Paper presented at the Learning Progressions in Science (LeaPS) Conference, June 2009, Iowa City, IA

TOWARDS A MODEL FOR THE DEVELOPMENT OF AN EMPIRICALLY TESTED LEARNING PROGRESSION

The learning progression (LP) is a construct that has been recently adopted by the science education community as a possible way to create a coherent science curriculum. As of yet, the field has not reached a consensus on the definition of a learning progression, its structure or its relationship to other similar constructs. The definition of a LP that guides our work is that a LP must ultimately include not only an ordering of concepts that build toward a more sophisticated understanding of an important idea, but also provide learning strategies to support student development along the progression, and assessments to place students on the scale defined by the LP. Due to the model of learning we use to guide the development of the LP, it is also important to specify the connections students must make between ideas within and across domains to develop conceptual understanding. We have developed a taxonomy of progressions that facilitates communication about the various points in the development and empirical testing process. In this paper, we discuss our strategies for developing and empirically testing a theoretical LP and the challenges that we have and are still facing in this process.

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Recently, there has been an effort to change the focus of the science curriculum from shallow coverage of a broad range of concepts to the development of an integrated understanding of a few core ideas (Duschl, Schweingruber, & Shouse, 2007). In order to further this effort, the science education community has begun to employ the idea of a learning progression as a means of organizing and aligning the science content, instruction and assessment strategies to provide students with the opportunity to develop conceptual understanding of a relatively small set of big ideas of science. However, the science education community has yet to reach a consensus on the definition of learning progressions or a methodology for developing them.

Our research group has and continues to focus on developing, refining and empirically testing a hypothetical learning progression (HLP; see Table 1), which is developed from the logic of the discipline as well as from what is known about student learning of the big idea. The HLP that we are developing and testing describes how grade 6-14 students may develop conceptual understanding of concepts related to the structure, properties and behavior of matter–the nature of matter. In this paper, we describe our working definition of a learning progression, its structure and its relationship to other, similar constructs. In addition, we discuss the strategies we are using to develop the HLP and the challenges that we have and must still address in order to successfully develop, empirically test, and refine it.

Table 1
Taxonomy of terms related to the process of developing, refining and empirically testing learning progressions.

Construct	Working Definition
Learning progression (LP)	1. Organizes the content of the discipline and describes a potential route towards more sophisticated knowledge. 2. Explicitly specifies the connections between ideas students need to build an integrated knowledge framework. 3. Links the content to appropriate phenomena or models that students should be able to explain 4. Provides potential instructional strategies and learning tasks to help students move from one level to the next
Hypothetical learning progression (HLP)	A learning progression developed based on the logic of the discipline ***and*** current learning research to describe a route for students to move from more naïve conceptions to a level of understanding closer to that of an expert.
Empirical progression (EP)	Developed from examining how students' ideas develop by the analysis of various assessment tasks. Used in the refinement and empirical testing of the HLP and HLT
Hypothetical learning trajectory (HLT)[a]	1. Addresses a specific learning goal 2. Specifies the means (e.g., contextualization, learning tasks, instruction) that will help students meet the learning goal 3. Includes potential student ideas and difficulties – Subset of a HLP – One or more HLT will describe how students can move from one point in the HLP to another – Provides *specific* instructional strategies and learning tasks for moving students from one point in the learning progression to another
Empirically-tested learning trajectory	A hypothetical learning trajectory that has been implemented in the classroom and evaluated through the results of learning and assessment tasks.
Empirically-tested learning progression	A sequence of empirically tested learning trajectories that were developed based on the HLP and together describe specifically how to move students toward conceptual understanding of the big idea in science over an extended period of time

[a] (Baroody, Cibulskis, Lai, & Li, 2004; Clement & Sarama, 2004; Simon, 1995)

What is a Learning Progression?

A learning progression (LP) describes how students may develop more expert understanding of a big idea of science over a broad, defined period of time (Smith, Wiser, Anderson, & Krajcik, 2006). The move towards greater expertise may be purely sequential in nature such that understanding of topic A is required before students can develop understanding of topic B. Alternatively, a LP may describe how students develop a more complex model, where knowledge of topic A becomes more sophisticated by incorporating new ideas and making new connections among these and other ideas from related topics (e.g., developing a more scientifically accurate model).

A LP addresses a defined range of content within a discipline (Duschl, et al., 2007). The low anchor provides a description of the knowledge and reasoning that should be held by students prior to beginning to develop understanding of concepts contained in the LP. The knowledge and skills students are expected to develop by the end of the progression, the upper anchor, are drawn from what educational research has defined to be developmentally feasible, and are also related to goals of science literacy and societal needs and expectations (Mohan, Chen, & Anderson, in press). Each step, or level, along the progression should be logical and comprehensible. Learning research should guide the description of the levels and the appropriate points to introduce the concepts to students through appropriate instructional strategies and learning tasks. We take the position that more appropriate instructional strategies and learning tasks will help overcome some of the reported difficulties related to students developing understanding of challenging content. (Margel, Eylon, & Scherz, 2008).

The levels of a LP do not necessarily describe a unidirectional route to more sophisticated understanding. For example, at times it may be necessary to step back to a simpler model to help students develop understanding of more complex ideas. However, a LP should only describe productive steps towards achieving the upper anchor. While we expect that students may use less sophisticated or non-normative models as they struggle to understand new ideas, we do not include them in the LP unless there is empirical evidence that students *need* to use them in order to build conceptual understanding of the desired content (i.e., would be a learning goal).

