complexity for Research on Learning Progressions

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Introduction

The National Research Council first offered learning progressions (LPs) as a potentially generative construct for science education in its 2007 report *Taking Science to School*. The report defined LPs as "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time" (NRC, 2007, p. 214).

In contrast to prior work that pursued a single best instructional sequence, "learning progressions recognize that all students will follow not one general sequence, but multiple (often interacting) sequences around important disciplinary specific core ideas (e.g., atomic-molecular theory, evolutionary theory, cell theory, force and motion). The challenge is to document and describe paths that work as well as to investigate possible trade-offs in choosing different paths" (NRC, 2007, p. 221). *Taking Science to School* anticipated that work on LPs would consolidate decades of prior research on student thinking and serve as the basis of curriculum development.

A burst of LP work followed the release of the NRC report.[1] Mapping out an ever increasing expanse of conceptual territory, there are LPs for most major topics in K-12 science curriculum, as well as for disciplinary practices including modeling (Schwarz et al., 2009) and argumentation (Berland & McNeill, 2010). Despite the initial expectations of multiplicity, most published LPs describe a single, levels-based sequence from a lower to an upper anchor; some present a small number of alternative sequences. With a few notable exceptions, the analyses supporting these LPs rely on cross-sectional studies that aggregate data across large numbers of students.

Our purpose in this essay is to challenge this mainstream notion of learning progressions, as generalizable sequences, or small sets of alternatives, studied and validated through statistical measures of large data sets.

We work from a premise that learning is complex, which we motivate briefly in the following section. From there we present two lines of argument. The first focuses on the notion of coherence, often treated as a static property of curriculum materials. We argue that coherence should be understood as a dynamic aspect of learners' experience, dependent on the myriad different ideas that students draw on and try to make sense of in the moment. The second line of argument concerns practices of data aggregation that are designed to filter out variations within the statistical population, on the presumption that variations are conceptually insignificant noise. A view of

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[1] A Google Scholar Citation search for the phrase "learning progression" for each year 2006-2014 provides a coarse indicator of LP activity. A search in 2006, prior to the NRC report featuring LPs, yields 166 hits. The year of the report, 2007, yields 216 hits, and in years following: 257, 324, 420, 511, to finally a local peak of 801 publications in 2012.

learning as complex challenges that presumption: The idiosyncrasies of particular moments, we argue, are essential to student learning and to meaningful understanding of learning progressions.

The complexity of cognition and learning
Education research is taking up views of cognition and learning as complex (Amin, Smith & Wiser, to appear), complex in the sense of multiple, mutually influencing aspects of minds and contexts. These interactions lead to emergent behaviors, a general feature of complex systems, in which "more than a single cause or a few dominant causes are responsible for the behavior we wish to explain" (Mitchell, 2009, p. 41). Familiar examples include traffic jams and slime mold behavior (Wilensky & Resnick, 1999).

A complex system can be as simple as one pendulum swinging from the bottom of another, which swings from a fixed pivot.[2] The motion of the top pendulum affects the motion of the bottom, which in turn affects the motion of the top, making a feedback loop that can amplify deviations. A double-pendulum, like many complex systems, shows "chaos," where tiny differences in initial states result in very different trajectories (Shinbrot, Grebogi, Wisdom & Yorke, 1992).

A great many studies document feedback in cognition, at scales ranging from individuals to institutions. Kahneman (2011) described examples of "reciprocal priming effects": Subjects' having walked slowly for five minutes were faster at recognizing words related to old age; thinking of old age makes people move more slowly. Subjects holding a pencil in their mouths in a way that forced a "smile" found more humor in cartoons than those who held the pencil in a way that forced a frown; finding humor makes people smile. How people hold their bodies, whether in expansive "high-power" or contracted "low-power" poses, affects how powerful they feel (Carney, Cuddy, & Yap, 2010), which affects how they hold their bodies. Of course, people's emotions influence each other, communicated by those same facial expressions and body language.

Within education, Yackel and Cobb (1996) discussed "reflexivity" in the formation of disciplinary norms, with "goals and largely implicit understandings" influencing and influenced by shared expectations (p. 460) among students and their teacher in a mathematics class. At a larger scale, Vaught and Castagno (2008) showed that educators' attitudes and perceptions about race influenced and were influenced by institutional patterns and structures across a school system. And so on: The complex systems of minds within social and material situations involve vast numbers of "parts" in interaction.

What happens in science class
To consider a scale relevant to LP research, we offer a brief example of student thinking from science class. We focus on how students treat anomalous data, "evidence that contradicts their preinstructional theories" (Chinn & Brewer, 1993).

