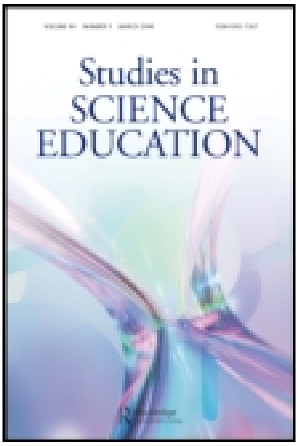

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Learning progressions and teaching sequences: a review and analysis

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Learning progressions and teaching sequences: a review and analysis

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Our paper is an analytical review of the design, development and reporting of learning progressions and teaching sequences. Research questions are: (1) what criteria are being used to propose a 'hypothetical learning progression/trajectory' and (2) what measurements/evidence are being used to empirically define and refine a 'hypothetical learning progression/trajectory'? Publications from five topic areas are examined: teaching sequences, teaching experiments, didaktiks, learning trajectories in mathematics education and learning progressions in science education. The reviewed publications are drawn from journal special issues, conference reports and monographs. The review is coordinated around four frameworks of Learning Progressions (LP): conceptual domain, disciplinary practices, assessment/measurement and theoretical/guiding conceptions. Our findings and analyses show there is a distinction between the preferred learning pathways that focus on 'Evolutionary LP' models and the less preferred but potentially good LP starting place curriculum coherence focused 'Validation LP' models. We report on the respective features and characteristics for each.

Keywords: science learning progressions; mathematics learning trajectories; didaktiks; teaching experiments; teaching sequences; assessment

Introduction

Advances in cognitive and sociocultural psychology, recognition of the importance of disciplinary discourse practices in learning, the scaffolding of learning with tools and technologies, along with the adoption of 'assessment for learning' instructional strategies are factors, among others, that have led scholars to advance positions that learning ought to be coordinated and sequenced along conceptual trajectories (Driver, Leach, Scott, & Wood-Robinson, 1994), developmental corridors (Brown, 1997) and learning progressions (National Research Council [NRC], 2007). An examination of developments in education over the past 100 years as well as the concomitant understandings that have emerged in the foundational educational fields of psychology, philosophy and pedagogy reveal a decades-long narrative about change and development. The narrative is one about the growth of knowledge over time. Such growth occurs among children and learners of all ages and within science disciplinary domains among communities of scholars as well. We have, to paraphrase the philosopher of science Dudley Shapere (1982) learned how to learn

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about nature and to paraphrase the educational psychologist Joseph Novak (1998) learned how to learn about learning, respectively. For Shapere learning how to learn applies to understanding the nature and the dynamic processes involved in the deepening and broadening of scientific knowledge. For Novak the phrase applies to the cognitive and sociocultural dynamics involved in understanding the disciplinary structures that comprise a domain of knowledge.

Learning progressions (LPs) in science education and learning trajectories (LTs) in mathematics education currently are seen as *de riguere* strategies for formulating and developing environments of learning that align curriculum, instruction and assessment. In this review, we present an analysis of proposed hypothetical learning progressions or trajectories, henceforth LP, and of strategies being used to empirically validate and/or describe learning pathways, progressions or trajectories. Perhaps, and not surprisingly given the 'newness' of the domain, what we see in LP research and development has many of the trappings that are akin to Kuhn's (1996) 'crisis' activity associated with the emergence of a new paradigm. That is, during the onset of a new organising framework for a discipline (e.g., seventeenth and eighteenth century chemistry) competing perspectives abound (Thagard, 1992) until such time the community settles on the next or new paradigm. In many senses this is how one can interpret the current flurry of competing perspectives around LPs.

Learning progressions are generally viewed by researchers as conjectural or hypothetical model pathways of learning over periods of time that have been empirically validated. Simon (1995), writing about mathematics learning, suggests that LPs include 'the learning goal, the learning activities, and the thinking and learning which students might engage' (p. 133). The interest in LP research represents a shift in emphasis from partitioned teaching of independent units/modules of instruction which focus on what we know (e.g., facts and skills) to coordinated sequential teaching that focuses on developing scientific and mathematic knowledge with accompanying cognitive and metacognitive practices.

The recommendation is that science/math learning be connected through longer sequences of instruction (e.g., immersion units, LPs, LTs) that function vertically across grades/years and horizontally within a given school year. The rationale is to facilitate the learning of core knowledge and practices that are critical for development of science/maths knowledge and reasoning. The research synthesis found in *Taking science to school* (NRC, 2007) informs us that developing rich, conceptual knowledge takes time and requires instructional support employing sound assessment practices. The LPs approach to the design and alignment of curriculum, instruction and assessment is grounded in core knowledge theories of cognitive development and learning. The focus is for LPs to be built around the most generative and core ideas/practices that are central to the discipline and that support students' learning.

An examination of UK and US school curricula reveals dated, disconnected and isolated units of instruction to be the norm (NRC, 2007; Osborne & Collins, 2000; Schmidt, Wang, & McKnight, 2005). Learning progressions are seen as offering a promising strategy for the redesign and reform of curriculum, instruction and assessment. Corcoran, Mosher, and Rogat (2009) state 'progressions can play a central role in supporting the needed shift toward adaptive instruction' (p. 9) and that there are many possible learning outcome benefits of establishing LPs. A key component of LPs is instruction-assisted development of learning. Learning progressions are designed to employ robust learning performances (Wilson, 2009) that serve as 'assessments for learning' (Black & Wiliam, 1998). The LPs represent pathways of learning that are based on research of students' progress, like the well research learning pathway on matter and the atomic molecular theory (Smith, Carey, & Wiser, 1985; Smith, Wiser, Anderson, & Krajcik, 2006) and rational numbers (Confrey & Maloney, 2010). There are two general types of LPs: (1) bottom-up LPs, where the selection of topics and learning pathways are grounded in iterative assessments that obtain evidence of student learning and build on it, and (2) LPs where the selection of topics and pathways is based on a logical task analysis of content domains and personal experiences with teaching (e.g., American Association for the Advancement of Science [AAAS], 2001; Harlen, 2010).

Our review focuses on Science Learning Progressions in K–12 (Key Stages 1–4) with occasional references to mathematics learning trajectories. Publications from five topic areas are examined: teaching sequences, teaching experiments, Didaktik, learning trajectories in mathematics education and learning progressions in science education. The review is guided by two research questions:

(1) How are LPs being created? What decision criteria and frameworks are being used to arrive at or propose a 'hypothetical learning progression or trajectory'?
(2) How are LPs being validated and described? What measurements, evidence and contexts are being used to empirically establish and refine a 'hypothetical learning progression or trajectory'?

The review is both on current thinking (Confrey & Maloney, 2010; Harlen, 2010; Lehrer & Kim, 2009; NRC, 2007; Ruthven, Laborde, Leach, & Tiberghien, 2009; Von Aufschnaiter & Rogge, 2010) and on the foundational perspectives that have contributed to the development of LP thinking (Brown, 1992; Driver, Leach, Millar, & Scott, 1996; Duit, Gropengieβer, & Kattman, 2005; Lijnse, 1995; Westbury, Hopmann & Riquarts, 2000). The bulk of the publications reviewed for LP research are drawn from recent journal special issues, conference reports and monographs whose titles are listed in the Appendix (Alonzo & Gotwals, in press; Clements & Sarama, 2004; Corcoran, Moser, & Rogat, 2009; Daro, Mosher, & Corcoran, 2011; Duncan & Hmelo-Silver, 2009). We open the review with a section on 'Foundation Perspectives' that have informed LP research.

Next, we present the review of LP studies that is organised in three sections. The analytical frameworks in each section were used to examine the characteristic and features of LPs. Section 1 looks at both Domain/Topic Frameworks and Disciplinary/Scientific Practices Frameworks. Sections 2 and 3 look at Assessment and Measurement Frameworks and Theoretical/Guiding Conception Frameworks, respectively. Lastly, we turn to issues, implications and recommendations that will hopefully be helpful in productively and thoughtfully advancing the field of LP research and development.

Foundations of learning progressions

How did the community of scholars examining children's science learning arrive at the notion of LPs? The decision for organising science curriculum, instruction and assessment around LPs emerges from several US national initiatives coordinated by the NRC and the National Assessment Governing Board (NAGB). While there were many such initiatives, three are noteworthy here. One initiative is the NRC Board of Testing and Assessment panel that was commissioned to examine and review developments in assessment and measurement of science learning (NRC, 2005). The panel was charged with providing new guidelines for the design of State examinations that resulted in the report *Systems for state science assessments* (NRC, 2005). Another, was the NAGB initiative for the revision of the National Assessment of Educational Progress (NAEP) Science Framework (NAGB, 2008). The third initiative was the NRC research synthesis panel on children's science learning in grades K–8 (ages 5–13) producing the report *Taking science to school* (NRC, 2007).

Across the three panels' membership there was some common representation and thus ideas and information from one initiative influenced and informed other initiatives. Particularly influential to the NAEP panel and NRC K-8 panel were two commissioned reports from the Board of Testing and Assessment panel:

(1) 'Implications of research on children's learning for assessment: Matter and atomic molecular theory' (Smith, Wiser, Anderson, Krajcik, & Copolla, 2004) and
(2) 'Tracing a prospective learning progression for developing understanding of evolution' (Catley, Lehrer, & Reiser, 2005).

The reports examine how emerging learning performances could inform and address 'assessment for learning' (Black & Wiliam, 1998) practices that, in turn, inform adaptive instruction decisions. The question posed was: what might a learning sequence for a core idea in science, with accompanying assessments for monitoring progress and informing instruction-assessed development, look like if that sequence were to take place across a grade-band; e.g., grades K–8? Grounded in prior research on student's domain-specific learning, the two reports recommend that the sequence or progression ought to attend (1) to the development and use of *conceptual understandings* and (2) to the development and use of *scientific practices*.

The NRC (2005) report and the NAGB (2008) science framework are representative of the burgeoning knowledge and expertise developing in the areas of assessment and measurement of learning. Both reports are grounded in two prior NRC reports: *Knowing what students know* (2001) and *How people learn* (1999). Respectively, these two reports present research syntheses on measuring learning and on the cognitive and social dynamics for nurturing learning. Looking across the developments involving the NAEP 2009 Science Framework and the surrounding set of NRC reports we see the assessment conversation shifting. The focus is now on 'learning performances' for both assessment *of* and *for* learning that may function along 'vertical pathways' (College Board, 2009) and that can attend to matters of assessment coherence (Wilson, 2004). Using the language adopted in *Science: College Board Standards for college success* (College Board, 2009) the conversation is currently about essential knowledge combining with science practices to generate performance expectations that are assessed employing evidence-centred design principles (Mislevy & Riconscente, 2005).

Since the publication of *Taking science to school* (NRC, 2007) there has been a rapid proliferation of paper presentations, manuscripts, symposia, dedicated conferences and special journal issues on LPs. Scanning across the landscape of LP frameworks one sees a great deal of diversity, dangerously perhaps too diverse. A close examination of the LP research and development reveals the existence of a wide variety of theoretical, methodological and goal commitments. Progress, in part, will reside in the research community settling 'disciplinary matrix' type issues concerning the establishment of exemplars for the field. Thomas Kuhn (1996) introduced the Disciplinary Matrix to explain how communities of scientists come to consensus about agreed upon Symbolic Generalizations, Models, Values and Exemplars. Today we refer to such consensus building practices as the model-based practices found in the growth of scientific knowledge. In this review, we seek to begin a conversation about the emergent consensus views about theoretical, methodological and goal commitments for conducting LP research and for describing optimal learning pathways.

Our review begins with a consideration of five foundational LP research domains. Decades of research have contributed to developing our thinking about the importance of sequential pathways for learning and teaching. Looking at these foundational perspectives helps to gain some insights on the guiding conceptions LP researchers are or are not using today. We view these foundational domains as frameworks that have influenced the thinking and framing of science learning around learning progressions. The five domains are: didaktiks and teaching experiments, theory of mind and metacognitive development, conceptual change research, pedagogy and learning trajectories. What we present are brief overviews of these five foundation perspectives fully recognising that each perspective is much more complex and comprehensive. A comprehensive review is well beyond the scope of this article but a few highlights of the research in each domain are important for interpreting LP designs.

Didaktiks and teaching experiments

Didaktiks is a European form and tradition of education that has contributed to our thinking about the framing and development of instructional sequences. Klette (2007) describes this tradition 'as a relation between teachers and learners (the who), subject matter (the what) and instructional methods (the how)' (p. 147). Hopmann (2007), in a review of the German Didaktik tradition outlines the historical development of Didaktiks. At its core, Didaktiks is a matter of order, sequence, choice; features we feel align with contemporary thinking regarding US standards revision and attention to LPs. The late-nineteenth century Didaktik tradition in Germany and Nordic countries was established during the emergence of national/regional educational systems that stressed centralised planning and local implementation/practice. Within the frame of order, sequence and choice, Hopmann writes, 'Didaktik became the main tool for creating space for local teaching by providing interpretative tools for dealing with state guidelines on a local basis' (p. 113). The interpretation of Didaktiks across Europe led to a variety of modes but Hopmann points out they shared three common aspects, '(a) the concept of *Bildung*, (b) the embedded differential of matter and meaning, and (c) a concept of the necessary autonomy of teaching, thus continuing the above mentioned problems of order, sequence, and choice within their respective frames of reference' (p. 115).

Again, we feel these three common aspects have links to contemporary thinking. One in particular, Bildung, maps well to LP constructs regarding pathways of formative development and developmental corridors incorporating a focus on using knowledge and participating productively in disciplinary talk. Hopmann (2007) writes that 'The purpose of teaching and schooling is in this perspective ... the use of knowledge as a transformative tool of unfolding the learner's individuality and sociability, in short: the Bildung of the learners by teaching' (p. 115). The focus on matter and meaning accounts for the strong commitment to subject matter content and for the tradition in European nations that situate the study of science teaching and learning within disciplinary structures. Thus, we find a separation of the subject-specific Didaktiks of physics, of chemistry, of biology, etc. which is an acknowledgement that while there are some common disciplinary elements there are also salient and important structural disciplinary/content differences that inform subject matter Didaktik and pedagogical strategies.

Unlike US institutions of higher education, science professors of Didaktiks typically reside in disciplinary departments. Additionally, traditional approaches to Didaktiks (Linjse, 1995) will eschew psychological tenets of learning in favour of disciplinary epistemological and philosophical structures that initiate and offer learners a framework for formative development or bildung. For example, in a didactic project focusing on open experimenting in physics, Reinhold (2000) asks:

> How should learners experiment so that they acquire both a knowledge of physics content and adequate methodological and epistemological knowledge about physics such that (a) they are able to apply and use their knowledge in new contexts, (b) they are motivated to understand, and (c) they experience formative (bildend) development? (p. 300)

Reinhold (2000) addresses the issue of function or structure of elements of a system in open experimenting, he asks from an activity theory orientation, which things and individuals are elements related to a system? The approach he takes for his 'Didaktik' is to adopt the 'concept of complementarity' that is grounded in two conceptual frameworks: (1) Bohr's interpretation of quantum mechanics and (2) Hegel's dialectic concept of thesis and antithesis. Together these two frameworks are used to guide formative development about physics content and methodological and epistemological physics knowledge.

Only very recently has the next generation of professors of Didaktiks begun to consider cognitive and sociocultural dimensions of learning as critical dimensions of Didaktiks (Van Driel, personal communication, October 18, 2010). Klette (2007), as mentioned above, outlines how the Norwegian didaktical tradition has begun to examine more systematically the relations between teachers and learners (the who), instructional activities (the how) and subject/content matter (the what) by studying together pedagogical practices and curriculum analyses. For Klette, the contemporary research agenda involves conceptualising the teaching (instruction) and learning (construction) as linked and with incorporating 'a renewed interest in the *what* aspect regarding teaching and learning in schools' (p. 148, emphasis in original).

