

A critique of how learning progressions research conceptualizes sophistication and progress

Tiffany-Rose Sikorski, David Hammer, University of Maryland, College Park, MD 20742
tsikorsk@umd.edu, davidham@physics.umd.edu

Abstract: Researchers in science education have moved quickly to pursue “learning progressions,” defined by the NRC (2007) as “descriptions of the successively more sophisticated ways of thinking about a topic” (p. 219). Given the speed of its adoption, it is not surprising there are variations in how the notion is understood, regarding how to assess sophistication as well as how to conceptualize progress. We examine learning progressions by three leading groups, to challenge assumptions that (1) ideas are “more sophisticated” insofar as they align more closely with end-state canonical knowledge, and (2) student progress can be characterized as a sequence of levels. These assumptions conflict with advances in science education research toward views of learners’ knowledge and reasoning as complex, dynamic ecologies. By moving quickly to embrace learning progressions as an organizing concept for research, the community risks surrendering its own hard-won progress.

Introduction

In the past few years science education has turned toward *learning progressions* as an organizing concept for research. Learning progressions are “descriptions of the successively more sophisticated ways of thinking about a topic” (NRC, 2007, p. 214). Already, researchers have articulated learning progressions (LPs) for many different grade levels, topics, and aspects of science. Some LPs focus narrowly, such as on celestial motion (Plummer & Slagle, 2009). Others focus broadly, such as the LP for atomic-molecular theory (Smith, Wiser, Anderson, & Krajcik, 2006). There are also LPs focusing on students’ engagement in modeling (Schwarz, Reiser, Davis, Kenyon, Acher, Fortus et al., 2009) and other scientific inquiry practices. In addition to articulating these descriptions of progress, researchers have designed a variety of supporting materials for LPs, including assessment instruments, curricula, and instructional strategies.

Work on LPs has proceeded apace, as reported in a dedicated conference (Alonzo & Gotwals, 2009), a special journal issue (Hmelo-Silver & Duncan, 2009), a chapter in a National Research Council publication (NRC, 2007), and at least one literature review (Salinas, 2009). Recently, a working panel identified and discussed learning progressions from at least twenty different research projects, in part to define a common set of guidelines for future LPs (Corcoran, Mosher, & Rogat, 2009). Some researchers are even looking ahead to ways that LPs could be used to inform curricula and professional development (see for example Corrigan, Loper, Barber, Brown, & Kulikowich, 2009; Furtak, 2009).

Given the speed at which the community has adopted the notion of a learning progression, it is not surprising that there are variations in how that notion is understood. Much in particular depends on how educators understand “increasingly sophisticated,” and in this there is tension over whether to focus on disciplinary knowledge or on disciplinary practices (Hodson, 1988; Hutchison & Hammer, 2009). To focus on the former, we should consider an idea more sophisticated if it comes closer to current scientific understanding. To focus on the latter, we should consider an idea more sophisticated if it was generated and defended in ways that more closely resemble scientific practices, based on the evidence and reasoning available to students. That is, in considering what constitutes increasing sophistication, what aspect of the discipline should have priority?

Much depends as well on how educators conceptualize what constitutes progress. In this there is also tension, much of it tacit, over whether to expect a linear progression from one way or level of understanding to another, or whether to expect a variety of learning paths. Most advocates of LPs explicitly endorse the latter, but in practice published LPs more typically describe a sequence of levels.

In this paper we offer a critical review of three learning progressions, in student understanding of (1) heredity (Roseman et al., 2006), (2) force and motion (Alonzo & Steedle, 2008), and (3) matter (Carraher, Smith, Wiser, Schliemann, Cayton-Hodges, 2009; Wiser, Smith, Doubler, & Asbell-Clarke, 2009). The authors in each case are prominent researchers on learning progressions, and as a set, these LPs reflect a range of approaches and perspectives with respect to assessing sophistication and conceptualizing progress. We begin with a summary of each progression with respect to its scope, development, and substance.