Many factors determine the path that students may follow as they build understanding of a big idea, including the context, instruction, curriculum materials, and students' prior knowledge and experiences. Therefore, any LP must necessarily be considered hypothetical for even if it is empirically validated for thousands of students, a LP can never be described as the only way to move *all* students along the progression (Baroody, et al., 2004). Therefore, the final product can only be an empirically tested learning progression under a certain set(s) of conditions.

Characteristics of a Learning Progression

A LP must include not only an ordered description of how the important ideas can develop over time, but also: 1) possible instructional strategies and learning experiences that might help students move along the progression, 2) the difficulties students might have developing conceptual understanding based on current learning research, and 3) assessments that will define students' position on the progression. The potential instructional strategies might include what order ideas should be introduced to students to help them make sense of the content, as well as what type of experiences (e.g., phenomena, contextualization and learning tasks) might help students develop understanding of important concepts. The type of empirical data required for the point in the development and refinement process determines the type of assessments used to locate students on the LP. Therefore, a LP represents a potential path that is coherent and empirically verifiable by which students may develop knowledge and skills, and may be met by multiple instructional pathways.

The mathematics education community employs learning trajectories (LTs) to organize and design instruction of key ideas. They include the "consideration of the learning goal, the learning activities, and the thinking and learning in which students might engage" (Simon, 1995, p. 133) as they develop understanding of the desired content. LTs have their foundation in classroom practice, and thus include a *specific* description of how to support students in developing understanding of the learning goals (Clements & Sarama, 2004. Therefore LTs describe a smaller, more focused scope than LPs. Both constructs are informed by learning and cognitive research to identify hypothetical learning paths for an important idea within the discipline. They are both necessarily hypothetical due to their constructivist approach and must be revised iteratively based on learning research related to the success of the instructional strategies to help students move from one level to the next. Thus, while the constructs are similar, the scope of the content addressed by learning trajectories and LPs is different.

We consider hypothetical learning trajectories (HLTs) to be subsets of HLPs that describe specifically how to help students meet some or all of the learning goals that support students in moving from one HLP level to the next (See Figure 1). One or more HLTs (in sequence or pathway) may describe progress between the levels of the HLP. Learning experiments must be performed to test the viability of the potential strategies conjectured by the HLT (Cobb & Bowers, 1999). Thus, as the refinement process continues, the learning strategies become more specific and the relevant grain size becomes smaller and more focused in order to better characterize how student learning progresses.

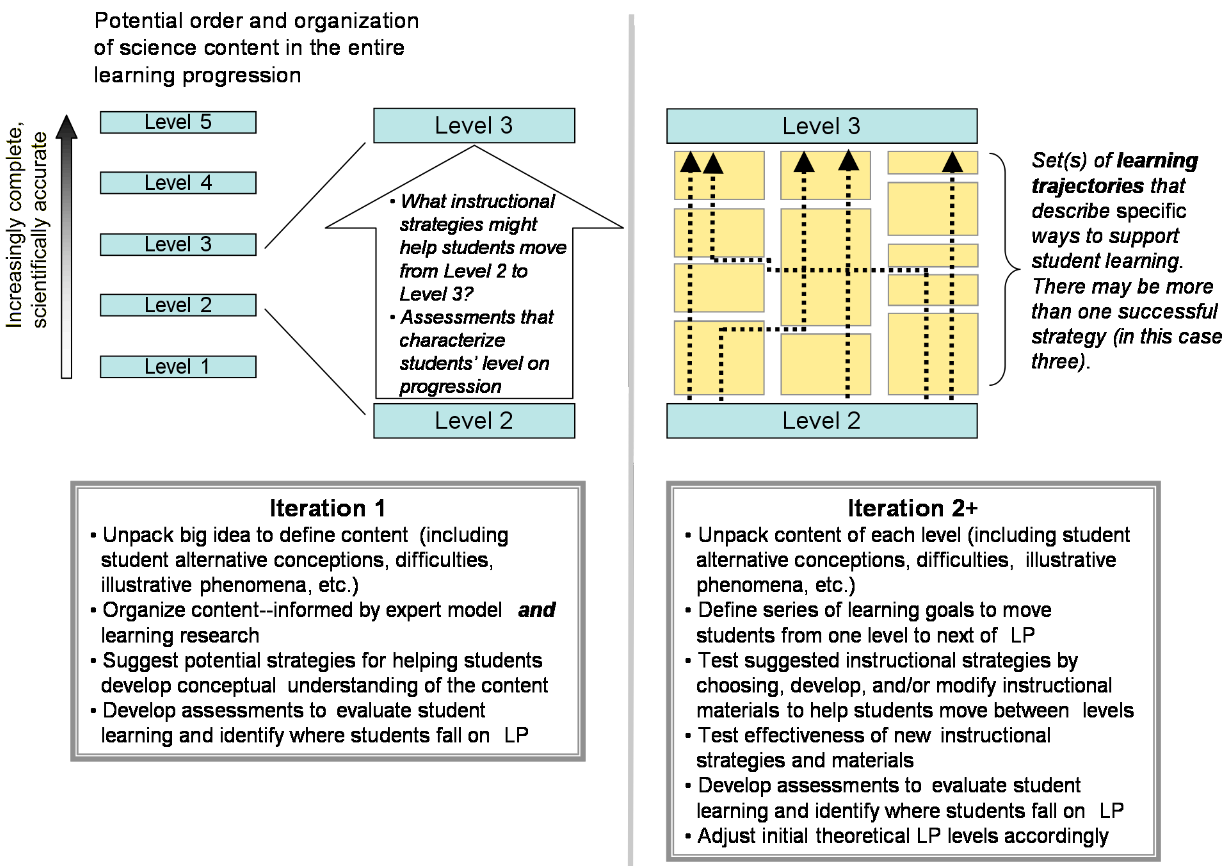

Figure 1. Model of a hypothetical learning progression and the process of development, refinement and empirical testing.