In science education, this didackical transition was strongly influenced by the research on conceptual change (Duschl & Jimenez-Aleixandre, in press; Treagust & Duit, 2008), on discourse practices (Duschl & Osborne, 2002; Michaels, Shouse, & Schweingruber, 2008; Mortimer & Scott, 2003) and on domain-specific subject matter learning (Duschl & Hamilton, 2011). Consider the example of the model of educational reconstruction (MER) research programme (Duit et al., 2005). The MER coordinates three domains of research: (1) investigations into students' perspectives, (2) clarification and analysis of subject matter content and (3) design of learning environments. Derived from the German ‘Didaktik’ tradition and culture of pedagogy, the MER offers a well-conceived framework for educational research as well as a context for conducting theoretical, basic and applied research. The corner stone of this research programme is the ‘Teaching Experiment’, an interview-type method that seeks to understand how individuals coordinate core conceptual understandings in domain-specific contexts (e.g., evolution, ecology, adaptation, cellular functions, among others).

Figure 1 is a graphical depiction of the teaching experiment format we drew as described by Claudia Von Aufschnaiter during her 2009 European Science Education Research Association (ESERA) keynote address. A description of this research method can be found in Von Aufschnaiter and Rogge (2010) and von Aufschnaiter, Erduran, Osborne, and Simon (2008). The research phase, we see, mapping to domain 1 of the MER framework, and the development phase mapping to domain 3. Students in dyads or triads are presented with situations/scenarios typically presented in the form of demonstrations of phenomenon and asked to employ think aloud protocols to reason through the task. For example, Reinhold (2000) developed a teaching task that involved the following light demonstration. Two cards are placed in a beam of light. The closest to the light source

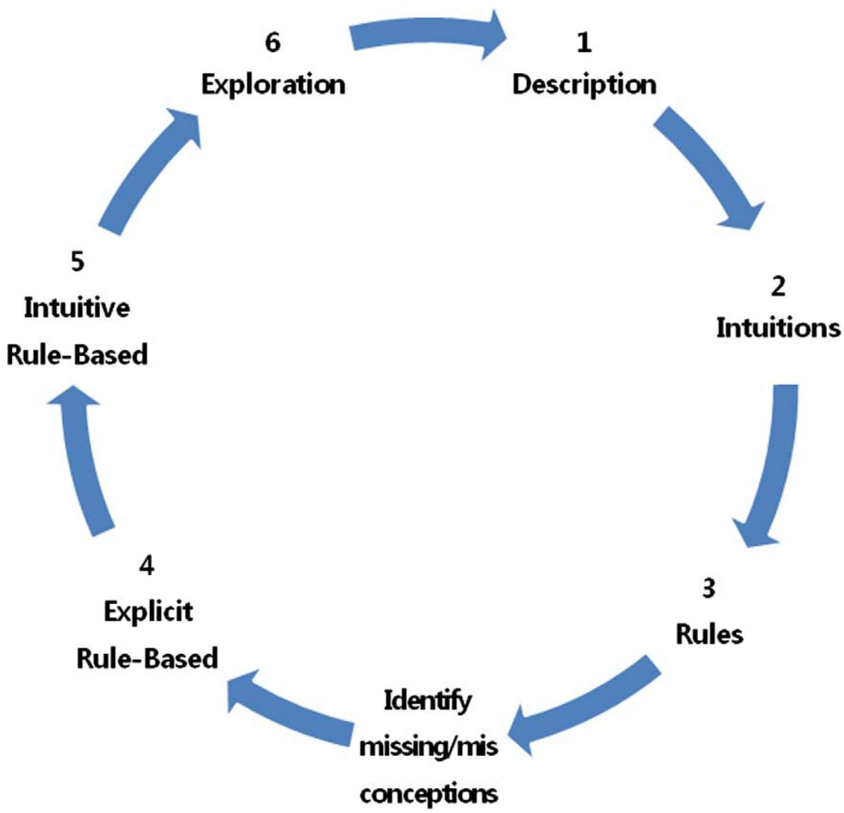

Figure 1. The didactical cycle of teaching experiments.
Note: Levels 1–3 are the research phases. Levels 4–6 are the development phases (from von Aufschnaiter, 2009; von Aufschnaiter & Rogge, 2010; Von Aufschnaiter et al., 2008).

is a card with a slit that produces a divergent light beam, the next card is one with a cut out square.

> If a square diaphragm is placed in the beam, we would expect a two-dimensional pattern of umbra and penumbra on the screen. Surprisingly, we see a three-dimensional dice on the screen. On a closer look, we also observe that the edges of the dice are more intensively emphasized as bright lines. How does this happen? (p. 302)

Lijnse (1995) produced an excellent research report that demonstrates the importance of teaching tasks in the design of curriculum and instruction. Lijnse explains that didaktik structure was derived from a critique of curriculum development and of individual cognitive constructivism. Lijnse argues that the curriculum efforts to improve science education started from the perspective of science without considering what students already know, therefore resulting in 'top-down transmission of science concepts' (p. 191). The efforts for students' conceptual change with the individual cognitive constructivism missed the point of guided teaching for students' own construction itself. Lijnse also insisted that a new science education research needed to engage students in a bottom-up learning process by carefully designing teaching tasks. As a theoretical way of designing such teaching tasks, he suggested the *developmental research* paradigm comprised of a cyclical process of theoretical reflection, conceptual analysis, small scale curriculum development and classroom research of the interaction of teaching-learning processes. The MER framework has many of these same features. He also introduced a possible didaktical structure as the final, empirically-based description and justification of the interrelated processes and activities.

Designing the didaktical structure regarded students' conceptual development as the transition of three successive periods from a ground level through a descriptive level towards a theoretical level. In addition, he considered a detailed description of possible didaktical structures for a certain topic as a 'scenario', which included learning tasks, their interrelations and students' actions with a teacher. The scenario of didaktical structure is implemented, closely monitored, put to the test, revised and, finally, ends up with a rather detailed domain-specific theory for teaching a particular topic (Lijnse & Klaassen, 2004).

The consideration of didaktik 'teaching experiments' is important for LP research. What is not clear is how the 'Didaktik' tradition enables classroom teachers themselves to perform effectively with diagnosis of students' perceptions, the clarification of subject matter content and the adaptation of learning environments. The question is does the Didaktische analysis process lead to a fixed set of guidelines for what and how to teach or does it provide for a flexible set of guidelines that can accommodate differences and thus be useful in adaptive instruction? Both ideas, the learning progressions and the scenario of didaktical structure, have some common elements in relation to considering the level transition of students' conceptual development and the cyclical or iterative processes of developing a scenario or a pathway to learn a topic. Our opinion is that didaktik research is a good source for identifying conjectural pathways of learning that can be examined as learning progressions.

Theory of mind and metacognitive development

A child's theory of mind is a critical precursor or foundation for reasoning. A theory of mind affords the understanding that knowledge can be subjective and people may have different interpretations of natural phenomena. This perspective is relevant in grasping both the revisionary nature of scientific knowledge and the existence of alternative models held by others for explaining a phenomenon. It follows that in order to engage in scientific argumentation (a core practice we would like students to master) children need to have a theory of mind and notion of false-belief that allows them to assume that explanations vary and that explanations may be more or less accurate depictions of the phenomenon in question. There is clear need to investigate the link between the development of children's theory of mind and their ability to benefit from engaging in modeling phenomena and arguing about alternative models and theories (NRC, 2007). It also follows that if learning environments do not present science as a theory-building or model-building enterprise with a specialised way of talking, writing and representing ideas, then these innate abilities may fade away (Gopnik, 1996).

The extensive research on infants and young children's cognitive development underscores the multitude of knowledge resources and reasoning capabilities children bring to formal schooling (Metz, 2009). Young learners are anything but empty minds. They are, within effective instructional conditions (Lehrer & Schauble, 2002), capable of noticing patterns and attributes in the natural world, linking the patterns and attributes to science concepts, developing explanations of natural phenomena and reasoning about abstract ideas in meaningful and productive ways (NRC, 2007).

Whether or not we chose to capitalise on children's emerging scientific reasoning abilities and further develop them depends on how we construe the goals of science learning and how such learning outcomes can be achieved. A focus on understanding the doing of science and how scientific knowledge is developed and evaluated will entail building on students' emerging ideas and capacities for representation, model-building, casual reasoning and the like.

Learning progressions are conceived as strategically developed cycles and sequences of instructional activities that guide learning pathways. The instructional agenda is to engage learners in successively more sophisticated ways of knowing and thinking about ideas, evidence, claims and/or practices that deepen and broaden as the students moves through learning progressions. As we contemplate LPs as an approach to the organisation and alignment of science learning, we should heed Schauble's (2008) cautionary advice that while we certainly want research on young children to answer the question 'Where does reasoning and learning come from?' we must also ask 'Where is reasoning going?' and 'What conditions support productive change?':

> Answers to the first question help us better understand the foundation on which further development can build. Answers to the second provide a sense of developmental trajectory, or more likely, trajectories. What characteristic changes are coming up? What pathways of change are usually observed? And answers to the third question focus on how those changes can get supported in a productive way. (p. 51)

A cornerstone recommendation for LPs functioning across K–8, 6–12 or other grade bands is to design them around the most generative and core ideas. Generative ideas refer to whether the topic is robust enough to allow further growth and development in terms of conceptual understanding – the knowing and of science practices – the doing. Such learning performances support and inform the assessment function of monitoring and mediating students' science learning. Core ideas refer to the sense that the LP sequence engages learners in building and refining explanatory frameworks and the accompanying practices for obtaining evidence and developing criteria to critique and communicate scientific ideas and claims.

Another recommendation is that the generative and core ideas should be *accessible* to students in kindergarten (or the beginning grade of the grade band) and have the potential for sustained exploration across K–8. The concept of accessible is important for several reasons: one is that research findings from theory of mind scholars indicate that young children are, in select domains, very capable of sophisticated reasoning, two is the criteria for accessible dictates when – grade/age level – an LP should begin and three is the need to establish empirically the foundational platforms or lower anchors from which the generative ideas and practices obtain.

The research on young children's thinking reported in *Taking science to school* (NRC, 2007) suggests that children are capable of abstract reasoning and theory building from very early ages but in select domains. The research on infants and pre-K children, and research on children's alternative conceptions, demonstrates that students do arrive to school with some core knowledge and as they experience the world around them they do develop explanations – albeit naïve ones at times. Promising core knowledge domains for the early development (pre-K–2) of reasoning include:

- Physical mechanics (locating patterns based on property size, shape and weight; describing and representing mechanisms for the causes);
- Biology (differentiating between animate and inanimate; describing and representing biological processes such as digestion, growth, reproduction and sickness);
- Matter and substance (measurement and representation of macroscopic properties and attributes); and
- Naïve psychology (engaging in meaning-making with others, recognizing that beliefs of others may be different from your own and for good reasons). (NRC, 2007)

The research on theory of mind and perspectives from evolutionary psychology is relatively recent. Nonetheless, it has already contributed to our reconceptualisation of how we view children as thinkers and as knowers. The excitement about this line of research is wondering what upper grade bands of schooling will look like as nascent forms of reasoning and understanding and critiquing and communication become increasingly more sophisticated from early grades to higher grades.

Conceptual change research

Thinking on learning progressions, teaching sequences and teaching experiments owes much to the conceptual change research programs among science education researchers, educational psychologists and cognitive scientists. From the science education research on children's learning in science (c.f., Driver et al., 1994; Driver et al., 1996; Osborne & Freyberg, 1985), we have learned that children have insights into how nature is organised and how science is done. Children view the world differently from adults.

Both the growth of scientific knowledge and the growth of children's scientific knowledge involve processes and mechanism about seeing nature in new ways. Conceptual change research has always had strong ties to philosophy of science starting with the classic Posner, Strike, Hewson, and Gertzog (1982) paper that grounded a theory of conceptual change learning on images of scientific theory change proposed by Kuhn (1996) and Lakatos (1970). Thus one long line of conceptual change research among psychologists has adopted cognitive schema theory to explain conceptual change processes by suggesting that science learning is similar to scientific theory change. For these pyschologists, learning is fundamentally theory-like and seen as an individual process of cognitive theory revision. On this view, children's new insights are explained by processes of appropriating a new set of theoretical lenses or mental models that can change the way a child understands a domain and develops new broader contexts of meaning. With this view of conceptual change, teaching sequences are constructed to teach to the misconception by providing experiences (evidence) that challenge learners' extant incomplete mental models leading to cognitive dissonance, new insights and conceptual change. The goal is to fix what is wrong in the child's thinking, to correct the mistakes. The translation of this view to the classroom has led to uniform instructional conceptual change teaching practices that might jump too quickly to the established scientific explanation. Consider the following excerpt from *Ready, set, science!* (Michaels et al., 2008) the practitioners volume based on the research synthesis report *Taking science to school:*

> Many teachers have their students do experiments or make observations with the hope that scientific understanding will miraculously emerge from the data. Being exposed to new information, however, is not the same as understanding or integrating that information into what one already knows. Real conceptual change requires that deeper reorganization of knowledge occur. (p. 41)

Driver et al. (1994) echo the same sentiment: 'New knowledge is the result not only of the broadening in use of existing conceptions or the addition of new notions. It also involves the reorganisation of conceptual schemes themselves' (p. 89).

The *Taking science to school/ Ready, set, science!* research review points out there are several different types of conceptual change with different levels of difficulty that require adjustments in instruction when confronting different cases. From easiest to most challenging, three broad types of conceptual change are (Driver et al., 1994):

(1) *Elaborating on a pre-existing concept*: for example, students may learn how anatomical features (e.g., teeth) convey information about the animal's lifestyle (e.g., diet). Later they might investigate other body parts and extrapolate other behaviors.
(2) *Restructuring a network of concepts*: thinking about a pre-existing set of concepts in new ways. Grasping the idea of air as matter, for example, requires a change in understanding of the concepts of both air and matter. ... Later they may come to see that all matter is made up of tiny particles and can exist in different 'phases'.
(3) *Achieving new levels of explanation*: this is necessary for the advance of students' scientific understanding. To understand atomic-molecular theory, for example, they need to understand that materials consist of atoms and molecules and ... understand the behaviors and interactions of these microscopic constituents of matter. (pp. 42–43)

The conclusion *from Taking science to school* is that too strong a focus on fixing 'misconceptions' in conceptual change teaching works against addressing these three types of conceptual change. The alternative '*knowledge-in-pieces*' view of conceptual change (di Sessa & Minstrell, 1998) does not view learning as proceeding from fixed theory structures but rather from a marshalling of 'facets' to make and remake conceptual networks. The position is that facets of concepts will vary, be flexibly used depending on the context. Here students' thinking is seen as grounded in intuitions or insights into meaning making that can be built upon. Again, from *Ready, set science!* (Michaels et al., 2008):

> What we call misconceptions may be necessary stepping stones on a path toward more accurate knowledge. They may coexist with some accurate ideas about the natural world. Mistaken ideas may be the only plausible way for a child to progress toward a more accurate understanding of scientific conceptions. … And not all errors necessarily require instructional interventions … they will generally self-correct without instruction as children go about their lives. (p. 44)

In our review of science learning progressions, teaching sequences and teaching experiments it is often quite evident when the researcher(s) is working from one or the other framework of conceptual change – the misconception-based *fix it* view or the intuition-based *work with it* view. Adoption of one or the other view of conceptual change also influences views about the epistemic learning goals in science education, typically ignored in the *fix it* view and considered in the *work with it* view. Developing epistemic criteria and evaluating the epistemic status of ideas are viewed as necessary elements in a conceptual ecology of science learning environments that seek to promote enculturation into scientific cultures and/or achieve Nature of Science (NOS) learning goals. Recent reviews of research call for a shift in thinking regarding epistemic goals of science learning (Duschl & Grandy, 2008; Erduran & Jiménez-Aleixandre, 2008; Kelly, Wickman, & McDonald, in press). The essence of this shift is the importance the epistemic status of students' ideas has in achieving new levels of explanation (Jiménez-Aleixandre, 2008). The recommended shifts are:

(1) away from a focus on the individual scientist to a focus on social groups or communities of scientists;
(2) away from a focus on contexts of discovery and justification of conceptual claims to a focus on the development, modification and evolution of epistemic claims;
(3) away from an exclusive focus on inquiry addressing the fit of concepts in scientific theories to a focus on the tools and technologies that give rise to new methods, measurements and practices in building and refining scientific models; and
(4) away from domain-general 'consensus view lists of NOS' to views of NOS that are situated practices associated with the broadening and deepening of the growth of scientific knowledge.

