LEARNING PROGRESSIONS TO SUPPORT COHERENCE CURRICULA IN INSTRUCTIONAL MATERIAL, INSTRUCTION, AND ASSESSMENT DESIGN

Topics that receive broad coverage with little integration provide a fragile foundation for integrated knowledge growth. In order to support the development of integrated understanding in science, coherent instructional materials should be developed to emphasize not only the learning of individual topics, but also the connections between ideas and across topics and disciplines. To build coherent instructional materials, designers can use empirically tested learning progressions as a ready-made artifact. However, well-developed coherent instructional materials should be designed, implemented, and tested as part the process of empirically tested learning progressions as well. Because the process of building such learning progressions is complex and iterative, research-based guidelines require fully articulating the process for designers use in their development of instructional materials. In this paper, we discuss six guidelines needed for learning progressions to inform the development of coherent curricula over the span of K-12 science education, focusing on organizing, identifying and specifying critical concepts within big ideas. We illustrate how these guidelines are applied to develop learning progressions and associated coherent instructional materials using a single principled and systematic design process, Construct-Centered Design. We conclude by stating major challenges for the development of a coherent curriculum based on LPs.

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Introduction

Coherence is an essential aspect of instructional materials to support the development of conceptual understanding of critical science ideas. Coherence is a systematic approach to aligning and sequencing specific ideas and the depth to which those ideas are examined in order to help the development integrated understanding in learners (AAAS, 2001; Schmidt, Wang & McKnight, 2005; Shwartz, Weizman, Fortus, Krajcik & Reiser, 2009). Researchers from the Third International Mathematics and Science Study have found that coherent curriculum is the primary predictor of student achievement in math and science (Schmidt, Wang & McKnight, 2005). However, in trying to address a multitude of standards (national, state, and local), the current U.S. science curriculum was not built to coherently help learners make connections between ideas within and among disciplines nor help develop meaningful structures for integrating knowledge (Fortus & Krajcik, accepted). The US curriculum approach has been referred to as the mile wide and inch deep approach because of its coverage of numerous topics at a superficial level. As a result, students lack foundational knowledge that can be applied to future learning and for solving problems that confront them in their lives. Therefore, it is important to address the lack of coherence in the U.S. science curriculum. To rectify this situation, the US educational systems needs a long-term developmental approach for designing coherent instructional materials that will support learners from K – 12 to make connections among important ideas and across disciplinary boundaries.

In response to the "mile wide, inch deep" approach to science education, researchers and educators have proposed a developmental approach that organizes the science curriculum around a few "big ideas" instead of the multitude of individual standards at the national, state and local levels (Smith, Wiser, Anderson & Krajcik, 2006). Big ideas, which are often used synonymously with core ideas, are defined as principles that are important for developing science literacy and that provide a foundation for future learning. The idea of a Learning Progression (LP) has been recently discussed as a promising tool for designing a coherent science curriculum because it organizes science content to provide a potential path for students to develop understanding of a big idea over time (Smith, et al., 2006; Duschl, Schweingruber & Shouse, 2007).

In this paper, we address the guidelines needed for learning progressions to inform the design of coherent curricula over the span of K-12 science education. Our proposed work is based on the experiences we have on the design and development of coherent instructional materials, the construction and refinement of learning progressions, and what we have gleaned from the literature. We start with explaining coherence in science curricula and our definition of LPs. We discuss how the guidelines of LPs can help build coherent instructional materials. In addition, we illustrate the development of a LP, and the associated assessments and instructional materials as an exemplar using a single principled and systematic design process that we call as Construct-Centered Design. Finally, we conclude with discussion of some of the challenges that the field faces in the development of LPs and associated coherent instructional materials.

