SCIENCE EDUCATION

Science Learning Progressions

New science education standards build upon research-based cognitive models of how learning unfolds over time.

Ravit Golan Duncan[1]* **and Ann E. Rivet**[2]

Guided by the 2011 U.S. National Research Council framework for science education (*1*), the most recent draft of the Next Generation Science Standards (NGSS) is briefly open for public comment (*2*). Key goals of this effort (*3*) include (i) reducing coverage to a select set of "big ideas" (e.g., atomic molecular theory, biodiversity, energy); (ii) providing a progression to facilitate coherence in learning of these ideas over the course of schooling; and (iii) promoting a practice-oriented approach to inquiry-based science learning.

This reform of standards is meant not merely to update content, but to shift the way U.S. kindergarten through high school (K–12) science education is conceptualized and implemented. The NGSS reflect an evolved vision of inquiry-based learning, emphasizing science as a knowledge-building endeavor. An improvement over prior science education standards (*4*), the NGSS are embedded in learning progressions (LPs)—research-based cognitive models of how learning of scientific concepts and practices unfolds over time. This stresses coherence in the conceptual growth of scientific reasoning across grades.

We discuss the theory and implications of the LP approach underlying the NGSS. We highlight key features of LPs and examine some challenges that accompany development and validation of these constructs.

Reframing the Science Content

Embodying a developmental approach to learning, LPs describe paths by which students might develop more sophisticated ways of reasoning over extended periods of time (*5*–*7*). LPs begin with consideration of learners' prior knowledge and build toward targeted learning goals through carefully designed instruction. These progressions define intermediate levels in students' understanding, derived, where possible, from research on student learning.

A feature of LPs, reflected in the NGSS's guiding framework (*1*), is that core disciplinary concepts are built and refined through engagement with the practices of scientific inquiry. The framework views scientific inquiry as a theory-building enterprise that uses systematic and evidence-based approaches to create models that explain the world around us (*8*). Scientists develop these models within a community with socially constructed and continually negotiated epistemological norms regarding what is knowable, how best to come to know it, and what counts as knowing (*9*). Such norms, often implicit, guide core scientific practices such as research design, data analysis, modeling, and argumentation and are thus critical to the development of valid and reliable scientific knowledge. The trio of concepts, practices, and epistemology is at the heart of the efforts to revise K–12 science standards.

The educational system includes LPs, classroom and large-scale assessments, and the curricula and instruction that drive learning. Assessment plays a major role in the development, validation, and use of LPs. Progressions in turn can inform science standards and are implemented through curricula and classroom instruction. Much of the research on LPs is in its infancy, and current models are largely conjectural owing to gaps in the research base. Nevertheless, they offer a productive starting place for developing standards, curricula, and assessments.

Leveraging Stepping-Stone Ideas

LPs differ from current descriptions of scope and sequence in two important ways. First, to the extent possible, they are grounded in research regarding how students actually come to understand core ideas in science rather than relying solely on normative knowledge in the domain. This is critical because intermediate steps in a LP may include understandings that vary from the canonical knowledge of science. Second, as opposed to adding more information or details over time, LPs focus on deepening understandings and developing increased complexity, applicability, and epistemological rigor with each learning opportunity.

Stepping-stone understandings on the LP path toward targeted knowledge in a domain can be substantially different from accepted scientific concepts. For example, at the middle school–level, students should understand genetic information as specifying the structure (and consequently, the function) of proteins (*10*). Such a conception, while grossly incomplete, is a highly productive intermediary that allows students to explain how genes bring about their observable effects. Similarly, establishing weight as a property of matter is important in early grades, necessary to understanding that even invisible things (e.g., gases and atoms) have weight (*11*). This targeted understanding conflates weight with a more scientific notion of mass, but serves as a productive step toward developing a full understanding of the particulate nature of matter in later grades. The term "mass" is meaningless to young learners and using it does not help them understand this concept.

It is important to differentiate between scientifically inaccurate ideas that are conceptually unproductive and understandings that are inaccurate, yet productive, and that can foster learning of more sophisticated understandings.