Contemporary philosophical views of the growth of scientific knowledge (c.f., Duschl & Grandy, 2011; Godfrey-Smith, 2003; Knorr-Cetina, 1999) have adopted naturalistic accounts to explain the emergence of new conceptual (what we know), methodological (how we know) and epistemological (why we believe) criteria or standards for the growth of scientific knowledge and the mechanisms of scientific reasoning. Carruthers, Stich, and Siegel (2002) in the introduction to an edited volume examining the cognitive basis of science make the following comment about philosophers' rejection and questioning of logical positivism and of Kuhn's historical turn:

> It became important, then, to see science, too, as a natural phenomenon, somehow recruiting a variety of natural processes and mechanisms – both cognitive and social – to achieve its results. Philosophers of science began to look, not just to history, but also to cognitive psychology in their search for an understanding of scientific activity. (p. 4)

Grounded strongly in perspectives from philosophy of science, philosophy of mind and developmental psychology, the interdisciplinary approach to understanding science learning, knowing and doing has established in no uncertain terms that learning, cognition and reasoning are contingent on context and content. Twentieth-century interdisciplinary efforts in understanding science and science learning contributed to developments in both our understandings of science learning and our understandings of doing science.

In summary, having conceptual change as a learning goal is not about establishing a process of science as seeking justified true beliefs but rather it requires pursuing rational beliefs and explanatory coherence that are influenced and shaped by new tools, instruments, theories and methods. The strong recommendation from *Taking science to school* is that the teaching of conceptual knowledge should not be independent of learning science practices. In short, our understandings of the growth of scientific knowledge and scientific reasoning are grounded both philosophically and psychologically (Carruthers et al., 2002).

Pedagogy

A core recommendation emerging from the current US reform curriculum movement is establishing scientific measures and evidence for evaluating the success which curriculum and instruction models have on students' learning and achievement. Learning progressions are being identified as possible and plausible means for framing and obtaining these measures and the evidence. 'No Child Left Behind' and 'Race to the Top' legislation in the US have placed high priorities on measuring the progress of students, and schools, in terms of annual yearly progress in reading and mathematics. Within this political climate of educational accountability emerges the need to monitor students learning at the level of the classroom and to do so, on a frequent daily, weekly basis. Thus, we have the recent policy recommendations from *The Opportunity Equation* to pursue (1) the alignment of curriculum, instruction and assessment (C-I-A) and (2) the creation of core common standards (Carnegie Corporation of New York & Institute for Advanced Study, 2009; NRC, 2011).

The C-I-A alignment derives, in part, from research on the importance and role of formative assessments in the advancement of students' learning. The recognition given to formative assessments reinforces the distinction between 'assessment of learning' and 'assessment for learning' (Black & Wiliam, 1998) that, respectively, differentiates achievement measures from diagnostic measures. The monitoring of learning through formative assessments which inform instructional practices and teacher decision-making is often referred to as 'Adaptive Instruction' (Corcoran & Silander, 2009) and 'Keeping Learning on Track' (Wiliam, 2007). The adoption of formative assessment practices though demands within the C-I-A alignment agenda concomitant changes in curriculum and instruction models (Wilson, 2009). Learning progressions and learning performances are viewed as promising new models and mechanisms for C-I-A alignment in maths (Daro et al., 2011) and in science (Corcoran et al., 2009).

Writing about LPs in a summary report of a conference that brought together researchers engaged in LP research, Corcoran et al. (2009) posit four features to characterise LPs that can guide adaptive instruction:

(1) targeting core and generative disciplinary understandings and practices that merge science content with science practices;
(2) lower and upper boundaries that describe entry assumptions and exiting expectations for knowing and doing;
(3) descriptions of LPs that inform progress levels or steps of achievement; and
(4) purposeful curriculum and instruction that mediates targeted student outcomes.

Why a focus on adaptive instruction? Corcoran and Silander (2009) conducted a review of effects on high school (14–18 years old) student learning of instructional strategies. The strategies included interdisciplinary teaching, cooperative learning, problem-based learning, adaptive instruction, inquiry and dialogic teaching. Results found that well-designed student grouping strategies, allowing students to express their ideas and questions and offering students challenging tasks were powerful strategies for advancing student learning. In addition, adaptive instruction in which teachers monitor how students vary in what they are learning and adapt their instruction in response to students' progress and needs was found to be a strong factor that supports student learning.

The Corcoran et al. (2009) report also states 'progressions can play a central role in supporting the needed shift toward adaptive instruction' (p. 9) and that the following are possible learning outcome benefits of establishing LPs:

- providing a basis for setting standards that are tighter and more clearly tied to instruction;
- providing reference points for assessment to report on levels of progress and thereby facilitate teacher interventions and instruction-assisted development; and
- informing the design of curricula that are aligned with students progression (e.g., assessments for learning).

However, Corcoran et al. (2009) caution that while some promising efforts exist in select science domains and practices, the work is just beginning to produce valid and reliable evidence on the usefulness of progressions. A larger issue concerns whether progressions coordinated around core ideas and scientific practices are a potential alternative to instruction coordinated around standards. Another issue concerns the criteria we use to determine age appropriate or developmentally appropriate progressions; that is, is the proposed topic and pathway accessible to the learner. Metz (2009) cogently argues that we need a rethinking of 'developmentally appropriate' when adopting a learning progression perspective, children are more capable than we think.

Thus, a key pedagogical component of LPs is *instruction-assisted development* of learning that, like adaptive instruction, is grounded in learning performances that can serve as assessments for learning frameworks. Two LP research projects provide insights on how *instruction-assisted development* of learning can inform adaptive instruction strategies. First, Metz (2008) reports on two curriculum-based studies with first graders, one in botany research on plant growth and one in animal behaviour on crickets. The first grade students' instruction-assisted engagements in knowledge-building practices are based on curricula scaffolded around seven interrelated features of science practices that support productive engagement:

- immersion in strategically selected scientific domains;
- centrality of big ideas in the practices;
- entwining of content and process;
- centrality of curiosity as a drive for doing science;
- discovery and explanation as top level goals;
- challenge of making sense of the ill-structured; and
- the social nature of scientific knowledge-building-practices.

The initial versions of the curricula that demonstrated that children can design investigations around researchable questions and cope with uncertainty were designed and used successfully across several elementary grade levels (Metz, 2004). The first grade vignettes reported in Metz (2008) draw from beginning, mid-point and end of unit enactments of practices and show 'how the children's deepening knowledge supported the power of their thinking and increased responsibility' (p. 145).

A second example of instruction-assisted development is that by Lehrer, Schauble, and Lucas (2008). They engaged sixth grade students in school-year-long pond studies beginning in the warmer autumn months with measurements of a pond and then extended during the winter months to classroom investigations. A part of the instruction had students design and build models of ponds in gallon sized glass jars. This provided a basis for studying questions the students had about the ponds from the autumn investigations. Lehrer et al. report that unintended outcomes like algae blooms and bacteria colonies afforded opportunities to examine how ecosystems function. Subsequent efforts to model the pond ecologies were supported by weekly research meetings. Here students would exchange ideas and discuss relations between evidence and explanations. The struggles students had with the material design of the jar-ponds to engage in inquiry were found by the researchers to foster a pedagogy of inquiry.

End-of-year interviews with students were conducted to assess understandings about ecology and research design and beliefs about epistemology of inquiry. To get at views about the nature of inquiry, interviewers asked student to contrast the extended inquiry on ponds with boxed-up, hands-on science investigations. The researchers found that the weekly research meetings were a major influence on students' views about the nature of inquiry. Also, students reported that the repeated efforts and struggles to make the jar-ponds work were preferred over the clearer outcomes found in kits. Such a finding has important implications for research on motivating students to engage in science and build identities in science (Blumenfeld, Kempler, & Krajcik, 2006). With the right context students can develop sophisticated views about the nature of science.

Lehrer and Schauble (2004, 2007) maintain that with instruction-assisted inquiry, modelling and reasoning as scientific practices can support (1) sustained engagement with epistemic and social practices and (2) the construction of mathematical representational forms that afford quantification and investigation of relations among quantities. Lehrer and Schauble (2006) see engagement in resemblance representation tasks as an entrée to modelling. Lehrer and Schauble (2002) provide additional teaching examples and student artefacts of engagements in representation tasks that model data from investigations carried out by students in grades k–5. These instruction-assisted-development teaching sequences have students using and learning from data modelling, bridging mathematics and science, engaging in inquiry studies and using emergent representational forms.

The recommendation for LPs represents a shift in emphasis from teaching that focuses on what we know (e.g., facts and skills) to teaching that focuses on how do we know and on why we believe what we know over competing scientific claims. This, in turn, leads to recommendations that science learning be connected through longer sequences of instruction (e.g., immersion units, LPs) that function vertically across grade bands and horizontally within a grade level. The rationale is to facilitate the learning of core science knowledge and practices that are critical for development of scientific knowledge and reasoning. The position being advanced is developing rich, conceptual knowledge takes time and requires instructional support and mediation via sound assessment practices.

Learning trajectories

Another source that informs methodologies for the design and validation of learning progressions is Learning Trajectories, in particular as defined by the mathematics education community. Maths educators preceded science educators in thinking through the dynamics of coordinating ‘big ideas’ across longer grade bands by approximately a decade. In the introduction to a special issue of ‘Hypothetical Learning Trajectories’ (HLT), Clements and Sarama (2004) attribute the beginnings of HLTs to two sources. One is the ‘Realistic Mathematics Education (REM) Group’ from the Netherlands Freudenthal Institute (Gravemeijer, 1994) that advanced an agenda of developmental progression learning experiments ‘that involves conjectures about both a possible learning route that aims at significant mathematical ideas and a specific means that can be used to support and organize learning along this route’ (p. 82). The REM approach studies students’ informal solution strategies to instructional tasks with the goal of establishing guidelines for the order of instructional tasks that promote participation in types of thinking and learning.

The second contributor is Simon (1995) who proposed a constructivist model of pedagogical thinking for HLTs. According to Simon, an HLT is comprised of ‘the learning goal, the learning activities, and the thinking and learning in which the students might engage’ (p. 133). The focus of the research, like that in REM, is the development of tasks that are connected to students’ thinking and learning. Clements (2007) calls this the ‘learning model’ stage in his Curriculum Research Framework. The learning model for Clements begins with clinical interviews to ascertain students’ knowledge that includes ‘conceptions, strategies, intuitive ideas, and information strategies used to solve problems’ (p. 44). Next, this static model is tested and extended with teaching experiments that examine tasks and teacher interactions that elicit students' thinking and reasoning with the goal of establishing models of mathematical thinking and learning (Steffe, Thompson, & Glaserfeld, 2000). Such models, Clements (2007) asserts, may be grounded in the historical development of mathematics, observations of informal solution strategies or the emergent mathematical practices of student groups (Cobb & McClain, 2002; Gravemeijer, 1994). These working models then establish learning trajectories that are the basis for sequences of activities that help avoid the fragmentation and short curriculum strands common in textbooks. The research process is inherently iterative as learning from tasks is examined on a day-to-day basis. The goal is the development of instructional sequences that are justified by both theoretical deliberations and empirical data (Gravermeijer, 1994).

Clements and Sarama (2004) note that 'the nascence and complex nature of learning trajectories has led to a variety of interpretations and applications', a description that applies equally well to science education learning progressions today. The conceptions of LT above and in the articles found in the 'Special Issue: Hypothetical Learning Trajectories' (Clements & Sarama, 2004) focus on instructional sequences, activities and learning goals within grade levels targeting select mathematical tasks and reasoning. This grade level focus, task sequence driven perspective contracts with the grade band focus and practices perspective of learning progressions in science education.

An important and noteworthy exception in mathematics education is the pioneering research of James Kaput. Kaput (1994) established a research programme on studying the mathematics of space and time, calculus or simply the processes of change as a topic to introduce in elementary grades and then build across grades. An important element of the research programme was the use of computer simulations. Rochelle and Kaput (1995) used computer supported learning with SimCalc to introduce the composable components of calculus learning. SimCalc uses animations in which actors motions are governed by graphs that when edited reveal mathematical relationships.

In summary, each of the foundational areas discussed here makes a contribution to our thinking about the development of learning and the development of instruction-assisted pathways to support learning and reasoning. The preceding decades have provided useful research to inform our criteria for proposing, refining and developing LPs. As will be discussed in the LP review sections to follow, the theoretical framings adopted from the above foundational domains effect the guiding conceptions LP researchers and designers use to conduct the LP studies. And, the effects are on both the creation of LPs as well as on the validation and description of LPs.

Review of learning progression studies

The sources for the papers and articles used in the review derive from the publications listed in the Appendix. The manuscripts and articles are listed in Table 1 where you will find LP grade level/band as well as domain/topic of study information. The LP review is presented in three sections. In the first section, publications addressing LPs for *science domains/topics* and for *science practices* are reviewed. The second section reviews articles focusing on *assessment and measurement* issues in the development of LPs. In the third section, we take up the review of

Table 1. The lists of reviewed articles in analysing learning progressions.