Coherence

Building conceptual understanding of critical science ideas requires students to connect new ideas to existing knowledge, and interconnect knowledge from several core scientific content areas (Duschl, Schweingruber & Shouse, 2007). A coherent science curriculum should build ideas across time and disciplines by connecting ideas between relevant topics and by aligning the development of instructional materials, instruction, and assessment. In order to accomplish this, coherent instructional materials must be developed that provide students with learning opportunities that enable them to use and link ideas to explain and predict phenomena as well as to solve problems (Fortus & Krajcik, accepted). Schwartz and colleagues (2008) argue that learning goals should be the foundation for the development of coherent instructional materials. In their design model for developing instructional materials, the learning goals are used to ensure *intra-* and *inter-unit* coherence. *Intra-unit* coherence results from developing integrated understanding by focusing on a few key science ideas, rather than superficially covering many unrelated ideas in a single unit. *Inter-unit* coherence means that those same key ideas are addressed in multiple units within and across disciplines to construct integrated knowledge of those ideas across units and years. Coherence at the curriculum, inter-unit and intra-unit levels are all necessary in order to help students to develop integrated understanding of big ideas and ultimately help them become scientifically literate. To support the design of coherent instructional materials, LPs should be built taking into consideration important characteristics of coherence. In the following section, we describe LPs and discuss the guidelines need to develop LPs that can support coherence in a curriculum.

Guidelines for Building Learning Progressions to Support Coherent Curricula

Learning progressions (LPs) are research-based descriptions of how students build their knowledge, and gain more expertise within and across a discipline over a broad span of time (Duschl, Schweingruber & Shouse, 2007; Smith et al., 2006). LPs illuminate how learners can develop and connect concepts within and across disciplines as they progress towards a more sophisticated understanding of key ideas and skills necessary for developing science literacy. LPs should be informed by a long-term understanding of learning and development that is grounded in the findings of contemporary research in cognition, developmental education, and the learning sciences to characterize a path that students may follow in building integrated understanding of a big idea. A LP contains a lower and an upper anchor to define the range of content within a big idea, and defined levels of understanding between the anchors (Mohan Chen & Anderson, submitted; Stevens, Delgado & Krajcik, accepted). The lower anchor explicitly defines the knowledge that students must have before they can begin to develop understanding of concepts contained in the LP. The upper anchor describes the knowledge and skills that students are ultimately expected to hold at the end of formal instruction. It is drawn from what research in science education has defined to be developmentally feasible, and is also related to societal expectations and goals of science literacy (Mohan Chen & Anderson, submitted). The levels of understanding between the anchors describe a qualitatively different step of progressive understanding, as learners need to develop as they grow towards understanding of the upper anchor. As such, a LP describes a path that students may take from the lower to upper anchor. The path defines the ideas that students must learn for moving along the progression. They can provide a guide for a coherent science curriculum and as such inform the design of coherent instructional materials. The next sections propose six guidelines for building LPs and discusses of how they can support instructional materials design in a coherent manner.

Organize the Content around 'Big Ideas'

Organizing the curriculum around a few big ideas that define science literacy will help build coherence over the course of the K-12 science curriculum. Big ideas offer insight into the development of the field and have a key influence on explaining the major concepts in the domain. An understanding of a big idea equips the learner with the ability to explain a broad range of phenomena within and between disciplines (e.g., particle model of matter; Stevens, et al., 2007). The goal of learning progressions is to describe a potential path that students may follow as they develop understanding of a big idea. The big idea helps guide the definition of the upper and lower anchors to determine a range of LPs. If developers use such LPs as a guide in the development process, the instructional materials will have inter-unit coherence.

Identify and Clarify Critical Concepts within a Big Idea

Because big ideas are comprehensive, to completely define the critical concepts within a big idea, the selected big idea must be broken down into smaller components to explicitly describe the content contained within it. Part of the process of developing LPs includes identifying and explicitly describing the concepts that are critical for understanding a big idea. Being related to a big idea is not enough; to support coherent curriculum, the concept must build understanding of the big idea. In addition, the depth of understanding that is expected from students must be clearly defined, which helps to define the levels of the LP.