Developing Conceptual Understanding

Students who have developed conceptual understanding hold connected understanding of related ideas and apply their knowledge to new situations (Bransford, Brown & Cocking, 2000). As students work to make sense of new concepts, they connect new information to existing knowledge to build an organized, integrated, structural framework (Ausabel, 1968; Linn, Eylon, & Davis, 2004; Taber, 2001). However, the knowledge structures of many students' may not be organized frameworks, but compartmentalized ideas that are not put together in a systematic manner (diSessa, 1988). Such fragmented structures can make it difficult for students to apply their knowledge to explain new problems (Sirhan, 2007; Taber, 2004). Thus, although students may possess relevant pieces of knowledge, they may not be able to access and use their knowledge when facing new problems or learning new ideas. In contrast, experts have well-organized and integrated knowledge that is easily accessible, (Bransford, Brown, & Cocking, 1999; Chi, Feltovich, & Glaser, 1981).

We characterize the development of conceptual understanding multi-dimensionally, and visualize LPs as a progression of *sets* of ideas instead of isolated strands of knowledge (See Figure 2). In this way, LPs can accommodate strategic sequencing that promotes both branching out and forming connections among ideas within and across knowledge domains. (Stevens, Shin, Delgado, Krajcik & Pellegrino, 2007). This model requires the LP to explicitly specify the connections among ideas that students need to make between relevant ideas (see Figure 2). In contrast, an accretion model of learning would describe a linear, sequential path to greater expertise. While students may progress in this way along an individual strand of a multi-dimensional LP, the result would be limited to memorized knowledge. As shown in Figure 2, to move to a new level of understanding of ideas in one strand requires students to also develop understanding of ideas in other strands, which provides an opportunity for them to connect related ideas to develop integrated knowledge and achieve meaningful learning.

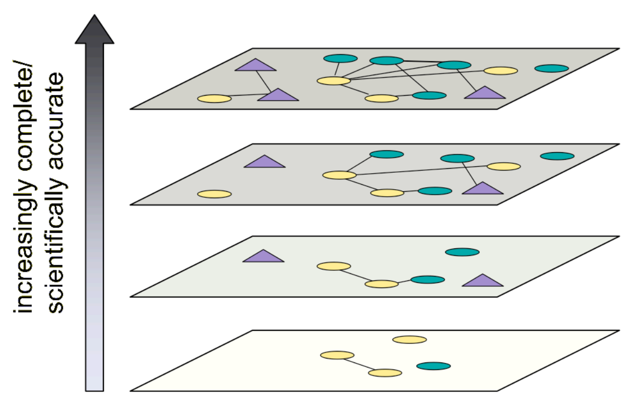

Figure 2. Representation of a multi-dimensional learning progression. The different shapes and colors represent ideas from different strands within the learning progression. The black lines represent connections among ideas in different constructs to build integrated knowledge.

The Process of Building a Hypothetical Learning Progression

Building a HLP is an iterative process that is consistent with design-based research (Collins, Joseph, & Bielaczyc, 2004). The first iteration of the HLP is based upon learning research in combination with expert organization of the discipline to suggest a preliminary order of concepts that students may follow to develop conceptual understanding. We followed the construct-centered design (CCD) process (Pellegrino et al., 2008), which combines aspects of learning-goal-driven design (Krajcik, McNeill, & Reiser, 2007) and evidence-centered assessment design (Mislevy, et al., 2003; Mislevy & Riconsente, 2005) to ensure the alignment of the science content in the HLP with the associated instructional strategies and assessments. This process involved unpacking the big idea to explicitly specify all of the content that is necessary to develop understanding of it over grades 6-14. We then generated: (a) *claims* that describe the knowledge, skills, or other attributes to be assessed and learned; (b) *evidence* that describe the behaviors or performances that are needed to support the claim; and (c) *tasks or situations* that will help students learn or provide a response that generates that evidence.

A principled and systematic approach to developing a HLP

The first step of the CCD process is defining the construct(s). A construct includes the ideas or concepts that we wish to learn about and measure (Wilson, 2005). As a proof of concept we first focused on two constructs–the atomic model (structure) and the electrical forces that govern interactions at the nano-, molecular and atomic scales. Defining the constructs involves specifying the range of content addressed by the LP and detailing what it means to understand the big ideas at levels appropriate for grade 6-14 students.

The upper and lower anchors define the range of the HLP. The upper anchor of the learning progression for grades K-8 for the atomic molecular theory by Smith and colleagues (2006) and other learning research informed the definition of the lower anchor of our progression. We defined the upper anchor based upon national standards documents (AAAS, 1993; NRC, 1996), ideas defined to be a foundation for nanoscale science learning (Stevens, Sutherland, & Krajcik, in press), and current learning research. We unpacked the principles and theories within the constructs to explicitly define the concepts crucial for developing an understanding of the constructs. As a step towards defining *how* students should know the content, the prior knowledge that is required both within and from other constructs is also specified. In addition, unpacking includes identifying potential student difficulties and alternative ideas related to the unpacked content.