Authors (year)	Title (*Journal*)	Topic	Grade spans	Main features	Method of assessment	Description of pathways
			Science domain/topics			
Alonzo and Steedle (2009)	Developing and assessing a force and motion learning progression (*Science Education*)	Force and motion	7	Smaller scale LP Diagnosis of LP levels with OMC items Identifying response consistency and language	OMC items OE questions	4 levels in nonzero net force, no net force, moving, or no motion with common errors
Duncan, Rogat, & Yarden (2009)	A learning progression for deepening students' understandings of modern genetics across the 5th–10th grades (*Journal of Research in Science Teaching [JRST]*)	Modern genetics	5–10	Genetic, meiotic, & molecular model Suggest eight big ideas in modern genetics	Learning performance & assessment tasks	Grade bands become LP levels: L1(5/6), L2(7/8), L3 (9/10)
Furtak (2009)	Toward learning progressions as teacher development tools *(LeaPS conference)*	Natural selection	9–10	Propose educative LP Support teachers' PD using LPs Student response, feedback strategy Professional learning community	Conceptual inventory of natural selection Formative assessment prompt	Content progression based on expert theory Mixed with the origin of traits and selective force From need-base change to natural selection
Gunckel, Covitt, & Anderson (2009)	Learning a secondary discourse: Shifts from force-dynamic to model-based reasoning in understanding water in socio-ecological systems (*LeaPS Conference*)	Water cycling	2–12	Progression in shifting from *primary Discourse* (force-dynamic reasoning) to *secondary Discourse* (model-based reasoning)	Written assessment & interview Progress variables	Force-dynamic, hidden mechanism, school science, & model-based reasoning

Table 1. (*Continued*)

Authors (year)	Title (*Journal*)	Topic	Grade spans	Main features	Method of assessment	Description of pathways
Lehrer and Schauble (under review)	Seeding evolutionary thinking by engaging children in modeling its foundations (*Science Education)*	Evolution	K–6	Variation, change, and ecology Conjectured trajectory called benchmark Content with practice		Benchmarks on variability, change, & ecology in evolution
Mohan & Anderson (2009)	Teaching experiments and the carbon cycle learning progression *(LeaPS conference)*	Carbon cycling	4–12	Alternative pathway for principle-first focusing on explaining Teaching experiment materials with process tools, molecular model kits, & hierarchy scale		Force-dynamic, conservation at macroscale, principled accounts at molecular scale, & principle based process/ systems
Mohan, Chen, & Anderson (2009)	Developing a multi-year learning progression for carbon cycling in socio-ecological systems (*JRST*)	Carbon cycling	4, & 6–12	Upper/lower anchors Developing LP framework by students' descriptions as to the level of achievement under status quo teaching	Written assessment & clinical interview	LP describes the transition between informal accounts and scientific accounts four elements forming accounts (life, material, scale, and model)
Plummer & Krajcik (2010)	Building a learning progression for celestial motion: elementary levels from an Earth-based perspective (*JRST*)	Celestial motion	1, 3, 8	Learning trajectories as sub-progressions Planetarium instructional intervention & pre-post test	Clinical interviews Construct map	Based on the logic of discipline, authors' analyses of students' concepts, and comparing prior/after intervention
Songer, Kelcey, & Gotwals (2009)	How and when does complex reasoning occur? Empirically driven development of a learning progression focused on complex reasoning about biodiversity (*JRST*)	Biodiversity	4–6 & 8 weeks	Trial of integrating content progression and inquiry reasoning progression five-step process of LP development	MC/OE items assessment Embedded assessment	Content progression from 4th to 6th 4 levels of inquiry reasoning progression

(*Continued*)

Table 1. (*Continued*)

Authors (year)	Title (*Journal*)	Topic	Grade spans	Main features	Method of assessment	Description of pathways
Stevens, Delgado, & Krajcik (2010)	Developing a hypothetical multi-dimensional learning progression for the nature of matter (*JRST*)	Atomic structure and electric force	7–14	Hypothetical/empirical multi-dimensional LPs Construct centred design Potential instructional strategies	Open ended assessment task with interviews	4 levels from atom as sphere with unspecified force to Bohr/Electron cloud model with electrical force, to orbital and linkage of energy
Wiser, Smith, Doubler, & Asbell-Clarke (2009)	Learning progressions as tool for curriculum development: Lessons from the INQUIRY project *(LeaPS conference)*	Matter	3–5	Upper/lower anchors Stepping stones Lever concepts Linchpins From weight, size, material, volume, & density to matter		Grades become levels From hefted to measured weight From heavy for size to density etc.
			Science practices			
Berland & McNeill (2010)	A learning progression for scientific argumentation: Understanding student work and designing supportive instructional contexts (*Science Education*)	Argumentation	2, 3, 7, & 12	Three dimensions of argumentation practice Instructional context, argumentative product & process	Coding and comparing data according to initial framework	Comparison of four cases From simpler to more complex in argumentation
Lehrer & Schauble (under review)	Seeding evolutionary thinking by engaging children in modelling its foundations (*NARST conference)*	Data representation	K–6	Integration of content and practice: variability with counting & modelling, change with drawing, measuring, & computation of species Generative principle to guide instruction		Benchmarks on variability, change, & ecology in evolution

Table 1. (*Continued*)

Authors (year)	Title (*Journal*)	Topic	Grade spans	Main features	Method of assessment	Description of pathways
Schwarz, Reiser, Davis, Kenyon, Acher, Fortus, et al. (2009)	Developing a learning progression for scientific modelling: Making scientific modelling accessible and meaningful for learners (*JRST*)	Modeling & metaknowledge	5, 6 6-week units	Model as generative tool for explaining & predicting Changeability of model as to understanding level Focused on modeling itself Instructional sequences for modeling practice	Construct map	4 levels from simple illustration to multiple modelling with explaining/predicting four levels from unchangeable model to changeable with explanatory power & evidence
			Assessment/measuring			
Briggs & Alonzo (2009)	The psychometric modelling of ordered multiple-choice item responses for diagnostic assessment with a learning progression (*LeaPS Conference*)	Psychometric Attribute Hierarchy Model				
Carraher, Smith, Wiser, Schliemann, & Cayton-Hodges (2009)	Assessing students' evolving understandings about matter (*LeaPS Conference)*	Matter Measuring	3–5	INQUIRY project Shift from perception-centred to model-mediated thinking; Quantitative reasoning & understanding measurement	Clinical interview within longitudinal design Instructional intervention (treatment/control group)	

(*Continued*)

Table 1. (*Continued*)

Authors (year)	Title (*Journal*)	Topic	Grade spans	Main features	Method of assessment	Description of pathways
Catley, Lehrer, & Reiser (2005)	Tracing a prospective learning progression for developing understanding of evolution	Big Ideas, Core Concepts, Conceptual Ecologies				
Draney (2009)	Designing learning progressions with the BEAR assessment system (*LeaPS Conference)*	BEAR assessment system				
Masters, Adams, & Wilson (1990)	Charting of student progress	Progress Variables				
Lee & Liu (2010)	Assessing learning progression of energy concepts across middle school grades: The knowledge integration perspective	Knowledge Integration model				
Lee, Johanson, & Tsai (2008)	Exploring Taiwanese high school students' conceptions of and approaches to learning science through a structural equation modelling analysis				Structural Equation Modeling	
Plummer & Slagle (2009)	A learning progression approach to teacher professional development in astronomy	Teacher Education			BEAR	

Table 1. (*Continued*)

Authors (year)	Title (*Journal*)	Topic	Grade spans	Main features	Method of assessment	Description of pathways
Steedle (2008)	Latent class analysis of diagnostic science assessment data using Bayesian networks				Latent Class Analysis/Bayes Net	
Steedle & Shavelson (2009)	Supporting valid interpretations of learning progression level diagnoses *(JRST)*				Bayes Net Theory/Latent Class Analysis	
West, Rutstein, Mislevy, Liu, Levy, DiCerbo, et al. (2009)	A Bayes net approach to modelling learning progressions and task performances (*LeaPS Conference)*				Bayes Net	
Wilson (2009)	The structured constructs model (SCM): A family of statistical models related to learning progressions (*LeaPS Conference)*					
Wilson (2009a, b)	Measuring progressions: assessment structures underlying a learning progression *(JRST)*				BEAR/Construct modelling	
Wilson (2009)	Measuring progressions: assessment structures underlying a learning progression *(JRST)*	Construct map				

(*Continued*)

Table 1. (*Continued*)

Authors (year)	Title (*Journal*)	Topic	Grade spans	Main features	Method of assessment	Description of pathways
			Alternative framework			
Carraher, Smith, Wiser, Schliemann, & Cayton-Hodges (2009)	Assessing students' evolving understandings about matter (*LeaPS Conference)*	Matter Measuring	3–5	INQUIRY project Shift from perception-centred to model-mediated thinking; Quantitative reasoning & understanding measurement	Clinical interview within longitudinal design Instructional intervention (treatment/control group)	
Confrey & Maloney (2010)	The construction, refinement, and early validation of the equipartitioning learning trajectory				Clinical Interviews	
Furtak, Morrison, & Henson (2010)	Centering a professional learning community on a learning progression for natural selection: transforming community, language, and instructional practice *(ICLS conference)*	LPs for teacher development				
Heritage, (2008)	Learning Progressions: Supporting Instruction and Formative Assessment					
	On the role and impact of formative assessment on science inquiry teaching and learning *(NSTA conference)*	Floating and sinking, buoyancy				

Table 1. (*Continued*)

Authors (year)	Title (*Journal*)	Topic	Grade spans	Main features	Method of assessment	Description of pathways
Salinas (2009)	Learning progressions in science education: two approaches for development (*LeaPS Conference*)	Escalated/ landscape approach to LPs				
Sikorski & Hammer (2010)	A critique of how learning progressions research conceptualizes sophistication and progress (*ICLS Conference*)	Level of LPs				

publications addressing *theoretical/guiding conceptual frameworks* used in the development of LPs. Important to note is that all the research reviewed below is of high quality with respect to method and to evidence. For purposes of communicating general features about LP research we have chosen studies that stand up as exemplars of the type of LP research being conducted. We also make references to how the characteristics and features of an LP represent either '*Validation LP*' or '*Evolutionary LP*'.

Science domains/topics and science practices learning progressions

The review of LPs on science domains/topics and on science practices is divided into four subsections. First, we examined the core ideas and science practices of LPs. Second, we examine the boundaries of LPs in terms of lower and upper anchors. In addition, we review the lower anchors in terms of the accessibility of the target concepts and the upper anchor in terms of the abstractness of the learning goals. Third, we analyse the LP's intermediate steps taken between the lower and upper anchors. Then, using the intermediate steps as guidelines we identify how instruction-assisted development or adaptive instruction strategies are used. Fourth and finally, we consider how LPs present coherent pathways to monitor students' learning concepts and engagement in practices from the lower to the upper anchor.

The core ideas for learning progressions – concepts and practices

In general, we found that the LPs for science domains/topics and science practices are usually determined on the basis of (1) perceived disciplinary importance or (2) inclusion in standards documents (e.g., celestial motion, force and motion, atomic structure and electrical force, argumentation, etc.). Arguments for 'foundational status' or generative importance of concepts or practices are often omitted. The intent of learning progressions is to provide opportunities for learners to achieve increasing levels of sophistication with using knowledge in doing science; e.g., science practices. Thus, while the development of LPs focusing on conceptual domains is valuable, the goal expressed in *Taking science to school* is to development cognitive and social scientific practices as well. Thus, we were surprised to find that many LPs for science domains/topics usually did not integrate science practices and that LPs focusing on practices did not integrate domain knowledge. Two articles demonstrate this separation of core ideas about concepts and practices.

Plummer and Krajcik (2010) developed a LP for celestial motion in astronomy lessons in elementary and middle schools. This LP is associated with a set of embedded learning trajectories related to the sun's path, the moon's path, the patterns of stars' moving and changes in the moon's appearance when seen from Earth. These four embedded learning trajectories can be viewed as separate yet complementary construct map components (Wilson, 2009). That is, a single learning progression on Sun–Earth–Moon motions consisting of four separate learning-trajectory-construct-maps that are taught in sequence. This taxonomy framework for LTs and LPs (Stevens, Shin, & Krajick, 2009) is discussed later in the paper. The content of the learning trajectories in the LP did not attend to science practices, but focused instead on understanding the nested astronomical concepts.

An example of an LP that stresses science practices is that by Berland and McNeill (2010). This LP articulates a learning progression for argumentation

Table 2. BEAR Assessment Model.

Building block	Principle
Construct Map	*Developmental perspective (based on the cognitive theory of learning)*
Defines and represents what students know and can do at different levels as they continue learning for a certain construct	Learning is a continuum and students improve from less expert ideas to more expert ideas
The Item Design	*Match between instruction & assessment*
Assessment tools that help to observe what students can do at different levels of the construct map	The item design should be integrated within the instruction and daily activities of the classroom.
The Outcome Space	*Management by teachers*
Identification and scoring of students' responses (outcomes) and matching with the appropriate level of the construct map by the teachers	Moderation sessions designed for teachers to create a consistent scoring and interpretation of the students' work
The measurement model	*Evidence of high quality assessment*
Used to make inferences about students' learning	Aims to create consistent measures with multiple instruments for comparisons to determine change or progress
Multidimensional Rasch-based item response model is used as the psychometric approach and helps the construction of Wright map	

practices across three dimensions: instructional context, argumentative product and argumentative process. Argumentation is seen as a central goal of science education and a significant way for engaging students in knowledge construction. Although Berland and McNeill examined students' argumentative discourse occurring in classes studying biodiversity, ecosystem, force and motion and natural selection, the target progress variables were argumentative product and argumentative process. Development related to understanding science concepts was missing. In other words, they reported students' achievement of generalised practices of argumentation independent from progress on disciplinary concepts.

When we did find integration between core ideas about concepts and practices, the LP descriptions were more thorough. But we also found that the integration of concepts and practices varied in one of three ways:

(1) separate LP development of conceptual domains and science practices and then merging the two together;
(2) stressing LP development of core science content principles over science practices; and
(3) embedding or situating science practices into domain-specific conceptual contexts.

The biodiversity LP by Songer, Kelcey, and Gotwals (2009) represents a juxtaposition of a content progression with an inquiry reasoning progression, e.g., an evidence-based explanation. This LP first reports a linearly sequenced biodiversity content progression which is then used as a template to merge a developmental pathway for aligning inquiry practices to the evidence-based explanation progressions. The focus is on outlining curricular activities for content teaching, rather than showing student development along the two progressions in one coordinated pathway. The content sequence of curricular activities proceeds from bottom to top in a linear progression. The practices-based progression meanders as a conjectural pathway through the biodiversity teaching units. In Songer (2011), an extended LP for climate change biology, we do find content learning and practice learning integrated into one LP.

Anderson and colleagues (Gunckel, Covitt, & Anderson, 2009; Mohan & Anderson, 2009; Mohan, Chen, & Anderson, 2009) are examples of integrating science concepts and science practices in LP studies with an emphasis on core understandings of scientific principles that are situated in practice learning. The selection of LP conceptual domains making up carbon and water cycling were based on social usefulness for comprehending global warming and helping learners become environmentally literate. The researchers considered environmental science literacy as the interrelation among discourse on environmental issues, practice of explanation/prediction in the events of carbon/water cycling and knowledge about complex system of carbon and water cycling. Thus, the LP for carbon cycling focused on joining the domains of knowledge and practice; e.g., students' accounts of mechanisms to generate, transform and oxidise organic carbon tied to students' reasoning about using the knowledge within mechanisms. The water cycling LP integrated scientific principles with explaining/predicting practices about the movement of water and substances in water to represent accounts of students' reasoning and to ascertain levels of performance.

A third case of integrating science practices and concepts is Lehrer and Schauble (2004, 2011). Lehrer and Schauble characterise pathways of understanding for variability, change and data modelling in the study of an LP for modelling evolutionary processes. They regard the interrelation among variability, change and data modelling as critical seeds of evolutionary reasoning. In addition, they articulated important intermediate levels or 'benchmarks' in the conjectured trajectories, thereby setting out in more details the learning pathways. For example, the practice 'variability' is described by a subset of related 'benchmark' practices, e.g., inscribing difference, measuring difference, making distribution, modelling distribution and competing models. The practice 'change' is described with a subset of representational 'benchmark' practices that include drawing, measuring rates and establishing computations of change in organisms and in populations.

Lehrer and Schauble's approach to LP development begins by immersing students in circumstances where modelling and representation provide explanatory power for addressing questions of interest. In this way, they integrated the core concepts with the accessible practices of modelling and representing. This approach to learners' development through productive engagement in disciplinary practices represents an alternative way of integrating practices with concepts and of using instructional design for monitoring the progress in students' understanding and practice.

Boundaries of learning progressions: lower and upper anchors

Learning progressions have a beginning point and an ending point that can span months, semesters or years. *Taking science to school* refers to the beginning point as the 'lower anchor' which represents the knowledge children bring with them to school. This beginning knowledge is often grounded in sensory-based observations of commonly occurring natural events. In this way the lower anchor disciplinary concepts of LPs are said to be accessible to learners since they have some awareness of the phenomenon. The 'upper anchor' represents the expectations we have of students learning at the end of the LP. That is, what students should know and be able to do. In the following two subsections, we first examine how researchers choose to establish the lower anchor as a starting point for the LPs and then we discuss the ways researchers conceptualise upper anchors. We also consider the accessibility of target concepts for the lower anchor and the abstractness of learning goals for the upper anchor, respectively.

Lower anchor and the accessibility of target concepts. The lower anchors of LPs often consist of macroscopic events, which are easily visible or related to students' everyday-experience or accounts. This characteristic of LPs ensures the target concepts of LPs are accessible to learners. For example, Mohan et al.'s (2009) learning progression on carbon cycling was based on five focused macroscopic events familiar to students: plants growth, animal growth, animal movement and weight loss, decay and burning. The lower anchor of this LP focuses on intuitive accounts that macroscopic events are the result of natural tendencies by differing agents and enablers. In other words, the growth of plants is a natural process enabled by food, water or sunlight. Mohan et al. labelled this kind of reasoning and accounts as *force-dynamic*, which is closely related to children's informal everyday experiences and discourse. Using macroscopic events and considering the force-dynamic accounts as the lower anchor make this LP appeared to be accessible to early years' learners.