This clear definition of the content contained within the big idea provides designers with a coherent description of the science concepts that should be addressed. In particular, it provides a guide for defining the learning goal or series of learning goals required to move from one level of the progression to the next. Maintaining the explicit link to the big idea(s) ensures the intra- and inter-unit coherence of the instructional materials developed to help learners move through the LP.

Specify Students' Prior Knowledge, Experiences, and Potential Difficulties

Conceptual understanding requires learners to connect new information to existing knowledge to build an organized, structural framework (Ausabel, 1968; Taber, 2001). As such taking students' prior knowledge and experiences into account is a critical step as designers work to create instructional materials that help students develop integrated knowledge. This information provides designers with a foundation on which to build instructional materials to help students develop conceptual understanding. Thus, LPs must include information about the ideas students often tend to hold about the content and with what skills or ideas students often struggle to learn. In addition, designers need to consider this information to define a lower anchor.

Specify How Students Use and Build Understanding of a Big Idea

LPs should define progressive levels that describe comprehensible and developmentally appropriate steps toward more sophisticated understanding of a big idea. Since conceptual understanding can be defined as the ability to connect related ideas and apply knowledge to new situations (Bransford, Brown & Cocking, 2000), it is important for LPs to specify not only the order in which students develop understanding of the important concepts, but also how they connect and use ideas within individual ideas, and among related ideas. The levels defined by a LP should not describe a linear, one-dimensional path towards greater understanding that historically has often been assumed. Instead, LPs must specify the connections between related ideas that students should be able to make, identifying and characterizing not only the ways in which students can develop understanding of the important concepts within individual, related concepts under the umbrella of the big idea, but also how they should *interconnect* and *reason with* the important concepts between related ideas. Thus, a multi-dimensional model of LPs, in which a LP contains a progression of *sets* of ideas within and among disciplines that describe how students can develop more expert knowledge, may be more useful. In this way, LPs provide a strategic sequence of ideas that describe how concepts branch off one another, how connections between concepts related to a big idea are formed and how the reason students should demonstrate with the idea. The sets of ideas that define the levels of a LP provide designers with a guide for helping students build conceptual understanding important concepts.

Provide Instructional Strategies

In addition to defining the levels that describe a progression towards understanding the upper anchor, LPs should provide possible instructional strategies that might help students build the integrated understanding required to move to the next level of the progression. Instructional strategies should be developed based on learning research, the potential student difficulties and alternative conceptions. The potential instructional strategies might include 1) the instructional sequence in which ideas are ordered to help students make sense of the content, 2) what connections between ideas students should make to develop integrated understanding, 3) what difficulties and alternative conceptions students might have in developing conceptual understanding, and 4) what type of experiences (e.g., phenomena, analogies, explanation, contextualization, hands-on activities) might help students develop understanding of important concepts. We view an essential aspect of LPs as identifying and describing relevant phenomena that illustrate and illuminate individual concepts, are accessible for students, and help scaffold learning. It is important that the illustrative phenomena explicitly link to concepts that build towards a big idea, in order to contextualize and illustrate the big idea. As such, LPs can provide insight into the key learning experiences that can support a broad range of students in developing integrated understanding of critical concepts within a big idea.

Provide Assessments

LPs should include assessments to place students on the scale defined by the LP. In order to measure integrated understanding, the assessments should measure student knowledge of not only important concepts of the big idea but also connections among the concepts (Smith et al., 2006). Furthermore, the assessments need to focus on students using their knowledge so that their reasoning becomes visible. Such assessments allow teachers, researchers and curriculum materials designers to obtain insight on how students organize their knowledge around important concepts within a big idea, which in turn informs the development and revision of their instructional materials and teaching practices.

So far, we have discussed the guidelines needed to build LPs for supporting the design of coherent instructional materials. Next, we describe the process of developing a LP and associated coherent instructional materials to illustrate the development and refinement of LPs taking into consideration the guidelines. We use a principled and systematic design process, which is called Construct-Centered Design, to build a LP that focuses on the development of grade 7-14 students' understanding of the nature of matter.