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[2] See, e.g., http://en.wikipedia.org/wiki/Double_pendulum.

As part of their investigation into why a puddle would disappear over the course of a day, a group of fifth-graders consider the possibilities that the water evaporated or that it seeped into the asphalt (Sikorski, 2012). Unsure how to proceed, they decide to pour some puddles and see what happens. They make one with twice as much water as the other, and they time how long it takes each to evaporate. The results surprise them in two ways.

The first surprise is that the asphalt is cool to the touch, on the stain where the water used to be. John had predicted it would be hot, thinking that evaporation involves heat. He finds, however, that it is much cooler, compared to the surrounding asphalt. Molly and John check other places to confirm the stain is always cooler. Trying to explain this finding, the group has a lively discussion, considering ideas including Leah's that asphalt would be cool if water soaked into it, and Ari's that puddles might act like "giant sunglasses" shielding the asphalt.

Later at their desks, the students work on writing their individual reports. While writing, Ari notices that the puddle that was twice as big did not take twice as long to evaporate, a second anomalous finding. The other students look up only briefly from their work to suggest that maybe the time to evaporate depends on "the ground" or "location" of the puddle. Ari wants to pursue the topic: Maybe the puddle with more water spread out faster, became thinner, and therefore evaporated more quickly. But he is the only one; the others continue with their reports.

"What," Chinn and Brewer (1993) asked, "are the conditions that lead to different responses to anomalous data? That is, why does a student ignore anomalous data in one instance, reject anomalous data in another instance, and abandon his or her pre-instructional theory in a third instance?" (p. 3). Here we can ask, why did the group take up trying to explain the first surprise but not the second?

Returning to our premise, the example shows many parts in interaction. In the first moment, the students were outside and free to move around; the discrepancy was tactile; John, a student with high social status, was the one to point out the discrepancy. In the second, they were indoors, sitting at desks working on completing the assignment; the discrepancy was numeric; Ari did not have high social status. As well, the dynamics involved feedback, e.g. John's interest raised other students', and their interest likely encouraged his. We can analyze what took place, in these instances, but the complexity of the dynamics makes it difficult to give a simple, general answer to Chinn's and Brewer's question.

We and our colleagues study learners' reasoning *in situ*, in elementary and middle school (e.g. Rosenberg, Hammer, & Phelan, 2006; Sikorski, 2012), high school (Elby, 2001; Hammer, 1997), college (Frank & Scherr, 2012; Watkins & Elby, 2013), and teacher development (Hutchison & Hammer, 2010; Watkins, Coffey, Maskiewicz, & Hammer, in press). Many other studies in the literature similarly depict the dynamics of classroom interactions and reasoning, from a variety of theoretical and methodological orientations (Engle, Langer-Osuna, McKinney de Royston, 2014; Leander & Brown, 1999; Rosebery, Ogonowski, DiSchino, & Warren, 2010).

Across all of these accounts, the dynamics of students' engagement show complexity: Many parts in interaction give rise to idiosyncratic particularities: An elementary class discussion about heat takes off after a fire drill, which had the students out in the cold without coats (Rosebery, *et al,* 2010); the substance of lively debate among fifth graders about whether orcas are whales interacts with the participants' social positions (Engle, *et al*, 2014); a high school episode centers on one resistant student (Leander & Brown, 1999); college students' thinking about basic kinematics shifts with how they place materials on their table (Frank & Scherr, 2012).

All of this research supports our premise for the remainder of this essay: Phenomena of cognition and learning are complex. We do not expect this to be controversial. Perhaps, though, it is too easy a premise to accept, a truism that does not inspire serious consideration, because however familiar the point, it has had little impact on systemic thinking about education.

In this next section, we argue that mainstream LP work has not attended to the complexity of learners' reasoning in conceptualizing coherence as a target of instruction. We then turn to the more general argument about data aggregation.

The target of coherence

> The promise of LPs lies in the potential to guide the coordination of teaching, instructional resources, and assessment with cognitive and metacognitive practices so that learning builds coherently. However, the field has not yet come to consensus on a more precise definition of what an LP is. (Sevian and Talanquer (2014, p. 11)

Part of the challenge of defining what an LP is, we suggest, concerns what it means that *learning builds coherently*. Is that coherence in the sense of the established body of knowledge, in the sense of learners' experience, or both?