In Alonzo and Steedle's (2009) force and motion LP, they did not describe anchor points explicitly, but expressed the progression of students' understanding of the topic continuously from the lowest level (level 1) to the highest level (level 4). The lowest level (i.e., lower anchor) of this LP was students' understanding of force as a push or pull no matter whether it is involved with motion or not. Similarly, the lower anchor of the LP for matter and atomic molecular theory (Smith, Wiser, & Carraher, 2010; Wiser, Smith, Doubler, & Asbell-Clarke, 2009) is based on research about students' naïve ideas about weight and material. For example, 'liquids and solids have same characteristics as material kind, but gases do not; weight is reliably assessed by hefting; or weight is not conserved across transformations of objects'. The lower anchors of these LPs reflect students' common errors, misconceptions or everyday 'folk' concepts about the topics. In addition, the lower anchor for these LPs focus on learners' perception-centered thinking that is tied to children's perceptual judgment and evidence of appearances (Smith et al., 2010). Such lower anchor features provide productive entry points and thereby make the LPs accessible to students.

Lehrer and Schauble (under review), in a component LP for learning practices used in evolution, recognize that the theory of evolution has several everyday knowledge entailments that could be productive resources for developing scientific explanations. The entailments are observable and measurable differences (1) between or within species, (2) changes over time in individuals growth or population fluctuations, and (3) between organisms' structural features and habitat. The lowest levels of the three entailments involve describing qualitative differences, observing and describing the current state of an organism or group of organisms and posing questions about where an organism lives. Thus, the lower anchor of learning performances is accessible in that it is related to basic practices for understanding the evolutionary concept through variability, change and ecology.

Starting LPs at higher grade levels presents additional challenges regarding the accessibility of lower anchors. Duncan, Rogat, and Yarden (2009) present a hypothetical LP for modern genetics including three levels of growing sophistication mapped onto grade bands from 5th–6th (level 1), 7th–8th (level 2) to 9th–10th (level 3). A tentative set of core ideas for modern genetics is presented with precursors of the core ideas establishing the lower anchor based on grade 5–6 students' conceptions. For example, when considering a gene's influence on organisms, Duncan et al. suggest that the lower anchor is to understand genes as a mediating mechanism. Namely, to see genes as a defining feature of living things present in most cells in the organism, as having instructions for the growth and functioning of living things and as the mechanism of inheritance from parents. Articulating such components and mechanisms requires sophisticated interdisciplinary awareness of chemical and physical interactions at a molecular level and of unobservable entities of cellular and molecular processes. Thus, we feel this LP is starting from a more complex place and raises questions about the accessibility to students. Basing a hypothetical LP on curriculum framework documents runs the risk of omitting important understandings about how children reason and make meaning. Following the thinking from the Smith, Wiser, Anderson, and Krajick (2006) LP on matter, we wonder if there are similar macro-type-properties that would make genetics and cellular functions accessible to 5th or 6th graders? What are the engagements with phenomenon and modelling/representation of phenomenon that offer a toe hold for lower anchors? Sorting out the conceptual pathways and trajectories seems to be an important precursor to making conjectures about lower anchors and the consequent LP.

Upper anchor and the abstractness of learning goals. The upper anchor represents the learning goals of the LP, with an emphasis on using knowledge and practices. *Taking science to school* represents upper anchors as the successive adoption of more accurate scientific understanding and increasing sophisticated science practices that together establish societal expectations for science literacy. The upper anchor goals and performance expectations will obviously vary depending on the targeted ending grade, e.g., 5th, 8th, 10th, etc. Not unlike the accessibility issue for the lower anchor, the upper anchor has to also attend to issue of appropriately targeted learning goals. If the learning goals are too sophisticated or if the LP learning pathways are ill conceived, then the upper anchor runs the risk of being too abstract or beyond the 'boundaries' of outcome learning expectations. We refer to this as the abstractness issue, that is, the complexity of upper anchor target concepts. Looking across the LP research reports, upper anchor abstractness is strongly related to hypothetical LPs that target college readiness, are based on curriculum frameworks and seek at early grade bands learning goals based on scientists' conceptions.

In the carbon cycling LP, Mohan et al. (2009) has as a 12th grade upper anchor knowledge and information scientifically literate citizens need to interpret environmental systems and to judge human impact on environmental systems in terms of chemical models. Thus, they identify as the upper anchor a suite of scientific principles or accounts regarding chemical processes, e.g., connected systems of generating organic carbon (photosynthesis), transforming organic carbon (biosynthesis and digestion) and oxidising organic carbon (cellular respiration and combustion). The accounts are labelled '*qualitative model-based accounts*' and contained descriptions of chemical changes constrained by foundational principles of matter/energy conservation and energy degradation. While this upper anchor may appear to be highly abstract, the learning pathway across multiple grades begins with accessible macroscopic characteristics in the lower anchor. Through a process of iterative design based research implementations and refinements of the curriculum sequence the researchers are working on reorganising the intricate network of domain-specific concepts and doing so in the context of scientific decision-making.

No one would argue that the pathways of learning are complex and thus the importance of intermediary steps within an LP to support learning, which we discuss in the next section. The same 'intermediary step' concerns would seem to apply to the sequence and coherence across linked LPs and for segments within LPs. Consider the LP for matter and atomic molecular theory (Smith et al., 2010; Wiser et al., 2009) that aims at upper elementary grades 3–5 and is a component of the broader K–8 hypothetical LP reported in Smith et al. (2006). The 3–5 LP upper anchor goal focuses on an important ontological re-conceptualisation of matter and density necessary for advancing thinking and learning. Importantly, the upper anchor is not at this point targeting scientists' understanding of expert theory (i.e., atomic molecular theory). Rather the upper anchor focus is on the development of quantitative reasoning and understanding about matter through measurement practices. Smith et al. (2006, 2010) and Wiser et al. (2009) show students at this age can consider weight and volume as an inherent property of matter, see gases as materials by measuring volume and weight and follow the conservation of matter across phase changes based on weight constancy. Thus, while the upper anchor shows high abstractedness compared with the lower anchor, the progress variable development of matter and density via measurement of physical properties and patterns of evidence provide an evidence for learners to engage in the targeted ontological re-conceptualisation. We view this partitioning and sequencing of upper anchors of as positive feature of LP research and design.

Often the societal expectations for learning goals are motivated by new technologies, new arenas of science and thus new economic/workforce agendas. In an LP for atomic structure and electrical force, Stevens, Delgado, and Krajcik (2010) take up complex learning pathways associated with nanoscale science and engineering learning. The upper anchor focuses on foundational understandings for nano self-assembly mechanisms. Namely, the focus is on the electron cloud and Bohr models for atomic structure and electron configuration and on electrical force models for chemical bonds. The upper anchor also addresses quantum mechanical models of atomic structure. While the logic and presentation of the LP by the authors is thoughtful and thorough, there are questions that come up about sequencing instruction for such lofty abstract domains that few students attain. The authors recognise the challenges and the competing perspectives about teaching quantum mechanics. Our issue is with the very high level abstractness of the targeted upper anchors and consequent conjectural learning pathways put forth for nanosciences, a domain of science still very much in formative development. Intermediary LPs across shorter grade bands would seem to be in order for any research agenda on science domains that seeks such abstractness. Students who understand the mechanisms and models about atomic electrical forces governing atomic interactions were very few. The education research community may need to be cautious about applying LP research models to domain topics that are highly abstract like quantum mechanical thinking.

In Berland and McNeill's (2010) argumentation LP we find an example of how levels of LP progress are used to show students' progressively more complex forms of argumentative discourse. Argumentation practice is seen as having three dimensions, argumentative products, argumentative processes and instructional context. The argumentative products are further delineated as having four components: (1) how claims are defended by evidence or reasoning, (2) whether counterclaims have rebuttals or not, (3) whether claims just address the questions or include causal accounts and (4) how the components of arguments are appropriate and sufficient. This LP is described not by the levels of achievement, but rather as moving from simpler argumentation practices to more complex ones. Thus, the targeted upper anchor practice of this LP is a highly elaborated practice skill defined by the researchers. For example, the argumentative progression focuses on the argumentative function in students' arguments here to mean whether students state and defend their claims as well as respond to others' claims through questioning, evaluating or revising. The argumentative progression is also assessed by the extent of students' spontaneous participating in argumentation. The focus on functions and on participation comes across as a form of evaluation of students' achievement. As such, the LP levels are more of a kind of scoring rubric for matching practice skills and less of a learning pathway for the development of argumentation practices.

In summary, stronger LPs have lower anchors that are accessible to learners whether through investigations in to macroscopic events or alignment with students' everyday experiences. When the upper anchor, compared to the lower anchor, shows more sophisticated levels of understanding there is a stronger LP. A caution though has to be made about LPs that have highly abstracted upper anchors. That is, whether the upper anchor targets scientifically accurate conceptual frameworks or targets obtainable societal expectancy for a literate citizenship.

Intermediate levels and instruction-assisted development

With regard to understanding and articulating learners' developmental pathways, it is important to identify intermediate steps or levels in the LPs. Smith et al. (2010) refer to the intermediary levels as 'stepping stones.' The stepping stones allow students to bridge successfully between lower and upper anchors with appropriate instructional intervention on the part of the teacher. While many researchers agree with the importance of instruction-assisted learning in LPs, a majority of the LP studies examined for this review do not report on these important instructional interventions. Only a few ongoing research programmes (Lehrer & Schauble, under review; Metz, 2011; Smith et al., 2010) attend to factors that effect instruction-assisted development.

Plummer and Krajcik (2010) presented explicit instructional interventions in their learning trajectories for celestial motion. They employed planetarium-based instruction to compare its outcomes with the initial learning trajectories of celestial motion. Then, they show how the instructional intervention made younger learners conception progress effectively. For example, prior to instruction, a few students expressed knowledge of the change in the sun's path length and change in altitude across the seasons. After instruction over half of the students had progressed toward level 3 giving an accurate description of the sun's path length and altitude. Details about the instructional interventions and how students progressed are missing. That is, not revealed in the study are the instruction factors that help students' progress from lower to higher levels of understanding.

The carbon cycling LP developed by Mohan et al. (2009) also did not report on any instructional interventions. The LP study reported on what students learned about carbon cycling under status-quo teaching. Mohan and Anderson's (2009) subsequent study, however, found that Mohan et al.'s (2009) carbon cycling LP had not focused enough on the amount of chemical details. They found that students who had known the names of systems, processes and materials about carbon cycling could not explain processes related to matter and energy changes in carbon cycling systems. Thus, they revised the carbon cycling LP to conduct teaching experiments for the purpose of developing sequenced teaching materials to support development of students' principle-based explanation. Mohan and Anderson's current study is still ongoing and the result of the teaching experiments work is not yet reported. However, they do suggest that the instruction-assisted development teaching experiments are contributing to refining the intermediate levels of the carbon cycling LP.

Furtak (2009) and Furtak, Morrison, and Henson (2010) investigated an 'educative LP' about natural selection, which included formative assessment prompts and feedback strategies for science teachers. The purpose of the educative LP is while students progress through the LP, support is given to teachers' professional development through participation in a professional learning community (PLC). The PLC consisted of science teachers and researchers and occasionally included scientists. Discussions focused on theory of natural selection, students' ideas about the topic and/or instructional approaches concerning formative assessments and feedback strategies. The feedback strategies are examples of instructional interventions.

Feedback strategies effectiveness were validated by teachers during discussions in the PLC meetings. The feedback strategies are still only hypothetical and have not all been empirically tested with teaching experiments. Furtak and colleagues are currently analysing classroom experiences to identify more feedback strategies that are proving to be successful instructional interventions. We see this research as an exemplar of learning progression with appropriate instructional interventions.

Wiser et al. (2009) and Smith et al. (2010) adopt a conceptual framework that stresses the importance of the intermediary levels of learning progressions. Using terminology such as anchor points, stepping stones, lever concepts and linchpins, they describe instruction assisted conceptual development that is based on learners' extant knowledge. Taking a narrower grade 3–5 perspective on Learning Progression for Matter (LPM) the goal is to help learners bridge from lower to upper anchors by supporting a series of broad reconceptualisations. The stepping stones are intermediate states in the bridging processes of the knowledge network. Lever concepts are core concepts present in the lower anchor (e.g., weight) and held to be important components for the target upper anchor concepts (e.g., mass, density). The lever concepts are salient in students' everyday thinking and intimately related/connected to other ideas. The linchpins are seen as organisers to express the structural aspects and/or relations among concepts in the upper anchor. Linchpins then are tools that make it possible to reconceptualise the lower anchor lever concepts. Therefore, these intermediary components in LPs targeting reconceptualisations operate as instruction assisted development.

For example, in the LP for matter (Smith et al., 2010; Wiser et al., 2009), knowing that weight is an inherent property of matter, and knowing that tiny visible things have weight or take up space, are important stepping stones in elementary school science for developing more sophisticated understandings about matter and density. Weight, size and material are seen as lever concepts for the development of the upper anchor concepts volume, density and matter. Measurement of lever concepts is an important component of the LPM to move students' from sensory experiences and a trust-your-senses-as-reliable-information epistemology to mathematical analysis as an epistemology. Quantification of weight and object size helps children to reconceptualise how weight changes or remains constant in tracing matter over time. The shift is from perception-centered thinking to model-mediated thinking and the development of quantitative reasoning and understanding of measurement (Smith et al., 2010). One of the linchpins in the LPM is the 'measure line', which is a linear quantified representation of measuring weight or volume. Wiser et al. (2009) used the measure line as an instructional intervention to help students record and represent/link the 'felt (hefted up) weight' with the 'scale (measured) weight' to produce a weight line. Thus, the stepping stones, lever concepts and linchpins were applied to the LPM as interventional instruction strategies, to support reconceptualisations that progress students from the lower anchor at third grade to the upper anchor at fifth grade.

Coherent pathways of learning and conceptual change

Considering the sequence or pathway of learning within a hypothetical LP, an assessment of coherence can be made. Examining the coherence and the step-like sequence of planned learning, instructional interventions and formative assessments it is also possible to interpret the model of conceptual change being employed. In this section, we examine how the LPs can be distinguish between one of two models for conceptual change – the misconception based '*fix it*' view of conceptual change or the intuition or productive misconception-based '*work with it*' view of conceptual change. How one conceives and establishes the lower and upper anchor and postulates instructional interventions and formative assessments for progression between the anchors sheds light on which conceptual change model dominates.

Looking across the LPs reviewed above, we found that many of the upper anchors targeted canonical understandings of a topic around a small set of concepts. Less frequent were upper anchors that focus on targeting learners' using networks of conceptual knowledge. In addition, the pathways from lower to upper anchors often reflected a misconception-based '*fix it*' view of conceptual change. Only a few progressions address developing more sophisticated ways of understanding and applying targeted knowledge concepts to contexts of use. The prevalent characteristic of the hypothetical pathways of LPs in science topics is to aim learners' conceptual change towards the scientific final form notion of correct understandings. In other words, the 'more sophisticated understanding' in LPs usually means, as indicated by Sikorski and Hammer (2010), being 'more completely aligned with the target canonical understanding of a topic' (p. 1035). The pathways of LPs for science practices show similar features in that they too frequently reflect a novice-expert sequence of practice achievements, one feature of validation LPs.

Alonzo and Steedle (2009) use as the lower anchor (level 1) students' naïve understanding that force is a push and pull regardless of type of motion. At the upper anchor (level 4) the net force applied to an object is understood to be proportional to its resulting acceleration, thus, in three progressive levels, addressing the scientifically accurate conceptions around force and motion. With relation to conceptual change, the force and motion LP develops learners' conceptual development as 'a linear acquisition of more elements of expert theory' (Sikorski and Hammer, 2010, p. 1036). This linear approach is explained, in part, as a consequence of using ordered multiple-choice (OMC) items in developing the LP.