Developing a Learning Progression using Construct-Centered Design

We chose to use the Construct-Centered Design (CCD) process, which is flexible enough to support the development of LPs, instructional materials, and assessments. The CCD approach was developed to be consistent with contemporary ideas on designing and constructing valid assessments (Pellegrino, et al., 2001; Mislevy & Riconscente, 2005), and on designing and building instructional materials (Wiggins & McTighe, 1998;

Gagné, Wager, Golas & Keller, 2005; Krajcik, McNeill & Reiser, 2008). Figure 1 shows a schematic of the CCD process. Because the foundation of the process focuses on the definition and explicit specification of content that lies within constructs, the process is termed as construct-centered design. Although described here as a sequential set of CCD steps, the process is interactive and highly recursive, with information specified at one stage clarifying and often modifying what was specified earlier.

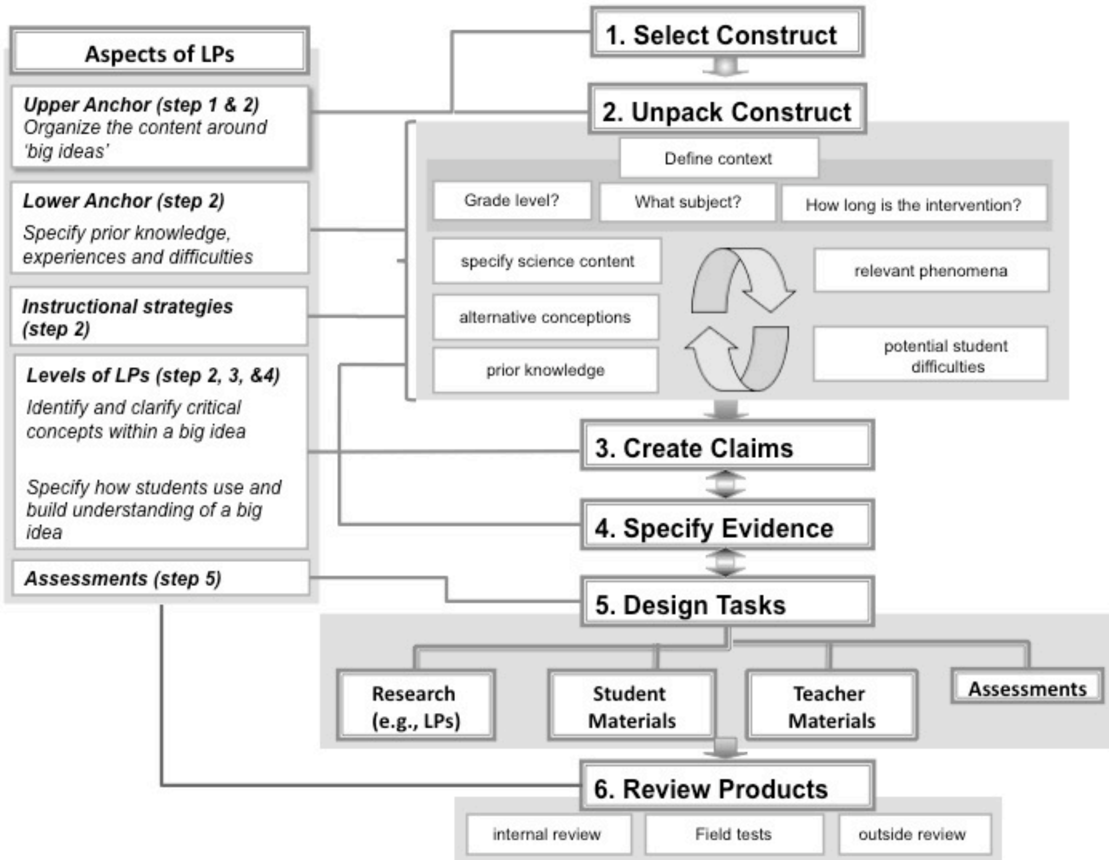

Figure 1. Relationship between the LP and the iterative CCD process

The following section illustrates how the CCD process can inform the development and refinement of LPs. Since the goal of this section is to illustrate how the CCD process provides a principled and systematic model for developing LPs and not the LP itself, we will limit the discussion of the science content. More detail can be found elsewhere (Stevens, Delgado & Krajcik, accepted).