Although inaccurate understandings can be conceptually productive stepping stones, the extent to which these should be reflected in standards and curricula is controversial. Developers are reluctant to present wrong ideas in standards, and teachers are concerned about teaching them (*12*). It is important to differentiate between scientifically inaccurate ideas that are conceptually unproductive and understandings that are inaccurate, yet productive, and that can foster learning of more sophisticated understandings. The former are simply wrong; the latter can be seen as incomplete, overly simplistic, or tied to only a few limited contexts. LPs suggest productive—yet at times inaccurate—and understandings that are important building blocks in the learning process. We believe it is counterproductive to shy away from such inaccuracies in the development of standards, assessments, and curricula. Conversely, stan-

[1]Graduate School of Education, Rutgers University, New Brunswick, NJ 08901, USA. [2]Teachers College, Columbia University, New York, NY 10027, USA.

*Author for correspondence. E-mail: ravit.duncan@gse.rutgers.edu

Published by AAAS

dards and curricula should set as goals such stepping-stone ideas and clearly articulate the basis for their conceptual usefulness.

Challenges to Assessment

When compared with traditional content-centered scope and sequence, LPs present advantages and challenges to the development and use of science assessments at both local and national scales. LPs can inform the design of assessments that capture the nature of students' developing understandings in nuanced ways, as opposed to simply whether or not they "got it." Likewise, assessments play a critical role in informing the development, validation, and use of individual LPs. Such assessments can detect the range of students' abilities, or levels of sophistication, as well as the appropriateness of particular assessment items for evaluating different student groups (*13*, *14*).

However, the process of developing assessment measures to diagnose levels of student reasoning on a LP presents challenges. Students at the high end of a LP tend to demonstrate reasoning that is robust and consistently applied to diverse assessment tasks. Students at the beginning of a LP typically perform poorly across items (*15*). Yet, at intermediate levels of a LP, students' levels of understanding may vary from item to item because their developing knowledge is not robust enough to be consistently applied to diverse situations and phenomena. Therefore, assessments need to attend to the context and features of items and how these are correlated with intermediary steps in a LP. We believe this is a challenging, yet tractable, problem addressed through partnerships of learning scientists, psychometricians, and assessment experts.

Content, Epistemology, and Practices

The LP approach emphasizes science as a theory-building social enterprise steeped in practices and epistemological norms. This perspective is dramatically different from the outmoded stepwise scientific method that is still the predominant focus of science instruction (*16*). For example, students frequently identify hypotheses to test, but these are not grounded in any model of the phenomenon under study. Experimental heuristics, such as "vary-one-thing-at-a-time," are used by students in an epistemological vacuum without consideration of the relevance of variables to the theoretical model. When students engage in developing explanations they commonly do not use evidence to support their arguments and rarely entertain more than one plausible explanation (*17*). Science education should instead engage students in the practices of scientific theory development. Students should generate evidence-based explanations and critique alternative explanations as part of a knowledge-building community with agreed-upon epistemological norms akin to those used by scientists (*18*).

Consequently, a LP perspective contends that all three aspects of deep understanding—content, practices, and epistemology—need to be inherently and consistently integrated throughout instruction across all grades (*1*). For instance, when learning about variation, a concept fundamental to understanding evolution, second graders can measure and model data of variation (practice) across multiple populations and develop a sense of what counts as valid and significant measures of variation (epistemology) (*19*). High school students can develop understanding of natural selection (content), argue about which of several potential environmental pressures are driving selection (practice), and identify what counts as credible evidence about the causal relation between the pressure and the adaptive trait (epistemology) (*20*). Helping students develop scientific knowledge that merges content, practice, and epistemology requires that they develop the knowledge for themselves, see its utility, and practice applying it across a range of contexts (*21*, *22*).