Alonzo and Steedle (2009) validated the initial progression with assessments for diagnosing students' understandings. The delineation of the levels employing 'students' language' is a positive aspect to highlight for this LP. The OMC items consisted of canonical questions and options in order to assess students' understanding levels. The conceptual change focus is at Michaels et al.'s (2008) most simple of the three types of conceptual change, e.g., elaborating on pre-existing concepts. In the LP for force and motion, connection to other conceptual networks was not clearly established and therefore it was not clear how more sophisticated ways of knowing are or will be taking place. Because the progression uses a '*fix-it*' conceptual change focus that seeks to validate the initial sequences and levels of progression we refer LPs like this as '*Validation LPs*' as opposed to '*Evolutionary LPs*' that refine and define the developmental pathway(s) through identification of mid-levels or stepping stones that are then used to bolster meaning making and reasoning employing crafted instructional interventions.

The Songer et al. (2009) biodiversity LP, as discussed above, developed two learning pathways; one in terms of content progression and the other in terms of inquiry reasoning progression. The learning pathway does not contain evidence of students' diverse perspectives or intuitions that support learners' development from a lower level to a higher level of understandings. Rather, the LP delineates a continuous learning sequence along the route of a grade 4 to grade 6 progression:

> [T]here are observable features of living things. … Organisms have different features that allow them to survive. → Every organism needs energy to live and gets that energy from food. … Only a small fraction of energy at each level of a food chain is transferred to the next level. → Organisms are grouped based on the structures they have in common. … Patterns of shared characteristics reveal the evolutionary history of groups. → …. (Songer et al., 2009, revised in Gotwals, Songer, & Bullard, 2009)

This representation of learning sequences, even though it covers three years of learning and was based on empirical evaluation assessments, has much in common with a 'scenario' of didaktical structure (Lijnse, 1995; Lijnse & Klassen, 2004). That is, while it focuses on learning tasks and their relations, the emphasis is on the elaboration of pre-existing concepts, with few details about intermediary steps. Therefore, we see this LP, too, as an example of a Validation LP because the learning sequence adopts the misconception-based '*fix it*' view and has as the upper anchor the goal of canonical knowledge.

Schwarz et al. (2009) developed an LP for integrating the elements of modelling practice with meta-modelling knowledge. This LP describes two dimensions of modelling practices: using models as generative tools for predicting and explaining and monitoring learners' improved understandings for when and how to use models. Meta-modelling knowledge in this LP, however, is not targeting development of science concepts through modelling practice, but focuses only on the practice of scientific modelling itself. Schwarz et al. illustrated and document what kinds of performances and understandings in modelling were possible with fifth and sixth graders. For example, the four levels addressing understanding models as generative tools that can be used for predicting and explaining do not show a pathway of progressing students' practice skill. The modelling levels are organised according to the criteria of how students constructed and used models, of what students considered important to capture in models and of whether students viewed models as useful for advancing their own knowledge as well as helping communicate with others. The consideration of this set of criteria presents the LP levels less as a pathway for guiding learning but more so as features of a scoring rubric with a view to identifying the practice skills of novices and experts. The modelling LP contains elements of a validation LP because it does not report on (1) learners' developmental pathways beginning learners' intuitions, (2) coupling conceptual knowledge and modelling practices or (3) instruction assistant developments that advance students across construct levels.

One example of an evolutionary LP is the hypothetical LP pathway for carbon-cycling (Mohan et al., 2009) that advances four levels of achievement from the lower anchor to the upper anchor. The first level lower anchor of achievement recognises learners' macroscopic descriptions (sense datum or common sense features) of natural processes such as plants, animals, dead things and objects with natural tendencies of agents and enablers/antagonists. The authors refer to these descriptions as force-dynamic accounts in that natural objects are given agency. The next remaining three levels address causal sequences of events involving hidden mechanisms at level 2, school science narratives about processes at level 3 and qualitative model-based accounts of carbon-transforming processes in systems at the upper anchor level 4. The upper anchor, in addition, targets the scientific knowledge that is seen as necessary for citizens to know about carbon cycling.

Gunckel et al. (2009) adopt a similar learning pathway in the LP on water-cycling. The levels of achievements in this LP begin with students' force-dynamic accounts and end with qualitative model-based reasoning. In level 4, students are expected to use scientific model-based accounts in explaining and predicting water cycling. Explanations in this level connect learners' observations to patterns and to models. Predictions in this level use data about particular situations along with principles to determine the movements of water and substances in water. The upper anchors of both the carbon and water cycling LPs more or less coincide with scientifically correct ideas and model-based accounts. At the same time, the upper anchors are also concerned with societal expectations for becoming a literate citizen. Accordingly, the lower levels are not based on misconceptions or inaccurate accounts of carbon cycling and water cycling mechanisms. Instead, the lower anchor accounts that reflect students' personal perspectives and views are seen as learners' productive intuitions for understanding carbon cycling and water cycling. Therefore, the researchers' perspectives on conceptual change reflects the intuition-based '*work with it*' view.

Another significant dynamic found in Mohan et al. and Gunckel et al.'s studies is how they elicited the conjectural or hypothetical pathways. They started from identifying target knowledge and practices, then designed and conducted written assessments and clinical interviews. Next, they grouped and coded students' responses to identify progress variables, levels of achievement and indicators of each level. This kind of iterative design that is based on bottom-up development and grounded in evidence of student learning is a critical feature '*Evolutionary LPs*'.

Lehrer and Schauble's (under review) LP provides an example of instructional design and coordinated investigation of student learning. Beginning with student investigations of ecosystems, they coordinated and situated instruction-assisted learning about variability, change and data modelling. The design of instruction was guided by several generative principles: posing and revising questions, comparing questions and investigations, participating in the design of investigations for answer questions, inventing measurements and representations and frequent whole-class participation in research meetings. Working from the instruction-assisted learning design, Lehrer and Schauble develop the conjectured trajectories levels based on descriptions and expressions of students' learning performances. For example, the benchmarks of understanding variability consisted of 'difference described' (level 1), 'difference measured' (level 2), 'distribution making' (level 3), 'modelling the distribution' (level 4) and 'competition of models' (level 5).

What we find is that the instruction-assisted episodes are linked with benchmarks of understanding. Thus, level 1 understanding is obtained via posing and revising questions, comparing other investigations, and participating in the development of means to answer questions. Level 2 and 3 are achieved through the instruction on inventing measurements and representations. Level 4 is achieved through participation in the design of investigations. Finally, level 5 is achieved through students' participation in the research meetings.

In this LP, the upper anchor and learning goal are not based on attainment of scientifically correct or canonical knowledge, but a societal expectation about reasoning with and about data and information. We also see that the lower anchor and intermediary 'benchmark' levels of understanding are not targeting students' misconceptions. Instead, students move toward the higher levels using the knowledge and practices established at lower levels. Thus, Lehrer and Schauble (under review) adopt the intuition-based '*work with it*' view of conceptual change. Their LP also stresses an instruction-assisted learning design that serves to mediate learners' pathway of development of understanding. We can regard this LP as '*Evolutionary LP*'.

Other exemplars of '*Evolutionary LP*' include the Metz's (2011) LP research on microevolution and the grade 3–5 'LP on Matter' (Smith, Wiser, & Carraher, 2010), as discussed above in the Intermediary Steps section. Both of these LP research programmes reflect many of the features of '*Evolutionary LP*' but in particular seek to refine and further define the levels or intermediary steps that describe more fully the learning pathways. It is this refinement of learning pathways over iterative design-based research activities that fundamentally distinguishes validation from evolutionary. The LP is not a predetermined 'target' but rather an empirically established learning pathway. Another common feature of the four exemplary '*Evolutionary LPs*' is the use of clinical interviews as an assessment method for mapping learning performances and progress across the stepping stones, benchmarks or intermediary levels of the conjectured learning progressions.

Assessment and measurement frameworks

As mentioned earlier, panel participants' discussions and conclusions during the development of two reports (NRC, 2005; NAGB, 2008) foregrounded the appearance of learning progressions in *Taking science to school* (NRC, 2007). These discussions also led to suggestions about (1) pathways for the alignment of C-I-As and (2) the coherence between standardised achievement tests (assessment of learning) and classroom formative assessments (assessment for learning). Thus, the design and development of learning progressions required a strong assessment agenda for measuring students' learning performances within any given learning progression sequence. Not surprisingly, measures of learning progressions have been appealing to researchers with a focus on assessments and measurement. Learning progressions are viewed as a way to create assessment systems with the qualities of *coherence*, *comprehensiveness and continuity*. In this section, we review frameworks from some of the prominent reports and research programmes on the assessment and measurement of learning.

The report on the measurement of learning *Knowing what students know* (NRC, 2001) provides a thorough synthesis of research on both summative and formative evaluation. The report argues that an effective assessment systems should align three components to form the 'assessment triangle': *observation* (assessment activities to observe student learning processes), *cognition* (cognitive processes planned to be achieved through instruction) and *interpretation* (scoring and interpretation of students' work) (see Figure 2).

Working from the NRC assessment triangle, the BEAR (Berkeley Evaluation and Assessment Research) assessment system also referred to as the 'construct

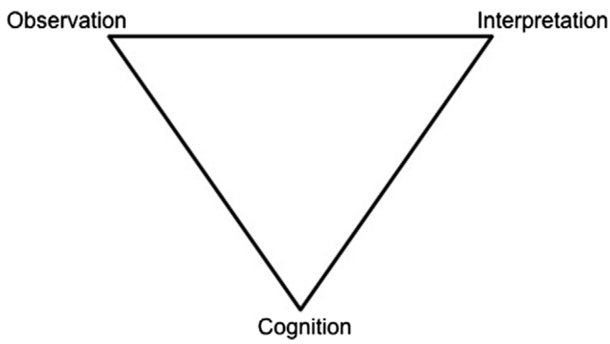

Figure 2. Assessment triangle.

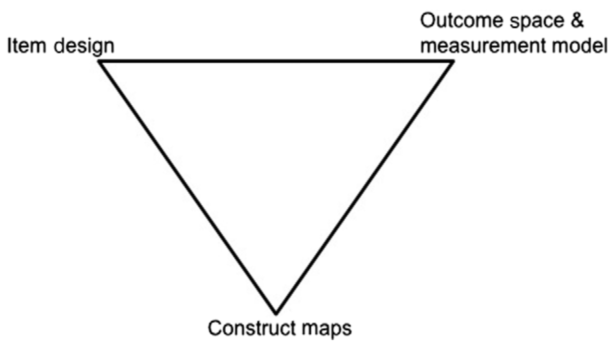

Figure 3. Building blocks of BEAR assessment system.

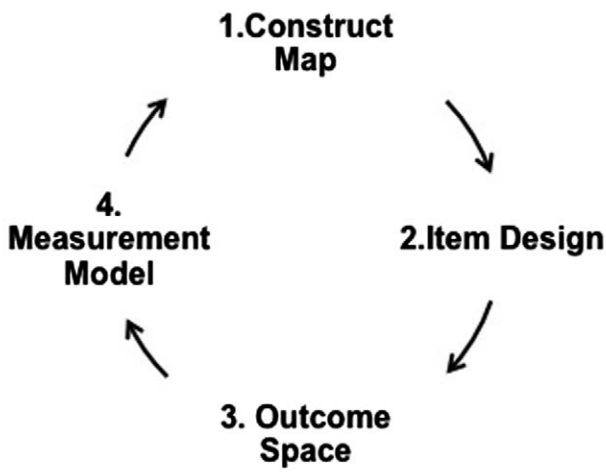

Figure 4. Iterative cycle of BEAR Assessment System.

modelling approach' (Kennedy, 2005; Wilson, 2005) introduces four building blocks – Construct Map, Item Design, Outcome Space, Measurement Model. The four building blocks are mapped to the assessment triangle (see Figure 3) and operationalised as the four principles of BEAR assessment system as seen in Table 2.

An important characteristic of the BEAR assessment system is that it is an iterative process (see Figure 4). The fourth building block, the measurement model, is not an end, instead, the interpretations from the measurement models should be used to inform the initial construct map and tailor it when necessary.

The first building block of the BEAR assessment system, *Construct Maps*, is created after determining and identifying progress variables (Masters, Adams, & Wilson, 1990; Wilson, 1990). Progress variables are derived from studies examining representative domains that a parts of core science topics. In any given representative domain, we can identify core concepts and observe students' understanding of these select concepts. The emerging pathway across different levels of understanding helps define the progress variable. As an example, Figure 5 shows different levels of student understanding in the topic 'Earth and Solar System'. There are three representative domains: the day/night cycle, the phases of the Moon and the seasons.

The second building block, *Item Design*, is an important step for two reasons. First, the items are the context for eliciting students' knowledge and understanding performances and, second, the items responses are where teachers and researchers observe students' learning performances and progress. Studies on learning progression have established different types of useful item structures to describe learning pathways. One is Alonzo and Steedle (2009) and Briggs and Alonzo's (2009) OMC item structure, a diagnostic tool for describing and ordering student understandings. Each OMC choice option reflects one understanding level of a progress variable. Two, is Mohan et al.'s (2009) use of open-ended written responses from which exemplar workbooks based on the written responses of randomly selected students are developed. The exemplar workbooks are then used to monitor and evaluate levels of students' responses. Three, is an alternative assessment item procedure used by Carraher, Smith, Wiser, Schliemann, and Cayton-Hodges (2009) that embeds open-ended tasks in a clinical interview design. Considering the fact that paper-pencil tests may overestimate children's naïve concepts and explanations, and the underlying principles, they advocate use of clinical interviews based on 10 tasks to elicit student understanding and identify productive intuitions. The clinical interview approach to tracing students' progression has been used in learning trajectories studies within the math education community, too. Confrey and colleagues (Con-

Level	Description
5 8th grade	Student is able to put the motions of the Earth and Moon into a complete description of motion in the Solar System which explains: • the day/night cycle • the phases of the Moon (including the illumination of the Moon by the Sun) • the seasons
4 5th grade	Student is able to coordinate apparent and actual motion of objects in the sky. Student knows that • the Earth is both orbiting the Sun and rotating on its axis • the Earth orbits the Sun once per year • the Earth rotates on its axis once per day, causing the day/night cycle and appearance that the Sun moves across the sky • the Moon orbits the Earth once every 28 days, producing the phases of the Moon COMMON ERROR: Seasons are caused by the changing distance between the Earth and the Sun. COMMON ERROR: The phases of the Moon are caused by a shadow of the planets, the Sun, or the Earth falling on the Moon.
3	Student knows that • the Earth orbits the Sun • the Moon orbits the Earth • the Earth rotates on its axis However, student has not put this knowledge together with an understanding of apparent motion to form explanations and may not recognize that the Earth is both rotating and orbiting simultaneously. COMMON ERROR: It gets dark at night because the Earth goes around the Sun once a day.
2	Student recognizes that: • the Sun appears to move across the sky every day • the observable shape of the Moon changes every 28 days Student may believe that the Sun moves around the Earth. COMMON ERROR: All motion in the sky is due to the Earth spinning on its axis. COMMON ERROR: The Sun travels around the Earth. COMMON ERROR: It gets dark at night because the Sun goes around the Earth once a day. COMMON ERROR: The Earth is the center of the universe.
1	Student does not recognize the systematic nature of appearance of objects in the sky. Students may not recognize that the earth is spherical. COMMON ERROR: It gets dark at night because something (e.g., clouds, the atmosphere, "darkness") covers the Sun. COMMON ERROR: The phases of the Moon are caused by clouds covering the Moon. COMMON ERROR: The Sun goes below the Earth at night.
0	No evidence or off-track

Figure 5. Construct map for student understanding of Earth in the Solar System (Wilson, 2009, p. 720).

frey, 2008; Confrey & Maloney, 2010; Confrey, Maloney, Nguyen, Mojica, & Myers, 2009), for instance, have been working on creating a learning trajectory for rational numbers by using the data from clinical interviews.