Step 1. Select the Construct

The first step in CCD is to choose the construct, which is a big idea and define the target learners (see Figure 1, step 1). We define the construct as the ideas that students are expected to learn and researchers and teachers want to measure (Messick, 1994; Wilson, 2005). The construct is essential for instructional designers, teachers, and researchers to understand as it specifies a set of ideas for which learners will study and be held accountable for understanding. Because students in different grade ranges have different knowledge and experiences that influence their learning, defining the target students helps guide the definition of the upper and lower anchors. The big idea, nature of matter is quite broad, including the structure, properties and behavior of matter. The portion of the LP discussed here focuses on how grade 7-14 students develop understanding of two constructs: the atomic model (structure) and the electrical forces that govern interactions between atoms and molecules.

Step 2. Define the Construct

The next step is to define the construct based on expert knowledge and research in the discipline (see Figure 1, step 2). This process, called unpacking, involves defining the ideas contained within the construct. To help define the range of content needed to be unpacked, the upper and lower anchors for the LP were defined. In this case, definition of the lower anchor was guided by the learning progression for atomic molecular theory for grades K-8 (Smith, et al., 2006), and additional empirical research. The upper anchor of the LP was defined based upon national standards documents (AAAS, 1993; NRC, 1996), ideas required as a foundation for NSE learning (Stevens, Delgado & Krajcik, in press) and current learning research related to expected understandings.

Using the defined upper and lower anchors as a guide, the principles and theories within the two constructs were unpacked to define what it means to understand them at levels appropriate for grade 7-14 students. Unpacking means that the constructs, in this example, the big ideas of atomic structure and electrical forces, are broken up into concepts that are crucial for developing an understanding of the construct. The depth of understanding that is expected from students at the upper anchor is also clearly defined in this step. Table 1 illustrates the science content related to electrical forces incorporated into the LP. 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. The unpacking process also included: 1) identifying potential difficulties students might have learning the content, 2) providing possible instructional strategies that may help student learning, and 3) identifying phenomena relevant to illustrating the concepts and based on previous learning research. The unpacking process is critical to the development of a LP as it helps identify the key concepts and principles within the construct, important connections between the concepts, and informs the development of instructional strategies to help students build integrated understanding.

Table 1

Science content defined between the upper and lower anchors for the learning progression for electrical forces

Electrical Forces
- Electrical forces depend on charge. There are two types of charge—positive and negative. Opposite charges attract; like charges repel

- The outer shell of electrons is important in inter-atomic interactions. The electron configuration in the outermost shell/orbital can be predicted from the Periodic Table.
- Properties such as polarizability, electron affinity, electronegativity describe how a certain type of atom or molecule will interact with another atom or molecule. These properties can be predicted from the Periodic Table.
- Electrical forces generally dominate interactions on the nano-, molecular and atomic scales
- The structure of matter depends on electrical attractions and repulsions between atoms and molecules
- An ion is created when an atom (or group of atoms) has a net surplus or deficit of electrons
- Certain atoms (or groups of atoms) ionize easier than others
- A continuum of electrical forces governs the interactions between atoms, molecules and nanoscale objects.
- The attractions and repulsions between atoms and molecules can be due to charges of integer value, or partial charges. The partial charges may be due to permanent or momentary dipoles.
- When a molecule has a permanent electric dipole moment, it is a polar molecule.
- Instantaneous induced dipole moments occur when the focus of the distribution shifts momentarily, thus creating a partial charge. Induced-dipole•induced-dipole interactions, result from the attraction between the instantaneous electric dipole moments of neighboring atoms or molecules.
- Induced-dipole•induced-dipole interactions occur between *all* types of atoms and molecules, but increase in strength with an increasing number of electrons.
- Polarizability is a measure of the potential distortion of the electron distribution. Polarizable atoms and ions can undergo distortions in their electron distribution.
- In order to predict and explain the interaction between two entities, the environment must also be considered