Three Learning Progressions

Roseman, Caldwell, Gogos, & Kuth (2006): Molecular Basis of Heredity

This LP aims to present the sequence of ideas that will lead to a "coherent understanding" of the two main functions of DNA: "determining the characteristics of organisms" and "passing information from one generation to the next" (Roseman et al., 2006, p. 1). The learning progression spans grades K-12, but the authors describe in more detail the sequence of ideas they propose students encounter in high school.

The authors drew on the *Benchmarks for Science Literacy*, the *Atlas of Science Literacy*, and a series of other standards documents, as well as on their own evaluation of the discipline and education research studies, to identify potential sequences of scientific ideas that could lead to an understanding of heredity. Roseman et al. (2006) propose an order of topics that deviates from the traditional textbook approach: they present "proteins before DNA" and "DNA before genes and chromosomes" (p.1).

The LP takes the form of a map and consists of two interrelated strands corresponding to the two main functions of DNA. Both strands connect to the learning goal: students' understanding that "heritable characteristics ultimately produced in the development of an organism can be observed at molecular and whole-organism levels—in structure, chemistry, or behavior" (Roseman et al., 2006, p. 6). For example, the LP has this sequence of ideas as part of the strand for learning the second function of DNA:

Drawing mostly from benchmarks in the Heredity section of *Benchmarks*' Chapter 5: The Living Environment, the learning progression expects students in grades K-2 to learn that offspring resemble their parents (rather than other kinds of organisms). In grades 3-5 students learn that for offspring to resemble their parents, there must be a reliable way to transfer information from one generation to the next. In high school, with their prior knowledge of cells and protein molecules, students are ready to learn about the link between proteins and DNA and, hence, between DNA and traits. (Roseman et al., 2006, p. 2)

The authors provide a similar description for students' progressively more sophisticated understanding of the first function of DNA.

Roseman et al. (2006) propose to continually refine and validate their LP. First, they will reconsider "the grain size and language of the ideas" in the LP, ensuring that they align with standards, activities, and assessments (p. 3). Second, they intend to clarify the boundaries of "what specific knowledge students are and are not expected to know" (p. 3). As well, the authors will review the literature to identify common misconceptions regarding each idea. The misconceptions will inform the design of assessments and instructional activities, as well as help clarify the language of the LP itself. Finally, the authors plan to identify phenomena that will help students overcome their misconceptions and master the ideas in the LP.

Alonzo & Steedle (2008): Force and Motion

Alonzo & Steedle (2008) are developing a learning progression to serve as an interpretive framework for assessment. This LP is designed to "diagnose" students' understanding of force and motion, particularly after an introductory unit on the topic (p. 3).

Alonzo & Steedle (2008) define LPs as "ordered descriptions of students' understanding of a given concept" (p. 1). They employ an "iterative process" of (1) hypothesizing a series of levels for student thinking, initially based on the research literature, (2) constructing and implementing related assessments to probe student thinking at each of the levels, and (3) revising the hypothesized levels based on the results of the assessments (p. 4). The goal of the revisions is to ensure that the LP captures the breadth of student thinking about force and motion, as well as to ensure that assessment items accurately diagnose students' level on the progression:

[T]he learning progression represents a hypothesis about student thinking, rather than a description. As such, it expresses a current idea about how student understanding develops, which can—and should—be revised in response to new information about student thinking. (Alonzo, & Steedle, 2008, p. 5)

Alonzo & Steedle (2008) used the *National Science Education Standards* for eighth grade to inform their initial hypothesis, specifically to define the highest level of the LP. They also conducted a review of the literature to compile a list of "common student conceptions" about force and motion, and ordered these conceptions into levels

“based upon research literature...and (occasionally) the relative difficulty of these ideas, as well as a logical consideration of proximity to the top level of the learning progression” (p. 7-8).

The current version of the LP consists of 5 levels (0-4) and describes students’ thinking at each level along four kinds of problems: force or no force, and motion or no motion. The LP also includes anticipated common errors at each level. For example:

Level 2

Student believes that motion implies a force in the direction of motion and that nonmotion implies no force. Conversely, student believes that force implies motion in the direction of the force.