The next step of the CCD process incorporates aspects of evidence-centered design (Mislevy, et al., 2003; Mislevy & Riconscente, 2005), which involves developing a set of claims and the evidence that support them for the relevant content for each of the constructs. The claims describe what students should be able to do with the knowledge at a particular level in the progression. The evidence describes the ideas and the connections within and between constructs that students need to demonstrate in their work in order to show they hold a particular level of understanding. The national standards documents (AAAS, 1993; NRC, 1996) and learning research in science education inform the development of the claims and evidence.

The evidence that students should provide in their explanations of a range of phenomena guided the definition of the levels of the HLP. Table 2 provides an example of how different levels of the progression are assigned to different evidence for the same claim. In this case, the claim involves the students' ability to convey a model of the atom in order to provide a level-appropriate explanation of a phenomenon. Figure 3 illustrates a portion of the HLP for the nature of matter relating the strands for atomic structure, electrical forces that govern interactions between very small objects and elements and the Periodic Tables. In order to develop integrated understanding, students must learn about all of the ideas within a level and be able to selectively apply the appropriate ideas to explain a range of phenomena. Students at Levels I-IV may be able to explain many of the same phenomena, but the complexity and scientific accuracy of the explanations will change as they move along the HLP.

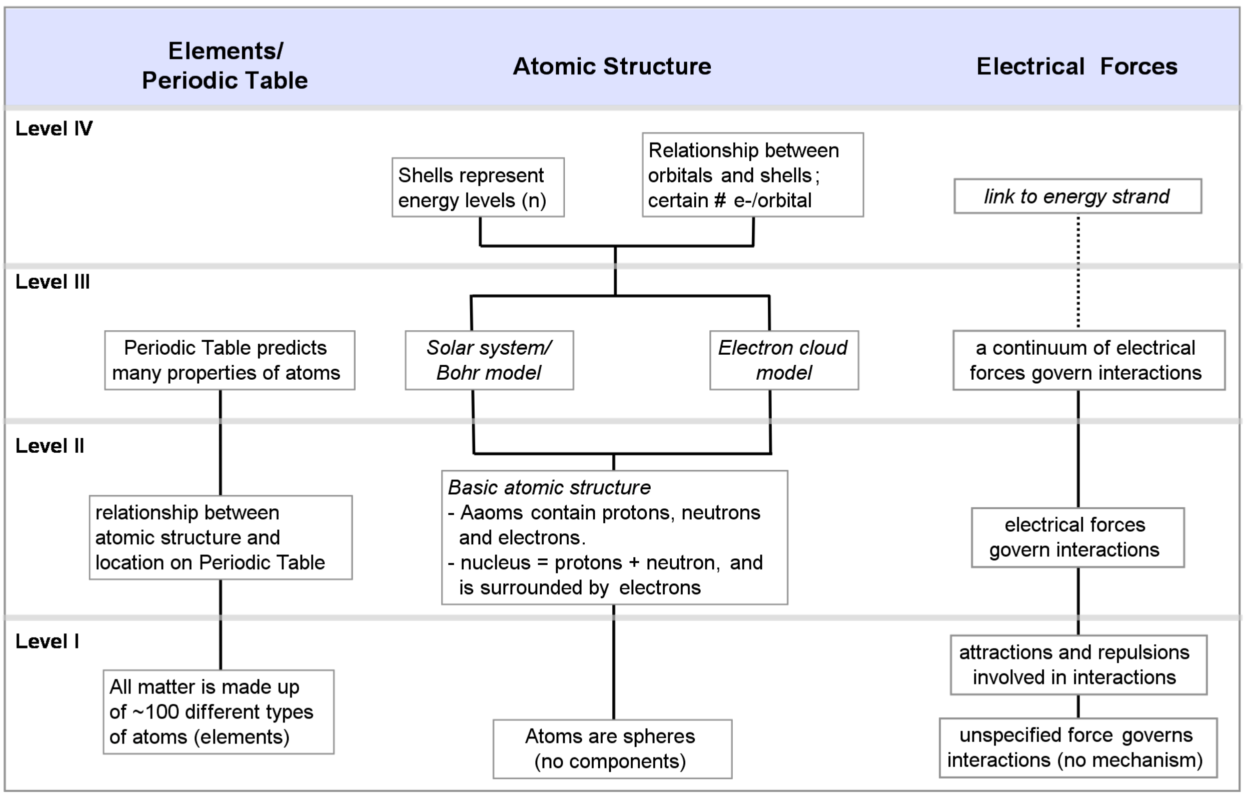

Figure 3. Representation of a portion of the hypothetical learning progression for the nature of matter (Adapted from Stevens, Delgado, & Krajcik, accepted)

For example, in a Level I student's model for the structure of a piece of water, the water molecules might be represented as spheres (or perhaps particles) that are too small to see with the unaided eye and contain no components. The particles in the liquid are close together and disordered. At Level I, the interactions between the water molecules (or particles) may be described with a simple attraction-repulsion model where two particles that make up water move toward each other, but once they get too close, they repel each other. When they reach Level III, students' models should still consist of particles that are too small to see and are close together and disordered. However, Level III, students should also integrate knowledge of elements, periodic trends, electrical forces and electron behavior of atoms within a water molecule in their models. For example, a Level III model should incorporate a more complex model of atoms and

Table 2
Examples of claims, evidence and tasks for the atomic structure construct[a]