The third building block, *Outcome Space*, focuses on the role of the teacher as the interpreter and the user of the data within classrooms. Recently, a number of researchers have started to use the learning progression frame to create professional development communities to help teachers in using and interpreting students' responses to trace progression of their learning (e.g. Plummer & Slagle, 2009). The learning progression frame has also been suggested as a way to improve instruction and formative assessment (Heritage, 2008). Moreover, Furtak and colleagues (Furtak, 2009; Furtak et al., 2010) are working on professional development communities for teachers to interpret students' responses on items and using their interpretation in iterative assessment cycles. They revise the proposed learning progression with the teachers and develop new 'Educative LPs'.

The fourth building block, *Measurement Model*, employs Rasch modeling techniques to create Wright maps for the interpretation of the students' scores. Rasch modelling helps reveal if there is a consistency with students' proficiency level and the item difficulty index (Embretson & Reise, 2000; Hambleton & Jones, 1993; Wilson, 2005). Although the Rasch-based model was commonly used as a statistical approach for the validity and the reliability of the students' scores, it was considered by Briggs and Alonzo (2009) as being a 'poor match' to show all the attributes of the items. Therefore, Briggs and Alonzo used the Attributed Hierarchy Method (AHM) based on the assumption that the constructs also have attributes which are ordered and change across levels of understanding. They concluded that AHM provides a more detailed understanding of the construct for which the researcher is creating OMC Items.

Other statistical measures used to validate or map a learning progression include Steedle and Shavelson's (2009) latent class analysis to check the validity of diagnosing the levels for learning progression, i.e., to understand if students belong to certain latent classes (different levels of understanding) which will align with the levels created for the proposed learning progression. West et al. (2009) used Bayesian statistics to map a proposed learning progression onto the evidence-based centred assessment activities (items). Wilson (2009) suggested the 'Structured Construct Model' to see how the construct maps related to the learning progression they belong to.

Our review of learning progressions in science education shows the strong influence of the BEAR assessment system on LP research. The Construct Modelling Approach, with its principles and building blocks on designing assignments to validate an LP, is a very valuable contribution to the understanding of learning performances. However, there are significant differences when using these measurement models for the formative *assessment for learning* as opposed to the summative *assessment of learning*. For example, there seems to be a disagreement on the type of items which would comprehensively assess student understanding (e.g. OMC, open-written-response-tasks, performance assessments, clinical interviews etc).

An important point of using LP frameworks to formatively assess students' learning of science has been the emphasis on frequent recognition of the student progress not only at the end of each level (see Figure 5), but also intermediate states of understanding within each level (Carraher et al., 2009). However, the studies on assessments constructed through the daily interaction between teachers and students suggest that formal formative assessments may not be sufficient to observe the complex nature of scientific learning and knowledge construction during class-

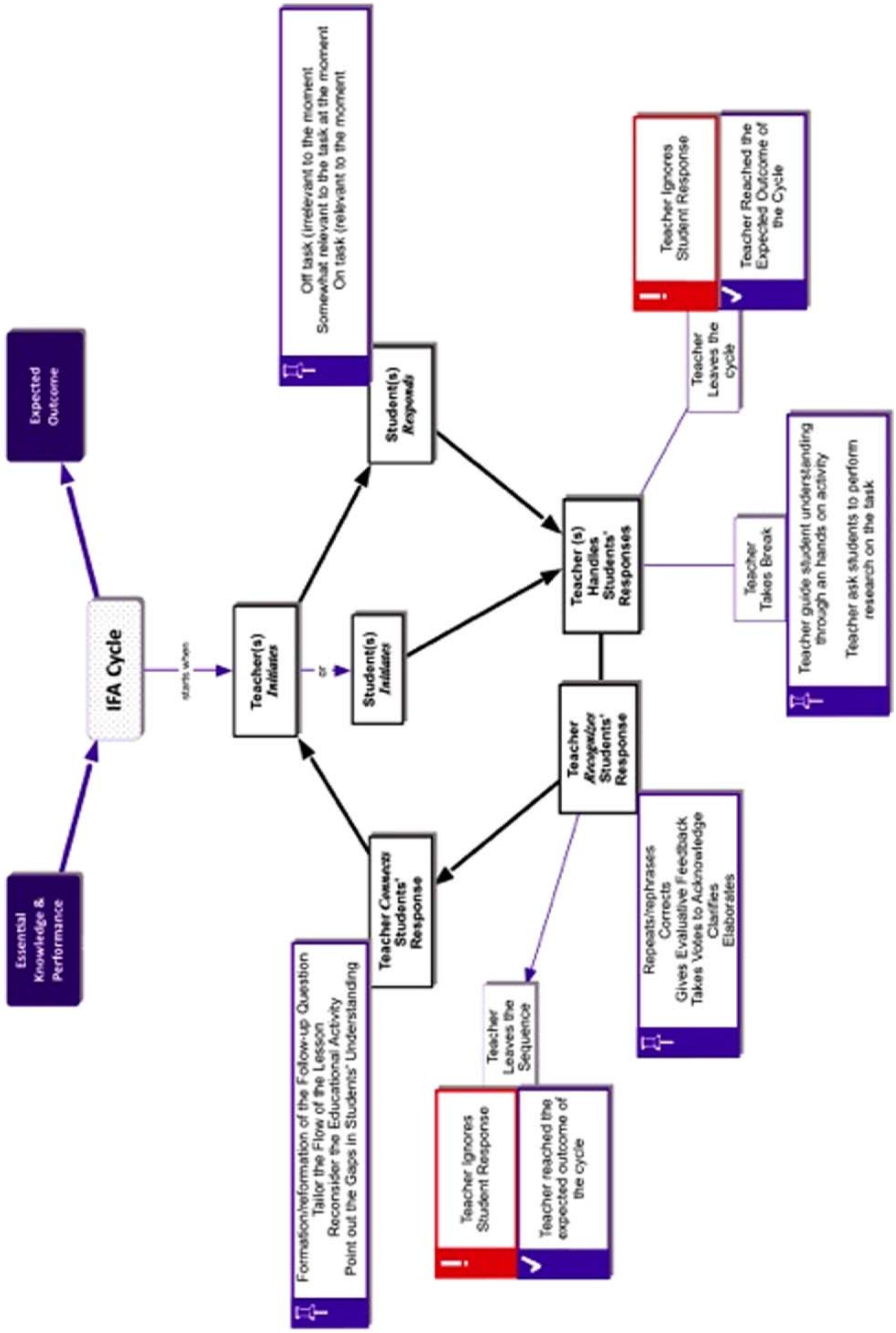

Figure 6. Informal formative assessment cycle.

room activities (Bell & Cowie, 2001; Ruiz-Primo & Furtak, 2007). In a recent study by Sezen (2011), four middle school science teachers developed a typical figure of teacher–student interaction that goes on almost in every minute of their science classroom, after they watched and reflected on their assessment practices recorded and prepared as video cases. Figure 6 shows an example of the complexity of this teacher–students interaction.

Thus, consideration of assessments constructed by the discourse moves between the teacher and students can help develop a more comprehensive understanding of students' progress and assist in identifying paths of conceptual and epistemic development of scientific ideas at the moment of learning. Teachers are the only ones who can guide this type of intense assessment practice and, therefore, we recommend studies on teacher education that would look for ways to help teachers to effectively assess students' progress in almost every minute of their instruction and diagnose students' needs and how LP framework works. The next section will examine how conceptual frameworks about learning and teaching influence the observation and measurement of learning and the design of LPs.

Theoretical/conceptual frameworks

There are two broad conversations taking place regarding LP and LT research and development. One is the research-based conversations and the other is the policy-based conversations. The research conversations are principally focused on the advancement of learning and the design of learning environments. The policy conversations are focused on the advancement of teaching and the design of professional learning communities that will advance the 'standards' reform movement. The research conversations focus is on sequence and developmental trajectories, while the policy conversations are centred on curriculum coherence issues.

LeMahieu and Reilly (2004) point out when discussing differences between assessment of learning and assessment for learning that, while the end game goals of student learning are certainly coupled, the data and information for one is quite different from the other. The two forms of assessment focus on different scales of time with inherently different intermediate goals – one focusing on the system, the other focusing on classroom/school communities of learners. We see some of this same tension between policy and research agendas in the design of learning progression frameworks. That is, to what extent is the framework (1) one that is attending to classroom learning and the advancement of understanding about learning pathways or (2) one that is attending to systemic reforms and the advancement of standards that are fewer, higher and coherent.

Adopting these two perspectives is helpful for teasing apart the various and sundry ways LP theoretical and conceptual frameworks are being considered and proposed. Some of major issues that surface are the strategies for C-I-A alignment, the role of assessment, the infusion of diagnostic assessments employing technological platforms, the development and coordination of beginning/ending points for LPs, the coordination and integration of multiple LPs, the grain size or scope of LPs and importantly teacher professional development.

The dominant definition for Learning Progressions is that which appears in Chapter 8 of *Taking science to school*: 'Learning progressions are 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 (e.g., six to eight years).' What is frequently left out of the definition are the next two sentences in the paragraph: 'They are crucially dependent on instructional practices if they are to occur. That is, traditional instruction does not enable most children to attain a good understanding of scientific frameworks and practices' (p. 219). Clearly, there is a great deal to consider in this definition and consequently there are many degrees of freedom for interpretation and this is precisely what one sees when looking at the LP research – many interpretations.

Learning progressions are descriptions

The content and reporting of LPs varies widely and even at this very early stage in the development of the field these wide ranging differences pose significant problems and challenges for the community of scholars. This diversity of thinking can be seen in the range of articles appearing in the *Journal of Research in Science Teaching* Special Issue on Learning Progressions. Some cautionary perspectives are found in the thoughtful commentary by Lehrer and Schauble (2009). One is that LP descriptions that report on implementing instructional tasks alone, without any consideration for teaching or curriculum interventions (e.g., the alignment issue), run the risk of not developing students' epistemic frameworks. Another comment is that ascertaining the role of assessments in advancing learning needs to take place at a large enough grain size/time scale to afford opportunities to look at the complexities of learning. Understanding the role of formative assessments in modular-based conceptually-driven science units, while valuable for building psychometric guidelines, has limited applications for the development of LP. For example, in a comment on Wilson (2009), Lehrer and Schauble (2009) suggest that class-level forms of evidence need to consider alongside evidence from individuals to engage in 'blending multiple levels of analysis to produce better resolution about learning' (p. 734). Their call for a 'measured sense of the complexities of this kind of work' (p. 734) in the communication of LP research is indeed valuable advice.

Looking across a wider array of LP publications that were part of the 2009 LeaPS conference, we see even more diversity in thinking (see Appendix). One major issue is that there is a lack of consensus about how LPs are to be described. One problem is settling on the topic that is capable of unfolding 'successively more sophisticated ways of thinking'. Another problem is generating the descriptions of these successions. The recommendation from *Taking science to school* is to begin LPs based on 'what is known about the concepts and reasoning of students entering school' (p. 219) the lower anchor. The intent here is for children entering kindergarten or the first year of school. While we can relax that notion a bit when children are entering higher grade levels we should not relax the requirement for LP designers to engage in a thorough consideration of the relevant existing research syntheses, e.g., from 'Foundations for Science Learning in Young Children' (Chapter 2, *Taking science to school*) and from 'Young people's understanding of science concepts: Implication of cross-age studies for curriculum planning' (Driver, Leach, Scott, & Wood-Robinson, 1994). Unfortunately, we see far too many recommendations of 'topics' for hypothetical learning progressions that are culled from, justified by, established disciplinary teaching sequences (e.g., Duncan et al., 2009), standards document reviews (Alonzo & Steedle, 2009; Furtak et al., 2010; Steedle & Shavelson, 2009) and curriculum frameworks (Harlen, 2010; Heritage, 2008; Roseman, Caldwell, Gogos, & Kuth, 2006; Salinas, 2009).

The generation of the descriptions of LPs is closely tied to the evaluation strategies for learning, i.e., what gets measured and what counts as evidence of learning. Talanquer (2009), in a thorough review of studies on students' reasoning about 'structure of matter', develops a description focusing on cognitive constraints. Lee and Liu (2010) evaluate and describe a learning progression of energy concepts through the lens of Linn's (Linn & Eylon, 2011) knowledge integration environment learning perspective. One of the more prominent tools used to describe learning progressions, as discussed above, is Wilson's (2005, 2009) BEAR Assessment Construct Modelling Approach, wherein levels of performance are developed and refined to capture/measure students progress on select variables. The measure of 'progress variables', though, is varied, involving order multiple choice items (Briggs and Alonzo, 2009; Steedle & Shavelson, 2009), open response items (Mohan et al., 2009) and performance items (Lehrer & Kim, 2009; Lehrer & Schauble, under review).

The generation of LP descriptions is also dependent on the measurement framework. Wilson (2009) sets out a construct map framework for defining levels of performance that has the potential for informing the design of LPs. Jin, Choi, and Anderson (2009), in a thoughtful and thorough presentation of a methodological framework for conducting LP research, demonstrate how Wilson's levels of performance approach takes time, going through iterative episodes of trialling the LP to develop, refine and ultimately establish levels of understanding or performance.

Another framework for the design of LPs is that by Shin, Stevens, Short, and Krajcik (2009), who advance the construct-centred design model for arriving at the design of LPs. In addition, Stevens, Shin, and Krajcik (2009) present a taxonomy framework that suggests processes for embedding teaching sequences into learning trajectories into learning progressions. Salinas (2009) offers two alternative frameworks for designing LPs. One is the escalated approach that constructs progressions in terms of levels, lower/upper anchors and having a strong empirical basis for monitoring progression. Many examples of escalated LPs are given above. The other framework is the landscape approach that examines the links and threads in levels that are used to establish a stronger analytical component for designing LPs. Salinas identifies *Project 2061's Atlas for Scientific Literacy* (AAAS 2001, 2006) as the centrepiece for this approach.

Yet another approach for measuring learners' progress within an LP is that of Rupp et al. (2009), who adopt evidence-centred design principles and Bayes' network analyses to monitor the development of conceptual and epistemological learning. There is potential here for the development of technology supported diagnostic assessments. Penuel et al. (under review) is an example of how such design principles and network analyses can be effectively used with classroom response systems to help define pedagogical patterns to guide subsequent instruction based on measures of students performances. Penuel et al. introduce pedagogical patterns as a construct for both understanding and designing teachers' patterns of formative assessment practices and thus provide an example of how thorough LP descriptions are dependent on instructional practices.

General findings from three framework reviews

Given the nascence of the field on LPs and LTs we are more inclined to raise new questions and identify challenges than to propose recommendations as we present our findings and impressions. The field is new but with strong links for foundational domains. The published research we reviewed was found to be conceptually and methodologically rigorous. Our concern as expressed in the following nine findings is that the LP research domain needs to begin serious conversations about criteria and guidelines for both the initial framing and the resultant reporting of LP studies. We propose some suggested criteria in the Conclusion section of the paper.

Finding 1

How might we structure ways for comparing LTs and LPs? From our review experiences, we propose the following set of questions to guide the reading of research reports:

(1) How and on what grounds have the researchers arrived at the selection of the core idea for the LP/LT?
(2) What, if any, connections are there between the knowledge domain topic and science practices?
(3) How have the researchers established the lower anchor and the accessibility of the starting point/place for the LP/LT?
(4) How have the researchers established the upper anchor and the abstractness of the finishing point/place for the LP/LT?
(5) How, if at all, do the targeted instructional pathways/sequences serve to mediate learning?
(6) How, if at all, do the researchers refine the LPs/LTs?
(7) What, if any, alignments exist between curriculum, instruction and assessment.