For scientists, coherence is an essential feature of canonical understanding. To assess students' reasoning for *canonical coherence* means to check it for alignment with the established body of knowledge. The student's expectation, for example, that the puddle's evaporation would heat the asphalt, was not coherent in this sense. Almost all published LPs define their "upper anchors" in ways that involve canonical coherence.[3]

At the same time, it is central to LP work to focus on coherence in the sense of learners' experience (Roth and Givvn, 2008; Fortus & Krajcik, 2013). Research attends to students' own sensemaking, considering the ideas and evidence they have available, to identify ways their understandings build over time. In this work, it is critical to recognize that what students experience as

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[3] The Project 2061 *Atlas of Science Literacy* (2001) provides elaborate maps of coherence in this sense. It is designed specifically to represent not only the set of "benchmark" goals for student learning but also, critically, the connections among those goals.

coherent along the way may not be coherent in the sense of the target canonical understanding but still be a step in that direction.

The student's reasoning that evaporation causes heat did show coherence in this sense: It held together sufficiently in the students' minds to motivate their checking the asphalt and to have them surprised by the results. It could be part of an LP, if it were a sufficiently common, productive step for students.

Ideally, findings from mainstream LP research supports curriculum development to accomplish coherence in both respects: By identifying progressions of ideas learners experience as coherent and that build toward canonical understanding, LP research helps developers structure curricula around "storylines." The complexity of learning, however, makes this difficult to accomplish.

If learning is complex, then the dynamics of students' reasoning may often be particular and idiosyncratic. An idea such as this one, that evaporation causes heat, is not sufficiently common to emerge from aggregate data analysis, so it is not part of a learning progression, so it is not part of a storyline. Part of the question, then, is whether it is important for students to consider the idiosyncratic ideas like this that may come up. Another part of the question is how to keep students following the storyline, when there are more possible connections they could consider than the curriculum could feasibly plan to address.

To be sure, complexity does not require idiosyncrasy, and it is clear that in many cases there are predictable patterns of reasoning, such as the idea of water soaking into the ground (Tytler, 2000). However, complexity *affords* idiosyncrasy, and it is evident across research on learning, especially in settings that cultivate students' epistemic agency. Educators can design materials and arrange settings for student thinking, but students' experiences involve far more than educators can determine.

By these arguments, instruction that keeps students on track may do so at a cost to their own coherence seeking (Sikorski, 2012). That could happen through explicit direction ("That's a great question, Molly, maybe we can get to it later."). It could also happen through "narrative seduction" (Bruner, 1991), as when readers or moviegoers find the storyline so compelling that they do not check it themselves for plausibility or consistency.

That students have particular ideas, that they have the opportunities to pursue and assess and refine those ideas, is inherent to their taking up science as a pursuit. Students' progress in science entails their progress as epistemic agents, and the space of possible connections they may consider in their seeking is vast. For this reason, we argue, research and instruction should recognize idiosyncrasy as essential.

This points to a far more general problem concerning the rigor of aggregation.

The problem with aggregation

Imagine empirical research on the double pendulum we mentioned earlier, based on aggregate data across many copies of the system. Even if all the systems were identical to within the limits of measurement, for many regions of initial conditions they would behave very differently: Tiny variations would amplify. If the purpose were to identify conditions leading to a specific outcome, the study would fail. Averages or regressions or hierarchical linear models would shed little light on the systems' dynamics.

There are other ways to mathematize phenomena. For the double-pendulum, it is straightforward for physicists to write down the equations of motion, and from these derive the sorts of dynamics experimentalists observe. Other systems such as traffic and weather are far more difficult, with many more variables and parameters, and modeling these systems demands significant computational power. We do not anticipate such models of classrooms and learning, for practical use, any time in the near future. But in the meantime, it is a mistake to presume aggregate statistics will shed light on the dynamics of learning.

We are not arguing in general against aggregating data in large-N studies. For many targets of research, it is perfectly appropriate. Carney, Cuddy and Yap (2010) aggregated data across many subjects to establish that one's pose can affect one's feelings of power. But for many targets of research on complex systems, it is not helpful, in particular when the dynamics are such that tiny differences amplify rapidly—that is when the dynamics are chaotic.

A central challenge of research on many complex systems is to identify when the dynamics may become chaotic. Chaos is something civil engineers work to avoid in designing for traffic patterns and meteorologists must accept in understanding weather. Perhaps it is something educators should value.

Above we gave a quick example of student inquiry and noted many others that showed idiosyncratic particularities. We cannot draw it as a formal conclusion, but it seems a likely supposition, that these episodes involve chaotic dynamics. We suggest that chaos (in the technical sense!) is a standard part of life in healthy classrooms, when students are coming up with ideas, asking and pursuing their own questions, inherent in "explosions" (Manz, 2012) of student participation, and in the set and sequence of ideas students' conceive.