Claim	Evidence	Task
Students should be able to draw and explain a functional model of the atom. (*what is functional depends on their level on the HLP*)	*Level 1: The student model of an atom should include:* - atoms as spheres *Level 2: The student model of an atom should include:* - atoms are made of electrons, neutrons and protons - electrons are negatively charged, protons are positively charged, and neutrons are neutral - neutrons and protons are of similar mass, electron mass is much smaller *Level 3a: The student model of an atom should include:* - Level 2 evidence + - Electrons are in constant motion, limited to shell (3D)/orbit (2D) - Only a certain number of electrons allowed per shell *Level 3b: The student model of an atom should include:* - Level 2 evidence + - Electrons do not behave like macroscopic objects. - Electrons do not have a trajectory - It is impossible to know where an electron will be based upon where it has been (Heisenberg Uncertainty Principle) - The electron probability density describes the electron distribution - In the 'electron cloud' model where the 'cloud' describes the probability density of an electron provides a simplified way of visualizing the quantum mechanical behavior of an electron - Only a certain number of electrons allowed per shell *Level 4: The student model of an atom should include:* - Level 3b evidence + - The shells represent energy levels - Only certain amounts of energy will allow electrons to move between levels - Electrons are distributed in orbitals that surround the nucleus. - Only a certain number of electrons (two) are allowed within each orbital (Pauli Principle)	- Draw a picture of what you think an atom would look like (your model of an atom) and explain it. - (If appropriate) Tell me about the protons, neutrons and electrons in your model. How do they compare to each other? - *Clarify their ideas of electron motion*. For example, ask, do the electrons orbit around like planets? (or whatever is appropriate from their drawing)

[a] Adapted from Stevens, Delgado, & Krajcik, accepted

molecules–water consists of molecules, each composed of two hydrogen atoms and one oxygen atom. The shape of the water molecule and the relative differences in electronegativity, create a slight separation of charge due to a shift in the electron density that results in a polar molecule. The Level III model of the interactions between the water molecules should also include the idea of hydrogen bonding and the role the structure and type of atoms in the water molecule play in the ability of water molecules to interact in this way. Thus, although the claim is similar, the evidence that supports a Level I claim about the structure of water is quite different than that for a Level III claim.

Building an Empirical Progression

Building an empirical progression (EP) that describes how students' understanding develops after a certain instructional experience is a valuable part of building and refining a HLP. For example, numerous gaps in the research literature still exist related to student learning and understanding of important science concepts, despite the progress made in the field. In addition, the learning research related to the range and scope of content contained in a HLP generally has focused on a broad range of instructional materials and strategies implemented in a diverse set of contexts and cultures. Additionally, science education research tends to focus on student learning of a single science topic. In order to support the development of a multi-dimensional HLP, it is necessary to characterize how students select and combine ideas to explain phenomena, in other words, the connections students should make within and across topics. Using the same assessments to measure the understanding of students at different levels within the same science curriculum provides an image of how students may develop understanding as a result of current science instruction and helps us to ascertain whether they make connections among them. Despite the limitations of cross-sectional methodology, this approach provides a more coherent picture of student learning than comparing disparate research studies.

During the first iteration of the development process, we used a semi-structured interview based on tasks developed from the claims and evidence to characterize the development of students' knowledge as they move through various science curricula. We interviewed multiple sets of students, where each set of students included participants at the middle and high school (both before and after completing a chemistry course) levels from the same district (curriculum) selected to fill out a 3-D matrix of educational level, academic ability and gender. We also interviewed a small set of undergraduate students of varying academic majors. From this data, we built an empirical learning progression (EP) that describes how students' understanding develops under the *current* science curriculum (Stevens, Delgado, & Krajcik, accepted).

Characterizing the current state of student learning allows us to evaluate whether students are progressing toward the upper anchor as designed, or if new instructional strategies must be employed to follow the HLP. In particular, an EP provides insight into the concepts with which students struggle, what connections they find easy to make and which are most difficult, and may also help identify threshold concepts, which provide a door to developing understanding of a broad range of phenomena.

Figure 4 illustrates the relationship between the EP characterizing how students develop understanding of atomic structure with the relevant strand from the HLP. Students often did not progress readily from Level I to Level II understanding. In the interview, students often indicated that they had learned about basic atomic structure (i.e., composition of atoms is protons, neutrons and electrons; protons are positively charged, electrons negatively charged and neutrons neutral;

protons and neutrons make up nucleus, which is surrounded by electrons) in 5th grade, which was at least two years before the interview. Learning research indicates that it is unproductive to introduce unnecessary detail to students (Kedisou & Roseman, 2002). Instead, learning is more effective if a need for the knowledge is established (de Vos & Verdonk, 1987). In the elementary grades, students do not have a need for even a basic model of atomic structure in order to explain phenomena at in a level-appropriate manner. Thus, at that early point in the curriculum, atomic structure likely lacked meaning to them so they could not effectively integrate it into their knowledge structure. As a result, students' models of atoms often contained some unnamed entities–they had forgotten the details (Level 1a). In other cases, students named the sub-atomic particles correctly, then forget how they are arranged (Level 2a). In this case, the EP supports the postponement of instruction focusing on details of atomic structure until a point in the curriculum where knowledge of electrons and protons is necessary for explaining the elements and their arrangement on the Periodic Table and the electrical nature of the interactions among atoms and molecules (Level II of the HLP; see Figure 3).