Force: If a force is acting upon an object, it is moving.

2A: The force acting on an object could be the initial force (which is carried with the object and may dissipate over time).

No Force: If no force is acting upon an object, it is not moving.

Motion: If an object is moving, a force is acting upon it.

No Motion: If an object is not moving, no force is acting upon it.

Common Errors:

- If there is no motion, there are no forces acting.
- When an object is moving, there is a force in the direction of its motion.
 - 2A: This motion could be the force that put the object into motion initially.
 - 2A: This object may come to rest because the force it carries with it has been used up. (Alonzo & Steedle, 2008, p. 16-17)

In addition to creating descriptions of each level in the LP, Alonzo & Steedle have developed associated assessment items for diagnosing students' levels on the progression.

The Inquiry Project: Matter

The Inquiry Project is currently conducting research on 3rd-5th grade students' reasoning about matter, material, weight, volume, and density, in part to contribute to a learning progression on the nature of matter (Smith, Wiser, Anderson, & Krajcik, 2006). The group has yet to publish a complete LP for these grades. However, two recent Inquiry Project publications (Carraher, Smith, Wiser, Schliemann, Cayton-Hodges, 2009; Wiser, Smith, Doubler, & Asbell-Clarke, 2009) describe in detail the project's work on developing such a progression.

Wiser et al. (2009) frame the problem of designing a learning progression as follows:

[G]iven a single starting point (preschoolers’ concepts and beliefs in the matter domain) and a single target point (the atomic-molecular theory taught to adolescents in a majority of countries) in how many ways can the knowledge network evolve (when characterized at the level of concepts and beliefs)? (p. 4).

In alignment with previous work (Smith et al., 2006), the Inquiry Project grounds its work on LPs in a theoretical framework of conceptual change. In this view, students’ initial understandings of matter are fundamentally different—and incompatible—with scientists’ understandings. For example, learning the atomic-molecular theory of matter (ATM) requires massive "reconceptualization" of students' ideas about material and matter (Wiser et al., p. 2). Wiser et al. (2009) predict that there are only a few possible pathways to a learning goal such as ATM, because “knowledge network[s] can only change productively in very few ways” (p. 4). Carraher et al. (2009) anticipate that 3rd-5th grade students' progression in reasoning about matter will involve two interrelated changes:

- A gradual shift from (a) perception-centered thinking, that is, understanding and explanation closely tied to perceptual judgment and appearances, to (b) model-mediated thinking, informed by views about matter and drawing upon a set of increasingly advanced, inter-related concepts and scientific habits of mind.
- The development of quantitative reasoning and understanding of measurement that students can use to make predictions, interpret, and explain relationships among physical quantities... (p. 3)

The Inquiry Project has undertaken a three-year longitudinal study to explore these changes. The study involves the design and implementation of a novel curriculum aimed at "fostering the development of students' knowledge about

matter" (Wiser et al., 2009, p. 1). The Inquiry Project also conducts a series of clinical interviews to explore control students' (those exposed to a traditional curriculum) and treatment students' (those exposed to the Inquiry Project curriculum) ideas about matter-related concepts (see Carraher et al., 2009).

The Inquiry Project is currently in the process of gathering and analyzing data. They have confirmed some aspects of the lower anchor of their LP, for example, that "the distinction between material kind and weight are sporadic and context-dependent" (Wiser et al., 2009, p. 9). The authors are working to establish the "intermediate" levels—or "stepping stones"—of the progression (p. 1).

Sophistication and Progress

Despite the variety of definitions of *learning progression* circulating in the literature, they all share a general sense that LPs describe how students become more sophisticated with respect to some aspect of science (Salinas, 2009). Roseman et al. (2006) design sequences of concepts in the canon based on disciplinary knowledge as mapped by Project 2061. Alonzo & Steedle (2008) hypothesize, test, and refine sequences of student conceptions using both disciplinary knowledge and research on learning. Wiser et al. (2009) are looking for sequences of student conceptions interwoven with epistemologies and practices of science. Our focus in this critical review is on how each of these LPs assesses "sophistication" and on how each conceptualizes the dynamics of progress.