If so, the education community needs approaches to research that can capture and consider idiosyncrasy, not as statistical noise to eliminate but as part of the phenomena of interest.

Looking ahead

We have argued that the mainstream notion of LPs is inconsistent with the premise of complexity of cognition and learning on two fronts, one relating to how LPs conceptualize coherence and the other in how they aggregate data. Some researchers, however, work to address complexity.

Sevian and Talanquer (2014), for instance, describe the construction of a learning progression for chemical thinking that has complexity as a core theoretical commitment. Rather than a discrete list of ideas, their LP is more like a multi-dimensional potential energy surface, dimensions corresponding to aspects of student progress. Dips in the surface, or potential wells, are like dynamic attractors—emergent and relatively stable phenomena. The LP charts the "evolutionary path of such states from naïve to sophisticated ways of thinking, as well as the internal constraints and conditions (e.g. instruction) that support such evolution" (p. 14). By necessity, the lower and upper anchors of the LP are more well-defined than the intermediate stages or pathways between the attractors (Talanquer, 2009),

Sevian and Talanquer cite another LP design team, the Inquiry Project, as influential in their thinking (Wiser & Smith, 2008; Wiser, Smith, Doubler, & Asbell-Clarke, 2009; Wiser, Fox, & Frazier, 2013). Inquiry project LP work is longitudinal and small-n, aiming to see how individual students' ideas about matter evolve over time, using repeated clinical interviews (Carraher, Smith, Wiser, Schliemann, & Cayton-Hodges, 2009).

Ultimately, the desire for accessible models of progress in chemical thinking or structure of matter that can inform assessment and instruction may force upon these novel LPs a more discrete, levels-like format. Much depends on designers' choices for how to account for variability in students' ideas, and whether curriculum informed by LPs will support or work to reduce that variability.

Conclusion

The notion of learning progressions may itself be a "stepping stone," a "productive [way] of thinking that may support important re-conceptualizations" (Sevian & Talanquer, 2014, p. 15) in the research community's ongoing efforts to explain how student thinking and understanding evolves over time. Stepping stone ideas are thoughtful, plausible, and consensus-building intermediaries that push learners, and in our case researchers, toward new ways of thinking (Wiser, Fox, & Frasier, 2013).

As a stepping stone idea, LPs can support our own community's reconceptualization of progress. Duncan and Hmelo-Silver (2009) explain that student progress "is likely more akin to ecological succession than to constrained lock-step developmental stages" (p. 607). LP work that involves validation in close analyses of particular dynamics, and that prioritizes learners' coherence seeking, may help us reach our next level.

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References

AAAS. (2001). *Atlas of science literacy.* New York: Oxford University Press.

Amin, T. G., Smith, C. L., & Wiser, M. (to appear). Student conceptions and conceptual change: Three overlapping phases of research. In N. Lederman & S. Abell (Eds.), *Handbook of Research in Science Education.* New York Routledge.

Berland, L. & McNeill, K. (2010). A learning progression for scientific argumentation. *Science Education, 94*(5), 765-793.

Bruner, J. (1991). The narrative construction of reality. *Critical Inquiry, 18*, 1-21.

Carney, D. R., Cuddy, A. J. C., and Yap, A. J. (2010). Power posing: Brief nonverbal displays affect neuroendocrine levels and risk tolerance. *Psychological Science, 21*(10), 1363-1368.

Carraher, D., Smith, C.L., Wiser, M., Schliemann, A., & Cayton-Hodges, G. (2009, June). *Assessing students' evolving understandings about matter*. Paper presented at the Learning Progressions in Science (LeaPS) Conference, Iowa City, IA.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*(1), 1-49.

Duncan, R. & Hmelo-Silver, C. (2009). Learning progressions: Aligning curriculum, instruction, and assessment. *Journal of Research in Science Teaching, 46*(6), 606-609.

Elby, A. (2001). Helping physics students learn how to learn. American Journal of Physics, *Physics Education Research Supplement, 69*(7), S54-S64.

Engle, R. A., Langer-Osuna, J. M., & McKinney de Royston, M. (2014). Toward a Model of Influence in Persuasive Discussions: Negotiating Quality, Authority, Privilege, and Access Within a Student-Led Argument. Journal of the Learning Sciences, 23(2), 245-268.

Fortus, D. & Krajcik, J. (2013). Curriculum Coherence and Learning Progressions. In B. Fraser, C. McRobbie, & K. Tobin (Eds.), *Second International Handbook of Science Education*, Dordrecht: Springer Verlag.