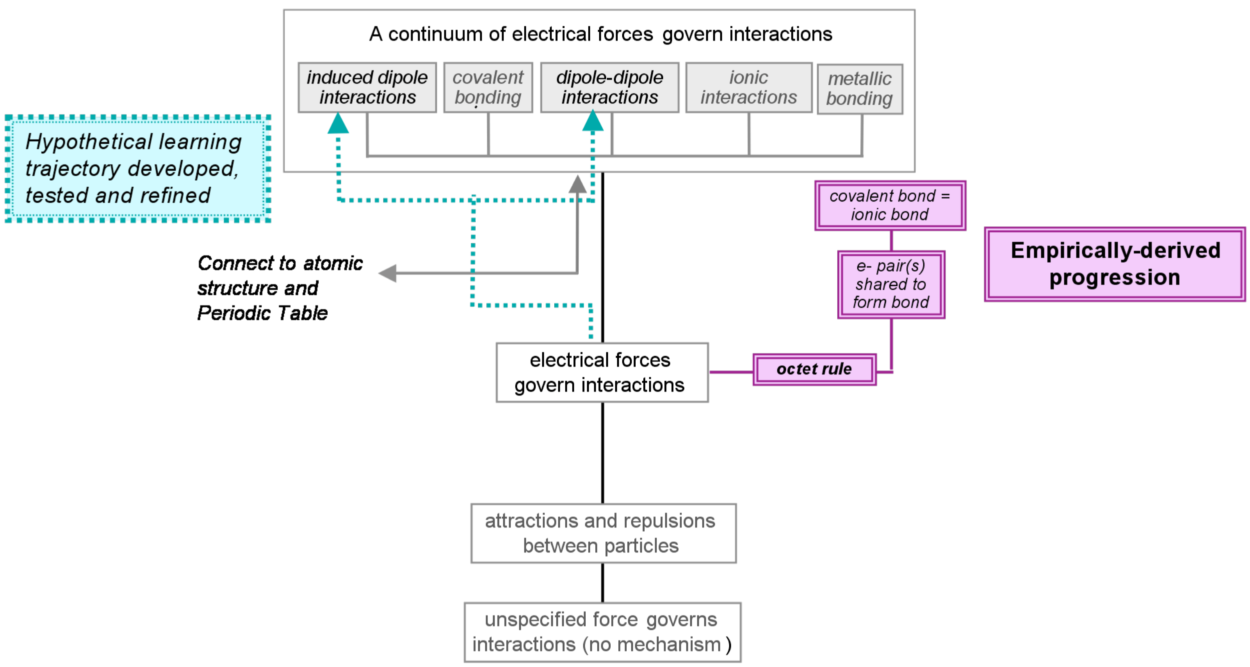

Figure 4. Characterization of the development of understanding of inter-atomic interactions with an illustration of the process of empirically testing a portion of a theoretical learning progression. (Stevens, Delgado, & Krajcik, accepted).

The Process of Empirically Testing a Hypothetical Learning Progression

In order to refine and empirically test a HLP, students must experience instruction that supports the learning described by the HLP. Because of the scope of the HLP and the iterative nature of the development process, it is more practical to test a portion at a time than through a single longitudinal study.

Testing a portion of a HLP empirically involves developing and testing an HLT that specifically defines the learning tasks and instructional strategies that will help students move along the relevant portion(s) of the HLP. The CCD process is also useful in this part of the process. Defining a learning goal, or set of learning that helps students move along the HLP is the first step in the development of an HLT. Unpacking the learning goals provides a fine grain-sized description of the content that students must understand. The unpacking process also includes identifying difficulties students may have learning the content and alternative ideas they may hold. Based upon the unpacking, a set of claims is generated. In this context, the claims are learning performances that define what students should be able to do with their knowledge and the type of scientific practices in which they should be able to engage. The evidence for the claims is associated with the HLP and current learning research specific to the scientific content addressed by the HLT. The next step involves generating learning and assessment tasks tied to the claims and evidence, then creating a logical instructional sequence to support students in building understanding of the learning goals.

Once the development process is complete, the empirical testing of the HLT begins with the implementation of the specific instructional strategies and tasks in the classroom. A new EP is developed based upon the measurement of student learning and compared to the HLP. The HLT and associated learning tasks and/or the HLP are then refined based upon the results and another iteration of the development process begins. As the HLP is iteratively refined and more HLTs are empirically tested, the HLP and EP should ultimately merge.

Beginning the Empirical Testing Process

While longitudinal studies would be the best way to empirically test a LP, the scope of a HLP, the challenge of tracking students across time while monitoring their learning experiences, and the iterative nature of the process of development, empirical testing and refinement make such studies impractical. Using relatively large grain-sized levels to help define and organize the science content of important, complex concepts (i.e., the big ideas of science) is useful in the first step of the development of HLPs to ensure coherence throughout the science curriculum. However, to empirically test the HLP, it becomes necessary to consider smaller steps between those large levels that explicitly specify a series of learning goals and the strategies that help students move from one level of the progression to the next (see Figure 1). Here we provide two examples at varying points in the empirical testing and refinement process.

In the process of developing a HLP that focuses on atomic structure and the electrical forces that govern interactions at the nano-, molecular and atomic scales, we identified gaps in the development of students' models of the structure of a solid in our EP (Stevens, et al., 2007). Although students appear to develop a richer model as they move through the curriculum, they did not develop understanding of the importance of the arrangement of particles or intermolecular forces. This may be due to the difficulty of the material, or inadequate instructional materials and instruction. In response to this question, our colleagues developed a HLT contextualized around a question about how geckos can walk on the ceiling to help high school chemistry students build understanding of these ideas (Short, Lundsgaard, & Krajcik, 2008). In addition, the instructional materials focused on polarity, electrostatic interactions, induction and the probabilistic nature of electron density, ideas which represent aspects of Level II and Level III on the HLP (see Figures 3 and 4).