Assessing Sophistication

It may be educational common sense that what students learn should be correct knowledge, beginning with simpler, more foundational ideas and building from there to more complex, difficult material. Children learn to count, then to add, later to multiply, and so on. Roseman et al. (2006)'s work is designed around that view of knowledge and progress. In their LP, the canonical ideas themselves constitute the pathways of learning, and these pathways are therefore naturally towards more complete, correct understandings (Furtak, 2009).

Alonzo & Steedle (2008), on the other hand, create a learning progression not from canonical ideas, but from students' ideas, both correct and incorrect. In this respect, the two LPs are quite different. Roseman et al. (2006) do not include students' alternative conceptions in their LP, a difference that we explore further in the section "Conceptualizing the Dynamics of Progress." With respect to their determinations of sophistication, however, the two LPs are similar. According to Alonzo & Steedle (2008), the force and motion LP describes

the thinking that students at that level could be expected to exhibit, including both the correct ideas that can be carried to the next level and the misconceptions that will need to be revised before students can reach the next level (p. 4).

Like Roseman et al., Alonzo & Steedle take "more sophisticated" to mean "more correct," that is more completely aligned with the target canonical understanding.

There are several reasons, however, to question the educational common sense that student learning should proceed as a sequence of conceptual attainments. First, such a sequence has not generally characterized progress within the sciences. Unlike basic ideas of arithmetic, which have been stable for millennia, basic ideas within science have gone through dramatic change. Concepts of life, matter, and energy that are foundational today were relatively recent constructions. (That life arises only from other life and the concept of energy are less than 200 years old; the idea that matter is made up of atoms is a notable exception, although the modern understanding of atoms as opposed to molecules is quite young.)

Moreover, it has happened often in science that the formation of a wrong idea has been generative for later progress. For example, the Caloric Theory treated heat as an invisible substance that is contained in hot objects and can flow into from them to cold objects. That incorrect idea was a stepping stone toward differentiating heat as an extensive quantity from temperature as an intensive quantity, as well as toward understanding energy as conserved (Chang, 2004). That is, the formation of a wrong idea may be a productive development in science. By including only correct concepts in their LP, Roseman et al. (2006) systematically omit the possibility of productive, incorrect ideas. And although their conceptualization of LPs does not necessitate it, Alonzo and Steedle (2008) do something similar by including among their hypotheses only sequences that become more correct over time.

Second, research on science learning has come to understand that progress is not entirely, or even primarily, about correct *concepts*. Indeed, the original emphasis of misconceptions research was that students' wrong ideas are often rational in ways that are constructive of scientific practices (Strike & Posner, 1985); in subsequent years Strike and Posner (1994) specifically revised their discussion of misconceptions to emphasize that "if conceptual change theory suggests anything about instruction, it is that the handles to effective instruction are to be found in persistent attention to the argument and in less attention to right answers" (p. 171). Minds, they argued, are

complex, dynamic *ecologies*. To determine the sophistication of student ideas by their alignment with the canon is to overlook other aspects of those ecologies.

One outcome of a focus on “right answers” is that, in the practices of assessment and instruction it encourages, students may learn to assess ideas by their alignment with the canon rather than by fit with the evidence and reasoning they have available (Coffey, in preparation). That is to say, measures of sophistication organized around alignment with the canon are often at odds with assessments of quality by the *practices* of science. How, for example, should a teacher think about a student's progress who develops an account of inheritance based on evidence of how a mother's behavior and health during her pregnancy affects offspring characteristics? That account may differ greatly from canonical understanding, but the student's reasoning in producing it may reflect nascent scientific practices of generating ideas from evidence and reasoning.