Frank, B., & Scherr, R. (2012). Interactional processes for stabilizing conceptual coherences in physics. *Physical Review Special Topics—Physics Education Research, 8*(2), 020101-9.

Hammer, D. (1997). Discovery learning and discovery teaching. *Cognition & Instruction, 15*(4), 485-529.

Hutchison, P. & Hammer, D. (2010). Attending to student epistemological framing in a science classroom. *Science Education, 94*(3), 506-514.

Kahneman, D. (2011). *Thinking, fast and slow*. New York: Farrar, Straus and Giroux.

Leander, K., & Brown, D. E. (1999). "You Understand, But You Don't Believe It": Tracing the stabilities and instabilities of interaction in a physics classroom through a multidimensional framework. *Cognition & Instruction, 17*(1), 93-135.

Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. Science Education, 96(6), 1071-1105. doi: 10.1002/sce.21030

Mitchell, S. (2009). *Unsimple truths: Science, complexity, and policy*. Chicago, IL: University of Chicago Press.

National Research Council (NRC) (2007). *Taking Science to School: Learning and Teaching Science in Grades K-8*. Washington, DC: The National Academies Press, 2007.

Rosebery, A. S., Ogonowski, M., DiSchino, M., & Warren, B. (2010). "The coat traps all your body heat": Heterogeneity as fundamental to learning. *The Journal of the Learning Sciences, 19*(3), 322–357.

Rosenberg, S., Hammer, D., & Phelan, J. (2006). Multiple epistemological coherences in an eighth-grade discussion of the rock cycle. *Journal of the Learning Sciences, 15*(2), 261-292.

Roth, K. & Givvin, K. (2008). Implications for math and science instruction from the TIMSS 1999 Video Study. *Principal Leadership*, 22-27.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Acher, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632-654.

Sevian, H. & Talanquer, V. (2014). Rethinking chemistry: A learning progression on chemical thinking. *Chemical Education Research and Practice, 15*, 10-23.

Shinbrot, T., Grebogi, C., Wisdom, J. & Yorke, J. (1992). Chaos in a double pendulum. *American Journal of Physics, 60*(6), 491-499.

Sikorski, (2012). Developing an alternative perspective on coherence seeking in science classrooms. Unpublished doctoral dissertation, University of Maryland, College Park.

Talanquer, V. (2009). On cognitive constraints and learning progressions: The case of "structure of matter." *International Journal of Science Education, 31*(15), 2123-2136.

Tytler, R. (2000). A comparison of year 1 and year 6 students' conceptions of evaporation and condensation: dimensions of conceptual progression. *International Journal of Science Education, 22*(5), 447-467.

Vaught, S. & Castagno, A. (2008). "I don't think I'm a racist": Critical race theory, teacher attitudes, and structural racism. *Race, Ethnicity, and Education*, 11(2), 95-113.

Watkins, J., Coffey, J. E., Maskiewicz, A. C., & Hammer, D. (in press). An account of teachers' epistemological progress in science. In G. Schraw, J. Brownlee, L. Olafson & M. VanderVeldt (Eds.), *Teachers' Personal Epistemologies: Evolving Models for Transforming Practice.* Charlotte, NC: Information Age Press.

Watkins, J. & Elby, A. (2013). Context dependence of students' views about the role of equations in understanding biology. *CBE—Life Sciences Education, 12*(2), 174-286.

Wilensky, U., and Resnick, M. (1999). Thinking in levels: A dynamic systems approach to making sense of the world. *Journal of Science Education and Technology, 8*(1), 3-19.

Wiser M., Fox V. and Frazier K., (2013), At the beginning was amount of material: a learning progression for matter for early elementary grades, in Tsaparlis G. and Sevian H. (ed.), *Concepts of matter in science education,* Dordrecht: Springer, pp. 95–122.

Wiser M. and Smith C. L., (2008), Learning and teaching about matter in Grades K-8: when should the atomic-molecular theory be introduced? in Vosniadou S. (Ed.), *International handbook of research on conceptual change*, New York: Routledge, pp. 205–239.

Wiser, M., Smith, C.L., Doubler, S., Asbell-Clarke, J. (2009, June). *Learning progressions as tools for curriculum development: Lessons from the Inquiry Project*. Paper presented at the Learning Progressions for Science (LeaPS) Conference, Iowa City, IA.

Yackel, E., & Cobb, P. (1996). Sociomathematical norms, argumentation, and autonomy in mathematics. *Journal for Research in Mathematics Education, 27*, 458-477.