Yet, the NGSS's push to intertwine practices with content and epistemological perspectives across the curriculum is replete with tensions and trade-offs. Questions remain regarding the most appropriate and effective ways to concurrently develop these aspects of scientific reasoning. Most research has (by necessity) elected to place one aspect in the foreground, with some focusing more on content while others focus more on practices and epistemology. We do not yet clearly understand how development of a specific practice affects, and is affected by, development of particular content understandings. It is likely that specific "big ideas" pair better with some practices than with others. Ongoing research is developing ways of theorizing about and examining these interactions and their effect on developing holistic understandings of science.

Engaging the Scientific Community

Given the time-consuming and resource-intensive nature of LP research, only a limited array of fully developed exemplar LPs exists to inform conversations about educational policy, curriculum, and assessment. Little is known about how existing LPs interact within and across disciplines. For example, there are several LPs that together describe development of the big idea of atomic-molecular theory across segments of the kindergarten through college continuum. Yet, stitching these discrete progressions into a coherent trajectory that spans schooling is not trivial. The field has yet to examine how cross-cutting big ideas, such as energy, develop concurrently within progressions across the biological, physical, and earth sciences. That being said, efforts around LPs build on available research in cognition and learning (*23*) and can help us make informed conjectures regarding the most productive directions for science standards, curriculum, and assessment.

As the NGSS come into play (with targeted completion in 2013), it is important for the scientific community to be partners in the dialogue, even as we are mindful of the promises and pitfalls of LPs and their translation into standards. Scientists need to be aware of the long view taken by this approach and the conceptual role of simplified stepping-stone ideas in the learning process.

References and Notes

1. National Research Council, *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (National Research Council, Washington, DC, 2011).
2. Next Generation Science Standards, www.nextgenscience.org.
3. B. Alberts, *Science* **329**, 491 (2010).
4. National Research Council, *National Science Education Standards* (National Research Council, Washington, DC, 1996).
5. T. Corcoran, F. A. Mosher, A. Rogat, *Learning Progressions in Science: An Evidence-Based Approach to Reform* (Center on Continuous Instructional Improvement, Teachers College, Columbia Univ., New York, 2009).
6. R. G. Duncan, C. Hmelo-Silver, *J. Res. Sci. Teach.* **46**, 606 (2009).
7. R. A. Duschl, H. A. Schweingruber, A. W. Shouse, Eds., *Taking Science to School: Learning and Teaching in Grades K-8* (National Research Council, Washington, DC, 2007).
8. R. N. Giere, *Philos. Sci.* **71**, 742 (2004).
9. P. Kitcher, *The Advancement of Science* (Oxford Univ. Press, New York, 1993).
10. R. G. Duncan, A. D. Rogat, A. Yarden, *J. Res. Sci. Teach.* **46**, 655 (2009).
11. M. Wiser, C. Smith, S. Doubler, in (*23*), pp. 359–403.
12. J. Foster, M. Wiser, in (*23*), pp. 435–460.
13. A. E. Rivet, K. A. Kastens, *J. Res. Sci. Teach.* **49**, 713 (2012).
14. M. Wilson, *Constructing Measures: An Item Response Modeling Approach* (Erlbaum, Mahwah, NJ, 2005).
15. J. T. Steedle, R. J. Shavelson, *J. Res. Sci. Teach.* **46**, 699 (2009).
16. C. A. Chinn, B. A. Malhotra, *Sci. Educ.* **86**, 175 (2002).
17. L. K. Berland, B. J. Reiser, *Sci. Educ.* **93**, 26 (2009).
18. M. Ford, *Sci. Educ.* **92**, 404 (2008).
19. R. Lehrer, L. Schauble, *Sci. Educ.* **96**, 701 (2012).
20. W. Sandoval, *Sci. Educ.* **89**, 634 (2005).
21. D. C. Edelson, *J. Res. Sci. Teach.* **38**, 355 (2001).
22. A. E. Rivet, J. S. Krajcik, *J. Res. Sci. Teach.* **45**, 79 (2008).
23. A. Alonzo, A. Gotwals, Eds., *Learning Progressions in Science: Current Challenges and Future Directions* (Sense Publishers, Rotterdam, Netherlands, 2012).

10.1126/science.1228692