For a number of years, the field has moved toward conceptualizing students' progress in science in ways that consider engagement in disciplinary practices (Engle & Conant, 2002; Ford, 2005). Progress in that engagement may involve students' pursuit of non-canonical, but by other criteria sophisticated, accounts of phenomena (Hammer, 1997; Russ, Coffey, Hammer, & Hutchison, 2009).

Unlike Roseman et al. (2006) and Alonzo & Steedle (2008), Wiser et al. (2009) work explicitly from a cognitive theory in which movement along a learning progression is more than just the linear acquisition of “more elements of the expert theory” (p. 9). Instead, they define movement along the progression such that students are put “in a better position, eventually, to understand a basic version of AMT” (p. 9). In this framework, “stepping stones” need not align with the logical structure of the end-state canonical knowledge, nor are they limited to concepts:

[T]hey are sets of concepts, beliefs, principles, models, numerical & mathematical understandings, and representational tools that provide students with coherent interpretations of a broad range of phenomena... (Wiser et al., 2009, p. 9)

The Inquiry Group acknowledges flexibility in determining stepping stones, especially for young students. For example, they considered two potential stepping stones in the fifth grade curriculum: (i) “a solid understanding, at the macroscopic level, of weight, volume, material, mass, and density, and their interrelations, consistent with the expert view”, or (ii) a particulate model of matter (Wiser et al., 2009, p. 10). The researchers opted for option (ii). That is, students are permitted to continue with their non-canonical ideas about mass and weight, for example, in order to pursue melting, freezing, evaporating, and a host of other phenomena explainable by particulate models of matter. The authors predict that pursuing a particulate model for matter will be more interesting to students, align more with students' expectations about science, and have “the most pay-off or ‘legs’ from a scientific perspective” by “introduc[ing] students to a productive new framework for thinking about matter” (p. 11).

It is unclear, however, whether the Inquiry Project will allow students' *non-canonical models* of matter to act as stepping stones in their progression. Allowing the development of non-canonical, but productive models is not prevalent in learning progressions literature, though Stevens, Shin, & Krajcik (2009) and Corcoran et al. (2009) for example suggest that non-canonical models might help students' move towards upper anchor understanding. Wiser et al. (2009) appear to be struggling with this aspect of the development of their LP:

A central issue is exactly what set of elements to include in a particulate model and how to introduce them in a way that helps students understand deeper epistemological issues about models, including their tentative revisable nature and their use as tools of inquiry. (p. 11)

This is an essential challenge for research on learning progressions: Conceptual understanding is only part of a complex dynamic, and LPs that treat it as a separable component may direct educational attention in such a way as to interfere with a healthy, productive cognitive and metacognitive ecology. Understanding the mind as a complex, dynamic ecology challenges another feature of LPs as well, namely the idea that students' conceptual knowledge can be characterized by levels. We turn to that aspect of our critique now.

Conceptualizing the Dynamics of Progress

A working panel on learning progressions recently suggested that any 'good learning progression' should contain a levels-like description of students' knowledge:

Levels of achievement that are intermediate steps in the developmental pathway(s) traced by the learning progression. These levels may reflect levels of integration or common stages that characterize the development of student thinking. (Corcoran, Mosher, & Rogat, 2009, p. 38)

Many groups have taken levels-based approaches to constructing LPs (see for example Mohan, Chen, & Anderson, 2009; Plummer & Slagle, 2009). A levels-based LP provides an organizing structure for “grouping similar sets of ideas” about a concept together and maps a clear pathway from initial to expert understandings (Alonzo & Steedle, 2008, p. 5). For example, Alonzo & Steedle’s LP consists of five levels, each describing a qualitatively distinct way that students might think about force and motion. The progression also suggests a possible pathway for “how student understanding develops”—that is, from one qualitatively distinct level to the next (Alonzo & Steedle, 2008, p. 30).

There are several reasons, however, to question a levels-based approach to characterizing students’ progress in science. In their work on validating the force and motion learning progress, Alonzo & Steedle (2008) highlight one potential problem: levels may not adequately describe the state of students’ knowledge.