Finding 2

What are the guiding frameworks for the design of LPs/LTs? Our review suggests there are typically three starting places for the design of LPs. Thus, even when invoking the definition of learning progressions 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 (e.g., six to eight years)’, the adopted guiding frameworks will shape the LP design and validation processes:

(1) Represents the LP research reports grounded in *achievement measurement models* like the NAEP or TIMMS frameworks. Grain size is typically smaller focusing on a week(s)-long unit of study and targeting students’ novice/expert conceptions as the lower/upper anchors. Links with practices are typically absent as are expectations for using knowledge. Psychometric measurement guidelines are applied to assessment models.
(2) Represents the LP research reports grounded in *cognitive learning assessment models* like the ‘assessment triangle’ and the ‘four Strands of Proficiency’. Grain size is typically larger focusing on months/years and considering multiple units of study. Lower/Upper anchors situate learning performances in terms of knowledge use crossed with scientific practices. Assessment practice is guided by both cognitive and social cultural psychological models.

(3) Represents the LP research reports grounded in *core standards C-I-A alignment policy models* like *The Opportunity Equation*. Grain size is very large, targeting end of grade band domain-general achievement (e.g., grades 4, 8 or 12). Lower/Upper anchors are established by diagnostic system measures employing sophisticated analytical models. Links between knowledge use and practices are minimal. Practices are more inclined to be domain-general inquiry process skills targeting investigations.

Finding 3

What model of conceptual change do researchers use? Teaching experiments, teaching or learning sequences, learning trajectories and learning progressions can be interpreted as frameworks for conceptual change and one can tell which model of conceptual change is being applied:

(1) Theory change, Schema theory, Student has misconceptions;
(2) Model-building/refining, Knowledge-in-Pieces, Student has intuitions.

Finding 4

What kind of LP is being produced? Considering both the initial LP design criteria and the criteria used for building and testing an LP, we see two broad patterns among 'Hypothetical LPs' – Validation LPs and Evolutionary LPs. A general feature of Validation LPs is the focus on *domain-general topics or practices* that frequently leads to one or the other, but not both, being attended to in the LP.

Finding 5

What is the strategy for linking knowledge with practice? The move to learning performances in assessments and evaluations of learning seeks to situate using knowledge in the context of one or more scientific/reasoning practices. There are a fair number of HLTs and LPs where we find a separation of science knowledge from science practices. With time the focus needs to be on knowledge networks and associated practices and not merely one-to-one correspondences.

Finding 6

How does a Learning Trajectory differ from a Learning Progression? The label learning trajectory is used differently in science education and in mathematics education. Some proposed science education frameworks see LTs being smaller components of LPs and teaching sequences as components for LTs. Our reading of the maths education literature on LTs does suggest that the sequences are a smaller time span and grain size and, importantly, the LTs have worked out the instructional tasks that align with the LT. The infusion of instructional tasks that align with development is less clear in science education LPs. There are only a few LPs that take up researching instruction-assisted development and learning environment dynamics. How to use LPs in actual teaching and planning is understudied. Shorter teaching experiments and action research with collaborating teachers are recommended.

Finding 7

What are the appropriate details for LPs? There is a wide range of time spans for LPs, some across grade spans, and some across lower/upper anchors with intermediate levels, within grades and across construct map levels. We find several procedures being used to establish lower and upper anchors for LPs to meet, respectively, the accessibility and abstractness criterion. Are LPs to be:

- Accounts of learning under defined instruction?
- Lists of statements outlining the process of learning?
- Longer-term teaching and learning sequences?

Finding 8

What are the acceptable measurement and assessment methods to be used when researching LPs? We find a wide range of methods and terminology for measuring and monitoring learning, e.g., facets, progress variables, stepping stones, benchmarks, reasoning construct map levels, practices construct map levels, knowledge construct map levels, cross sectional data, novice/expert, apprentice/expert and teaching versus learning sequences. Once again, building from Driver, Leach, Scott, and Wood-Robinson (1994), there is a need for more longitudinal studies to understand students' learning pathways.

Finding 9

How do science and maths education research differ on LTs and LPs? We have not done as in-depth a review of maths education as with science education. But we have benefited from the maths education reviews of literature on LTs. What we find as differences between the two communities are the following:

- In science more so than in mathematics, the hypothetical learning trajectories/progressions are derived from 'Validation' model approaches.
- Clinical interview to establish levels of understanding with learners is more prevalent among maths education researchers.
- Many science education researchers rely on dated models of conceptual change research.
- Many researchers in science and maths ignore the epistemic features of knowledge domains.

Conclusion

Our review is guided by two research questions: one that focuses on the design criteria used for posing a LP and one addressing the criteria for validating and describing the LP. Our review reveals that there are many competing perspectives among researchers regarding both questions. Perhaps this is as it should be in a new domain of research. But, like any community of learners or inquirers, in order to advance the agenda there needs to be some consensus on the guiding conceptions concerning questions, frameworks, methods and outcomes. For example, what perspectives about the core ideas, cross-cutting concepts and science practices are to be adopted? Which are the methods for validating or otherwise establishing learning progressions?

In 1994 *Studies in Science Education* published a two-decades research review of learners' cross-age, domain-specific understandings and reasoning in science education. This is a good source of well-studied domains in science learning. The article by Driver et al. (1994) pronounced that there was sufficient evidence from young people's conceptual understanding of science to coordinate curriculum around 'conceptual trajectories'. Curiously, some of today's leading LP researchers (e.g. Carol Smith, Marianna Wiser and Charles 'Andy' Anderson) were also influential contributors to these cross-age research studies. Driver et al. (1994) write:

> [I]t is suggested that cross-age research data on students' domain-specific reasoning in science, undertaken over the last two decades, provides an important information base on which decisions about such developmentally organised curricula can be made. (p. 76)

> [L]earning within a particular domain can be characterised in terms of progress through a sequence of conceptualizations which portray significant steps in the way knowledge within the given domain is represented. This sequence of conceptualizations we call a conceptual trajectory. While the notion of a conceptual trajectory does not describe a pathway in the reasoning of any individual student, it does, however, indicate in broad terms the nature of the changes in reasoning which may be demonstrated by students in particular curricular settings. (pp. 85–86)

In the conclusion of the paper Driver et al. caution that recommendations for curriculum planning and sequencing did not imply 'pathways in the development thinking of individual students. They are not longitudinal studies and no claims can therefore be made about the pathways in thinking individual students follow' (p. 93). They go on to say, '[a] different theoretical basis is needed to inform teaching from that required to guide curriculum planning and sequencing' (p. 94).

Since this 1994 seminal publication we can see in our review that different theoretical frameworks have since emerged and longitudinal studies of student learning have and are being conducted that have led to *alignment guidelines* for teaching and curriculum planning and sequencing and to *design experiment guidelines* for coordinating and conducting research on learning pathways, trajectories and progressions. We consider each set of guidelines.

Alignment guidelines

The NAGB redesign of the 2009 NAEP Science Framework began with a reconsideration of three areas wherein significant advancements had occurred since the 1996 NAEP Science Framework. The three areas are: advances (1) in cognitive science research, (2) in measurement and assessment theory and practice research and development and (3) in new models of scientific learning situated in using knowledge and doing science practices. The consideration of these three research-based advancements has led to policy positions calling for sequential and coherent learning across grade bands.

With regard to advances in cognitive science, the Driver et al. (1994) review links up well with the NRC *How people learn* and *Taking science to school* research synthesis reviews to demonstrate the progress that has been made. For example, in the final paragraph of Driver et al. (1994) they reinforce that there are three underlying strands that influence students conceptual reasoning; 'changes in students' ontologies within specific domains, changes in reasoning strategies and changes in epistemological commitments' (p. 97). Our review shows that learning progression researchers consider these elements of science reasoning as necessary elements in adaptive instruction and instructed-assisted learning strategies.

Advancements in measurement and assessment of/for learning aided by concomitant advancements in technologies and measurement theory have pushed educators, researchers and policy makers to no longer think of curriculum being independent of instruction or assessment. The advancements in measurement have also made it possible to examine learning performances where reasoning and science practices are situated in conceptual contexts; e.g., using knowledge. Our review has shown the importance feedback and mediation have on learning and the advancement of learning. Our review has also shown the range of frameworks being used to monitor learning, learning performances and the policy and classroom agendas that can shape these frameworks as well as the design of learning progressions. As Driver et al. (1994) recognised then, longitudinal studies of students' learning are critically important to advance our understandings of assisting learning.

The shift from science as inquiry processes and skills to science as a set of practices is very significant for the rethinking the nature of longitudinal studies and the design of curriculum, instruction and assessment models. Here, too, Driver et al.'s three underlying assumptions influencing students' conceptual reasoning come to bear. The research community has come to understand how important the discourse and epistemic reasoning practices of science are to learning science. The adoption of teaching sequences, learning trajectories and learning progressions afford opportunities to weave together concept and practices learning goals in a coherent manner.

Design experiment guidelines

Learning progressions are essentially hypothetical pathways for students' science learning. With regard to being hypothetical, the pathway needs to be plausible, not just an assumption made by researchers. Learning progressions as the plausible hypotheses have conjectural features, which are related to how student understanding can be developed through sustained and appropriate instructional practices in current or future research (NRC, 2007).

The process of developing LPs can be considered from the view of design experiments (Brown, 1992; Cobb et al., 2003). The process in developing classroom design experiments is to specify the assumption of starting points for learning pathway, elements of a trajectory and prospective endpoints. The assumed starting points are mainly based on students' current ability to learn a concept or conduct a practice. Cobb et al. (2003) pointed out the difference of assuming the starting points between well-researched topics and less-researched topics. In relatively well-researched topics, the starting points of design experiment can be assumed by drawing on the literature about students' initial interpretations and understandings of the topic. Therefore, design experiments may include reasonable levels of confidence as a conjectural pathway drawn from prior studies that dealt with the same topic (e.g. Smith et al., 2006). Thus, researchers may either evaluate or validate the conjectures with appropriate assessment tools. This kind of design experiment is related to the validation LPs, even though some exceptions exist.

Table 3. Validation LPs and evolutionary LPs.

Validation LPs	Evolutionary LPs
(1) LP based on validating a standards-based progression: instruction as intervention	(1) LP based on sequencing of teaching experiments across multi-grades: instruction as refining progression
(2) Theory-driven top/down approach	(2) Evidence-driven bottom/up approach
(3) Upper anchors as college readiness	(3) Upper anchors as targeted literacy
(4) Uses assessments to confirm learning models	(4) Uses assessments to explore learning models
(5) Progress variables steps and targets are fixed	(5) Progress variable steps and targets are flexible
(6) Adopts a misconception-based 'Fix It' view of conceptual change instruction	(6) Adopts an intuition-based 'Work with It' view of conceptual change instruction
(7) Theory building as conceptual change	(7) Model building as conceptual change
(8) Domain general orientation to topic selection	(8) Domain specific orientation to topic selection

Alternatively, in less-researched topics, researchers of design experiments typically need to conduct pilot work to establish a conjectural pathway including the starting points of understandings and the consequences of students' prior instructional experiences. The advantage of explicating this conjectural pathway at the outset of the design experiment is to identify and account for successive patterns in student thinking (Cobb et al., 2003). The teaching sequences in math and science employing design tools reported by Ruthven et al. (2009) represent another way to establish conjectural pathways. So, too, is the MER research model (Duit et al., 2005) a sound procedure to advance a conjectural pathway. With regard to design experiments and teaching sequences, the significant challenge is to formulate a pathway that materialises testable conjectures about both student reasoning and appropriate instructional interventions. From our review, these kinds of design experiments are related to the Evolutionary LPs. Presented in Table 3 are the characteristics and features we contend distinguish Evolutionary LPs from Validation LPs.

The Driver et al.'s (1994) petition for 'a different theoretical basis … to inform teaching'(p. 94) is here. One aspect of the theoretical basis is the alignment of curriculum-instruction-assessment frameworks that prescribe coherent learning pathways guided by adaptive instruction and instruction assisted practices. Another aspect is the conceptualisation of learning performances and the accompanying measurements and assessments that conjoin using knowledge with prescribed cognitive, epistemic and social practices. Then, there is theory of mind and cognitive research that establishes the importance of core or foundational knowledge for the advancement of knowing and reasoning.

Thus, the emerging theory of LPs is essentially grounded in foundational knowledge and pathways. An analysis of LP research studies must address two questions. How well developed is the identification of the foundational knowledge that facilitates and advances pathways of reasoning and understanding? How thorough is the description of the teacher mediated learning pathways? We should be asking questions about the criteria and features of LPs that then make it possible to judge a LP as complete, near complete, incomplete and flawed LP.

In this review we have drawn a distinction between ‘Validation LPs’ and ‘Evolutionary LPs’. Our position is that only the Evolutionary forms are conducting LP research that is attending to the development of foundational knowledge and to thorough descriptions of LP instruction assisted pathways. The Validation forms, while valuable (e.g. developing and testing assessment models; testing discourse strategies or instructional interventions), are only components or constituents of science learning and thus better labelled as teaching sequences, not learning progressions.

What, then, would be some of the criteria to demonstrate progress toward full complete depictions of foundational knowledge and instructional pathways? The LP design would need to be longitudinal following learners across several grade levels. This eliminates as LP research teaching sequence investigations that examine learning within single units that entail short durations of instruction (e.g. lesson sequences, unit modules). The foundational knowledge criteria also eliminate teaching sequences that focus on the conceptual demands of core idea domains but eschew the science practices. Typically such hypothetical learning trajectories begin from reviews of strand maps, curriculum guides or standards frameworks.

Canonical knowledge is not the same as learners’ foundational knowledge. What drops out in many teaching-sequence formatted trajectories is the consideration of the inherently diverse learners’ perspectives where the foundational knowledge resides. If the research examines conceptual development independent of knowledge use or a coupling with science practice(s), then the research should not be considered LP research. Considerations of knowledge use and coupling with science practices are criteria for LP research. What get reinforced in many Validation LPs are the novice-expert conceptual frameworks as lower-upper anchors. What get eliminated are (1) understandings of learners’ intuitions, learning pathways and instruction-assisted development that move learning along and (2) depictions of upper anchors and learning goals on the basis of societal expectations, not scientific expectations, for benchmark and performance expectations at targeted grades levels, e.g., 4, 8 and 12. Thus, plausible criteria for a complete or near complete LP would be construct map-level descriptions that articulate plausible incremental learning pathways that are linked to instructional-assisted practices/interventions. Development of these important incremental or intermediary levels is dependent on another LP criteria, the iterative implementation of assessment tasks and instruction-assisted development LP sequences, e.g., design experiments. Empirically validating a learning progression is not obtaining task-related progress variable evidence to affirm achievement of construct map levels. Rather, it is pathway development progress variable evidence that affirms the achievement but also and importantly affirms the links between instruction and assessment.

Learning progressions research programs that we see effectively addressing these criteria are:

- Smith, Wiser, and Carraher (2010), Wiser, Smith, Doubler, and Asbell-Clarke (2009)
- Lehrer and Schauble (under review)
- Lehrer, Schauble, and Lucas (2008)
- Metz (2004, 2008)
- Gunckel, Covitt, and Anderson (2009), Mohan and Anderson (2009), Mohan, Chen, and Anderson (2009)

The issue we are raising here concerns the quality of the reports, i.e., the depth and breadth of the claims being made that provide a thorough description of the pathway(s) for learning. Such thorough descriptions and only such descriptions will make it possible for theoretical work to get done and reported on the development of evidence-based learning and instruction-assisted development pathways. It is our hope that the Learning Sciences and Science Education research journal editors and reviewers will take up this call for the development of LP criteria.

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The authors would like to dedicate this article to the memory of Phil Scott, who as *Studies in Science Education* editor recruited the manuscript and guided the development of the article. As the article progressed and as our conversations with him deepened it became very clear to us that Phil himself was a pioneering contributor to the legacy of what we today call "learning progression" research. We were deeply saddened to learn just five days after last talking with him about the final version of the paper that we had lost such a scholar and a friend.

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Appendix

Special Issue of *Mathematical Thinking and Learning* (2004) ‘Learning trajectories’

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