A major challenge when empirically testing a HLT is that students must have the necessary prior knowledge in order to test the effectiveness of new instructional materials and learning strategies. For example, while gains were observed in student knowledge for certain learning goals, lack of prior knowledge limited students' learning about intermolecular forces. A subsequent revision of the HLT for intermolecular forces included helping students to build more of the necessary prerequisite knowledge, which improved the efficacy of the HLT and associated instructional strategies and tasks.

In another example, we found that students did not follow the HLP for inter-atomic interactions (see Figure 3; Stevens, et al., accepted). In particular, students explained the phenomenon of covalent bonding in Cl_2 and ionic bonding in NaCl using an alternative "octet" framework (Taber, 2000). By relying on this alternative framework to describe the interactions between atoms, students do not integrate all of the ideas necessary for explaining and distinguishing between these two phenomena. Students often only considered the number of valence electrons, neglecting electronegativity and charge of the participating atoms in their explanations. This alternative framework also often led students to describe the structure of sodium chloride as individual "molecules" of NaCl instead of a lattice.

While the octet model and Lewis dot structures are sufficient for explaining certain inter-atomic interactions, they cannot adequately explain *all* of them. Thus, an important strategy for helping students avoid this detour (see Figure 4) is to focus on the use of models in science, in particular that all models have limitations. In addition, focusing on the similarities of the range of interactions–that they are governed by electrical forces–as opposed to their differences (e.g., classification) should help students focus on the underlying events that occur when atoms (and molecules) interact with each other. For example, treating chemical bonding as a continuum of electrical forces has been shown to improve students' understanding of the range of ways that atoms interact to form chemical bonds (Levy Nahum, Mamlok-Naaman, Hofstein, & Krajcik, 2007). Based upon these and other potential strategies, a HLT that helps students relate their knowledge of atomic structure, periodic trends and electrical forces in order to explain chemical bonding must be developed and implemented to help complete the empirical testing of at potential path between Levels II and III on the HLP for the nature of matter.

Summary and Conclusion

We are currently completing a first iteration HLP that describes how grade 6-14 students can build conceptual understanding of the structure, properties and behavior of matter. This requires the incorporation of strands related to the particulate model of matter, kinetic theory, molecules and materials, conservation of matter, and energy into portion of the HLP for the nature of matter that focuses on atomic structure and the electrical forces involved in interactions at very small scales. The resulting HLP will describe student progress in terms of sets of ideas and focus on how students select and combine ideas to provide level-appropriate explanations of phenomena.

In parallel, in preparation to empirically test an extensive portion of the HLP, we are developing assessment tasks to thoroughly measure student understanding of the various levels of the HLP for the structure, properties and behavior of matter and locate students on the HLP. The assessments focus on four classes of phenomena related to the transformation of matter: expansion and compression, states of matter, dissolution and mixtures and chemical reactions. These phenomena provide a broad range of situations for students to apply their knowledge. Once we are confident that we can measure where students fall along the HLP, we will empirically test the low to middle levels using the instructional materials Investigating and Questioning the World through Science and Technology (IQWST) for middle school students. These instructional materials were designed to provide three years of coherent instruction within and across disciplines to support the development of integrated knowledge structures related to the nature of matter.

In this paper, we have presented a methodology that is flexible enough to support the broad range of design research required for the development, refinement and empirical testing of a hypothetical learning progression. We have adopted a systematic and principled approach (CCD) to guide all aspects of the iterative development process, which helps us maintain focus and ensures that we document our decisions (e.g., exactly what content is included, why certain content was *not* included, how levels were defined). This is especially important due to the scope of our HLP. The CCD methodology we have chosen parallels that of design research, supporting the iterative nature of developing an empirically tested LP. To facilitate communication about the various types of progressions that are part of the process of developing, refining and empirically testing a LP, we have defined a taxonomy of progressions. The terminology helps describe the different aspects of a LP identify the point in the research and development process.

The complete process of developing, refining and empirically testing an LP is, like all design research, challenging and time-consuming. However, if the field hopes to make progress on the development of meaningful science learning, it is necessary to undertake complex and extensive research and development.

References

American Association for the Advancement of Science (1993). Benchmarks for Scientific Literacy. New York: Oxford University Press.

Ausabel, D. P. (1968). Educational Psychology A Cognitive View. New York: Holt, Rinehart and Winston, Inc.

Baroody, A. J., Cibulskis, M., Lai, M., & Li, X. (2004). Comments on the use of learning trajectories in curriculum development and research. *Mathematical Thinking and Learning*, 6(2), 227-260.

Bransford, J. D., Brown, A. L., & Cocking, R. R. (1999). How People Learn: brain, mind, experience, and school. Washington, DC: National Research Council.

Chi, M. T. H., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science*, 5(2), 121-152.

Clements, D. H. & Sarama, J. (2004). Learning trajectories in mathematics education. *Mathematical Thinking and Learning,* 6(2), 81-89.

Cobb, P. & Bowers, P. (1999). Cognitive and situated learning perspectives in theory and practice. Educational Researcher 28(2), 4-15.

Collins, A. Joseph, D., & Bielaczyc, K. (2004). Design Research: Theoretical and Methodological Issues. *The Journal of the Learning Sciences, 13*(1), 15-42

de Vos, W. & Verdonk, A. H. (1996). The particulate nature of matter in science education and in science. *Journal of Research in Science Teaching*, 33(6), 657-664.

diSessa, A. A. (1988). Knowledge in Pieces. In Forman, G. & Pufall, P. B. (Eds.), Constructivism in the Computer Age (pp. 49-70). Hillsdale, NJ: Lawrence Erlbaum Associates.