Levels, as described by Corcoran et al. (2009), denote periods of consistency in students’ knowledge. In this view, a student who gives a Level 2 response on a Newton’s third law question, for example, should give similar responses on all Newton’s third law questions. Alonzo & Steedle (2008), however, found that students “do not respond consistently across problem contexts” (p. 29). That is, students can appear to be on two different levels simultaneously. Alonzo & Steedle attribute some of the inconsistency to ambiguities in the language of assessment items. However, the authors also acknowledge that students’ reasoning may be context sensitive, and so it may not be possible to “produce a single, reliable diagnosis of a student’s level” on a learning progression (p. 29).

Steedle & Shavelson (2009) investigated whether students’ responses on the diagnostic test designed by Alonzo & Steedle (2008) do indeed “reflect the systematic application of a coherent set of ideas needed to afford valid interpretations of learning progression level diagnoses” (p. 15). They found that in general, the answer is no—students do not respond in ways that suggest systematic application of a coherent set of ideas. In other words, students’ ideas are not accurately described by coherent, qualitatively different levels. The two exceptions to this finding are students “whose understanding is (nearly) scientifically accurate and those who believe that velocity is linearly related to force” (p. 15). The phenomenology of levels-like response patterns cannot be denied in these narrow exceptions. However, both Alonzo & Steedle and Steedle & Shavelson suggest that the levels-based approach is of limited use in instances where students show evidence of “unstable, context-dependent” reasoning (Steedle & Shavelson, 2009, p. 15).

Research on learning in science has been moving toward complex, dynamic views of cognition (Strike & Posner, 1992; Thelen & Smith, 1994; diSessa, 1993; Redish, 2004; Brown & Hammer, 2008). Rather than describe students as “having” or “not having” a particular level of knowledge, this research conceptualizes students’ knowledge as manifold, context-sensitive, and coupled to and embedded in the social and physical environment. Scherr (2008) for example documented how a college student could easily distinguish mass and density in one context, but conflated them in another. Frank (2009) documented multiple stabilities in how groups of students reason about motion. Smith (2005) found that she could alter infants’ performance on the Piagetian A-not-B task by changing their body positions or adding weights to their wrists. These and other results challenge the view that students possess a static “level” of knowledge, skill, or understanding.

Evidence that student knowledge is generally not well characterized as level-like at any point in time, clearly, raises questions regarding LPs composed of a succession of qualitatively different levels of knowledge or understanding. According to Corcoran, Mosher, & Rogat (2009), the levels approach

stems from a structural view of cognitive development which suggests that the development of student thinking may not be purely incremental but may proceed as a series of increasingly complex schemes for organizing understanding of the world which may be rather stable for periods of time, but which eventually are modified or even broken down and rebuilt to take account of new evidence and new perceptions... (p. 18)

That structural view is at odds with evidence of contextual sensitivity in student reasoning. Identifying levels of conceptual understanding becomes even more problematic when we consider views of how different aspects of learners’ cognition interact (Perkins & Simmons, 1988). Consider the challenge of describing students’ progress along two just dimensions: i) content knowledge of biodiversity and ii) generating evidence-based explanations. Songer, Kelcey, & Gotwals (2009) present one solution: create an LP for concepts in biodiversity, create a separate LP for generating explanations, and then measure students’ location on each. This approach, we suggest, misses the complexity of the interaction. Lehrer & Schauble (2009) make this point succinctly in their commentary:

We hope that Songer et al. will elaborate the meaning of complexity of explanation...We suspect that complexity interacts with the nature of the knowledge of biodiversity being assessed, and a syntactic definition may miss this interaction. (p. 732)

For an example from physics, understanding the Newtonian concept of *force* (or *mass*, or *energy*) is in close interaction with understanding the disciplinary practices of positing universal “laws” of nature, of expecting and working to construct underlying principles that govern *all* experience within a domain. Learning the concept *involves* participating in that practice; and for many students coming to a first appreciation of that practice happens in learning Newtonian mechanics. The inquiry practices and the conceptual understanding are inseparable.