Duschl, R. A., Schweingruber, H. A., & Shouse, A. (Eds.). (2007). Taking science to school: Learning and teaching science in grades K-8. Washington, D.C.: National Academy Press.

Kedisou, S. & Roseman J. E. (2002). How well do middle school science programs measure up? Findings from Project 2061's curriculum review. *Journal of Research in Science Teaching*, 39(6), 522-549.

Krajcik, J.S., McNeill, K. L., & Reiser, B.J. (2007). Learning-goals-driven design model: Developing curriculum materials that align with national standards and incorporate project-based pedagogy. *Science Education*, *92*(1), 1-32.

Margel, H., Eylon, B., & Scherz, Z. (2008). A longitudinal study of junior high school students' conceptions of the structure of materials. Journal of Research in Science Teaching, 45(1), 132-152.

Minstrell, J. (1992). Facets of Students Knowledge and Relevant Instruction. In Duit, R., Goldberg, F. & Niedderer, H. (Eds.), Proceedings of an International Workshop - Research in Physics Learning: Theoretical Issues and Empirical Studies. Kiel, Germany: The Institute for Science Education (IPN) (pp. 110-128).

Levy Nahum, T., Mamlok-Naaman, R., Hofstein, A., & Krajcik, J. (2007). Developing a new teaching approach for the chemical bonding concept aligned with current scientific and pedagogical knowledge. *Science Education* 91(4), 579-603.

Linn, M. C., Eylon, B.-S., & Davis, E. A. (2004) The knowledge integration perspective on learning. In Linn, M. C., Davis, E. A., & Bell, P. (Eds.), *Internet Environments for Science Education*. (pp. 29-46). Mahwah, NJ: Lawrence Erlbaum Associates.

Mislevy, R. J., & Riconscente, M. (2005). Evidence-centered assessment design: Layers, structures, and terminology. Menlo Park, CA: SRI International.

Mislevy, R. J., Steinberg, L. S., G., A. R., Haertel, G. D., & Penuel, W. R. (2003). Leverage points for improving educational assessment. Menlo Park, CA: SRI International.

Mohan, L., Chen, J., & Anderson, C. W. (submitted). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. Manuscript submitted for publication.

National Research Council (1996). *National Science Education Standards*. Washington, D.C: National Academy Press.

Pellegrino, J., Krajcik, J., Stevens, S. Y., Shin, N., Delgado, C., Geier, S. et al. (2008). Using Construct-Centered Design to align curriculum, instruction, and assessment development in emerging science. In G. Kanselaar, V. Jonker, P.A. Kirschner, & F. Prins, (Eds.). Proceedings from ICLS '08: *International perspectives in the learning sciences: Creating a learning world* (Vol. 3, pp. 314-321). International Society of the Learning Sciences: Utrecht, Netherlands.

Poster 2: Shin, N., Shawn, S. Y., Pellegrino, J., Krajcik, J. S., & Geier, S., C*onstruct-centered design*.

Roseman, J., Linn, M., & Koppal, (2008). Characterizing curriculum coherence. In Kali, Y., Linn, M. C., & Roseman, J. E. (Eds.) *Designing coherent science education*. NY, NY: Teacher College Press.

Short, H., Lundgaard, M. F. V. & Krajcik, J. S. (2008). How do geckos stick? *The Science Teacher* 75(8), 38-42.

Shwartz, Y., Weizman, A., Fortus, D., Krajcik, J., & Reiser, B. (2008). The IQWST experience: coherence as a design principle. *The Elementary School Journal* 109(2), 199-219.

Simon, M. A. (1995) Reconstructing mathematics pedagogy from a constructivist perspective. *Journal for Research in Mathematics Education*, (26(2), 114-145.

Sirhan, G. (2007). Learning difficulties in chemistry: An Overview. Journal of Turkish Science Education, 4(2), 2-20.

Smith, C. L., Wiser, M., Anderson, C. W. & Krajcik, J., (2006). Implications of research on children's learning for standards and assessment: A proposed learning progression for matter and the atomic molecular theory. *Measurement: Interdisciplinary Research and Perspectives, 4.*

Stevens, S., Shin, N., Delgado, C., Krajcik, J., & Pellegrino, J. (2007, April). Using Learning Progressions to Inform Curriculum, Instruction and Assessment Design. Paper presented at the National Association for Research in Science Teaching, New Orleans, LA.

Stevens, S. Y., Delgado, C., & Krajcik, J. S. (accepted) Developing a theoretical learning progression for atomic structure and inter-atomic interactions. *Journal of Research in Science Teaching.*

Stevens, S. Y., Sutherland, L. M., & Krajcik, J. S. (in press) The big ideas of nanoscale science and engineering: A guidebook for secondary teachers. Arlington, VA: NSTA Press.

Taber, K. S. (2004). Learning quanta: Barriers to stimulating transitions in student understanding of orbital ideas. *Science Education*, 89, 94-116.

Taber, K. S. (2001). The mismatch between assumed prior knowledge and the learner's conceptions: a typology of learning impediments. *Educational Studies*, 27(2), 159-171.

Taber, K. S. (2000). Multiple frameworks?: Evidence of manifold conceptions in individual cognitive structure. *International Journal of Science Education*, 22(4), 399-417.

Wilson, M. (2005). Constructing measures: An Item response modeling approach. Mahwah, New Jersey: Lawrence Erlbaum Associates.