Concluding Remarks

Our purpose in this presentation has been to lay on critical brakes to the adoption of learning progressions as the organizing concept and language for research on learning. By reviewing LPs constructed by several prominent groups, we hope to have illustrated how at least some LPs assume progress occurs as a sequence of conceptual attainments, monotonically increasing toward the end-state disciplinary view. Research in science education has slowly made progress toward views of learners’ knowledge and reasoning in a complex conceptual, metaconceptual, motivational and social ecology. The field should take care that the quick adoption of “learning progressions” as a construct for organizing work does not set that progress aside.

References

- Alonzo, A., & Gotwals, A.W. (Eds.). (2009, June). *Proceedings of the Learning Progressions in Science (LeaPS) Conference*, Iowa City, IA. Available from <http://www.education.uiowa.edu/projects/leaps/proceedings/>
- Alonzo, A., & Steedle, J. T. (2008). Developing and Assessing a Force and Motion Learning Progression. *Science Education*, 93(3), 389-421.
- Brown, D. E., & Hammer, D. (2008). Conceptual change in physics. In S. Vosniadou (Ed.), *International Handbook of Research on Conceptual Change* (pp. 127-154). New York: Routledge (Taylor & Francis Group).
- 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. Available from <http://www.education.uiowa.edu/projects/leaps/proceedings/>
- Chang, H. (2004). *Inventing temperature: Measurement and scientific progress*. New York: OUP.
- Corcoran, T., Mosher, F.A., & Rogat, A. (2009). *Learning Progressions in Science. A Evidence Based Approach to Reform*. Research Report # RR-63. Center on Continuous Instructional Improvement. Teachers College–Columbia University.
- Corrigan, S., Loper, S., Barber, J., Brown, N., & Kulikowich, J. (2009, June). *The juncture of supply and demand for information: How and when can learning progressions meet the information demands of curriculum developers?* Paper presented at the Learning Progressions in Science (LeaPS) Conference, Iowa City, IA. Available from <http://www.education.uiowa.edu/projects/leaps/proceedings/>
- diSessa, A. (1993). Toward an epistemology of physics. *Cognition & Instruction*, 10(2/3), 105-225.
- Engle, R.A., & Conant, F.R. (2002). Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a community of learners classroom. *Cognition & Instruction*, 20(4), 399-483.
- Ford, M.J. (2005). The game, the pieces, and the players: Generative resources from two instructional portrayals of experimentation. *Journal of the Learning Sciences*, 14(4), 449-487.
- Furtak, E. (2009, June). *Toward learning progressions as teacher development tools*. Paper presented at the Learning Progressions in Science (LeaPS) Conference, Iowa City, IA. Available from <http://www.education.uiowa.edu/projects/leaps/proceedings/>
- Frank, B. (2009). The dynamics of variability in introductory students’ thinking: Examples sfrom kinematics. Unpublished doctoral dissertation, University of Maryland, College Park. Available from <http://www.physics.umd.edu/perg/dissertations/Frank/>
- Hammer, D. (1997). Discovery learning and discovery teaching. *Cognition & Instruction*, 15(4), 485-529.
- Hmelo-Silver, C.E. & Duncan, R.G. (Eds.). (2009) Special Issue: Learning Progressions. *Journal of Research in Science Teaching*, 46(6), 605-737.
- Hodson, D. (1988). Toward a philosophically more valid science curriculum. *Science Education*, 72(1), 19-40.
- Hutchison, P. & Hammer, D. (2009). Attending to student epistemological framing in a science classroom. *Science Education* doi:10.1002/sce.20373
- Leher, R., & Schauble, L. (2009). Images of learning, images of progress. *Journal of Research in Science Teaching*, 46(6), 731-735.
- Mohan, L., Chen, J., & Anderson, C.W. (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. *Journal of Research in Science Teaching*, 46(6), 675-698.

- (NRC) National Research Council (2007). Learning Progressions. In Duschl, R. A., Schweingruber, H. A., Shouse, A. W. (Eds.) *Taking Science to School: Learning and Teaching Science in Grades K-8*, (pp. 213-250) Washington, DC: The National Academies Press.
- Perkins, D., & Simmons, R. (1988). Patterns of misunderstanding: An integrative model for science, math, and programming. *Review of Educational Research*, 58(3), 303.
- Plummer, J., & Slagle, C. (2009, April). *Children explaining celestial motion: Development of a learning progression*. Paper presented at the National Association for Research in Science Teaching Conference, Garden Grove, CA.
- Redish, E.F. (2004). A theoretical framework for physics education research: Modeling student thinking. In *Proceedings of the International School of Physics, "Enrico Fermi" Course CLVI*, E.F. Redish & M. Vicentini (Eds.), IOS Press, Amsterdam, 2004.
- Roseman J. E., Caldwell, A., Gogos, A., Kuth, L. (2006) *Mapping a Coherent Learning Progression for the Molecular Basis of Heredity*. Project 2061, American Association for the Advancement of Science. Available from <http://www.project2061.org/publications/articles/papers/narst2006.pdf>
- Russ, R., Coffey, J., Hammer, D., & Hutchison, P. (2009). Making classroom assessment more accountable to scientific reasoning: A case for attending to mechanistic thinking. *Science Education*, 93(5), 499-515.
- Salinas, I. (2009, June). Learning progressions in science education: Two approaches for development. Paper presented at the Learning Progressions in Science (LeaPS) Conference, Iowa City, IA. Available from <http://www.education.uiowa.edu/projects/leaps/proceedings/>
- Scherr, R. (2008). Gesture analysis for physics education researchers. *Physical Review Special Topics-Physics Education Research*, 4(1), 10101.
- 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.
- Smith, L.B. (2005). Cognition as a dynamic system: Principles from embodiment. *Developmental Review*, 25, 278-298.
- Smith, C., Wiser, M., Anderson, C., and Krajcik, J. (2006) Implications of Research on Children's Learning for Standards and Assessment: A Proposed Learning Progression for Matter and Atomic-Molecular Theory. *Measurement*, 14 (1&2), 1-98.
- Songer, N.B., Kelcey, B., & Gotwals, A.W. (2009). How and when does complex reasoning occur? Empirically driven development of a learning progression focused on complex reasoning about biodiversity. *Journal of Research in Science Teaching*, 46(6), 606-609.
- Steedle, J., & Shavelson, R. (2009). Supporting valid interpretations of learning progression level diagnoses. *Journal of Research in Science Teaching*, 46(6), 699-715.
- Stevens, S., Shin, N., & Krajcik, J. (2009, June). Towards a model for the development of an empirically tested learning progression. Paper presented at the Learning Progressions in Science (LeaPS) Conference, Iowa City, IA. Available from <http://www.education.uiowa.edu/projects/leaps/proceedings/>
- Strike, K., & Posner, G. (1985). A conceptual change view of learning and understanding. In L. West & A. Pines (Eds.), *Cognitive structure and conceptual change* (pp. 211-231). New York: Academic.
- Strike, K. A., & Posner, G. J. (1992). A revisionist theory of conceptual change. In R. A. Duschl & R. J. Hamilton (Eds.), *Philosophy of Science, Cognitive Psychology, and Educational Theory and Practice* (pp. 147-176). Albany: State University of New York Press.
- Thelen, E., & Smith, L.B. (1994). *A dynamics systems approach to the development of cognition and action*. Cambridge, MA: Bradford Books/MIT Press.
- 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. Available from <http://www.education.uiowa.edu/projects/leaps/proceedings/>

Acknowledgments

The authors would like to thank the members of the *Learning Progressions for Scientific Inquiry* project for their suggestions and feedback on this paper. This work was supported in part by the National Science Foundation under grant # DRL 0732233, *Learning Progressions for Scientific Inquiry: A Model Implementation in the Context of Energy*. The views expressed are those of the authors and not necessarily shared by the Foundation.