(Adapted from Stevens, Delgado & Krajcik, accepted)

Step 3. Create Claims

Claims specify the nature of knowledge and understanding expected of students regarding a particular concept (see Figure 1, step 3). In constructing a claim, vague terms like *to know* and *to understand* should be avoided. Rather, claims should specifically define what students will do with their knowledge using terms that describe cognitive activities (e.g., Bloom's taxonomy; Bloom, 1956). For example, students should be able to provide examples of phenomena, use models to explain patterns in data, construct scientific explanations, or test hypotheses. An important part of conceptual understanding involves the ability to connect related ideas and apply knowledge to new situations (Bransford, Brown & Cocking, 1999). Therefore, it is important that the claims specify how students connect ideas both within individual topics, and among related topics in order to describe how students build integrated understanding of the construct. As part of the development of the LP, a set of claims was developed for the relevant content for two constructs based upon the unpacked construct. The development of the claims was informed by the national standards documents (AAAS, 1993; NRC, 1996) and the learning research literature (see Table 2 for example).

Table 2

An example of the claims, evidence and tasks for assessing student understanding of ideas related to the nature of matter

Claim	Evidence	Task
Students should relate the structure and composition of an atom to the properties and behavior of atoms of various elements	*The student work should include:* - atoms are made of electrons, neutrons and protons - the number of protons determines the type of element - the outermost electrons determine how an atom can interact with other atoms - an unequal number of protons and electrons creates an ion - different types of atoms have different susceptibility to losing or gaining an electron - the susceptibility to be ionized can be predicted by the Periodic Table; metals tend to lose electrons; non-metals tend to gain electrons - the way atoms interact relates to how easily the atom gains or loses an electron - the way in which atoms interact with each other can often be predicted from the Periodic Table	Why do sodium and chlorine interact to form NaCl? Describe how the atoms interact with each other in these two substances.

(Adapted from Stevens, Delgado & Krajcik, accepted)

Step 4. Specify Evidence

The evidence specifies the aspects of student work that would be indicative that a student has the desired knowledge to support a specific claim or set of claims. The evidence step specifies the features of student's work products necessary to describe what behaviors or performances are needed to support the claim (see Figure 1, step 4). In particular, this step helps to explicitly define the expected level and depth of understanding of the target learners would demonstrate. Based upon the unpacked construct and a set of claims, we specified evidence for the relevant content for two constructs according to the national standards documents (AAAS, 1993; NRC, 1996) and the learning research literature. At this point, the levels of understanding defined by the evidence provided a guide for the definition of levels in the LP.

Step 5. Design Learning or Assessment Tasks

The tasks, which are generated based on the claims and evidence, provide a response that offers appropriate evidence to support the relevant claim (see Figure 1, step 5). The tasks can be either learning experiences that will help learners develop the knowledge in the claim, and (or) assessments that measure whether learners have the knowledge stated in the claim. The assessment or learning tasks are designed to elicit or generate students' performances to allow for a judgment to be made about whether sufficient evidence exists to support the learning *claim*. A single assessment task or situation may provide evidence for more than one claim; multiple tasks are necessary to assess a single claim. An individual claim, its evidence and corresponding task may link to a single level on the progression. Table 2 provides an example of a claim, its corresponding evidence and an associated task. Based upon the claims and evidence, three products were developed: a learning progression, assessment tasks and instructional strategies

Learning Progression for the Nature of Matter

The claims and evidence were used to refine the levels according to learning research and the logic of the discipline. Figure 2 illustrates the LP for the nature of matter. The levels in the LP represent sets of ideas that describe a path towards developing a more complex understanding of the construct. The sets of ideas within a level connect to explain a variety of phenomena; higher levels describe the phenomena with greater scientific accuracy. In this way, the levels of the LP describe increasing levels of sophistication of a model that describes the structure and behavior of matter.

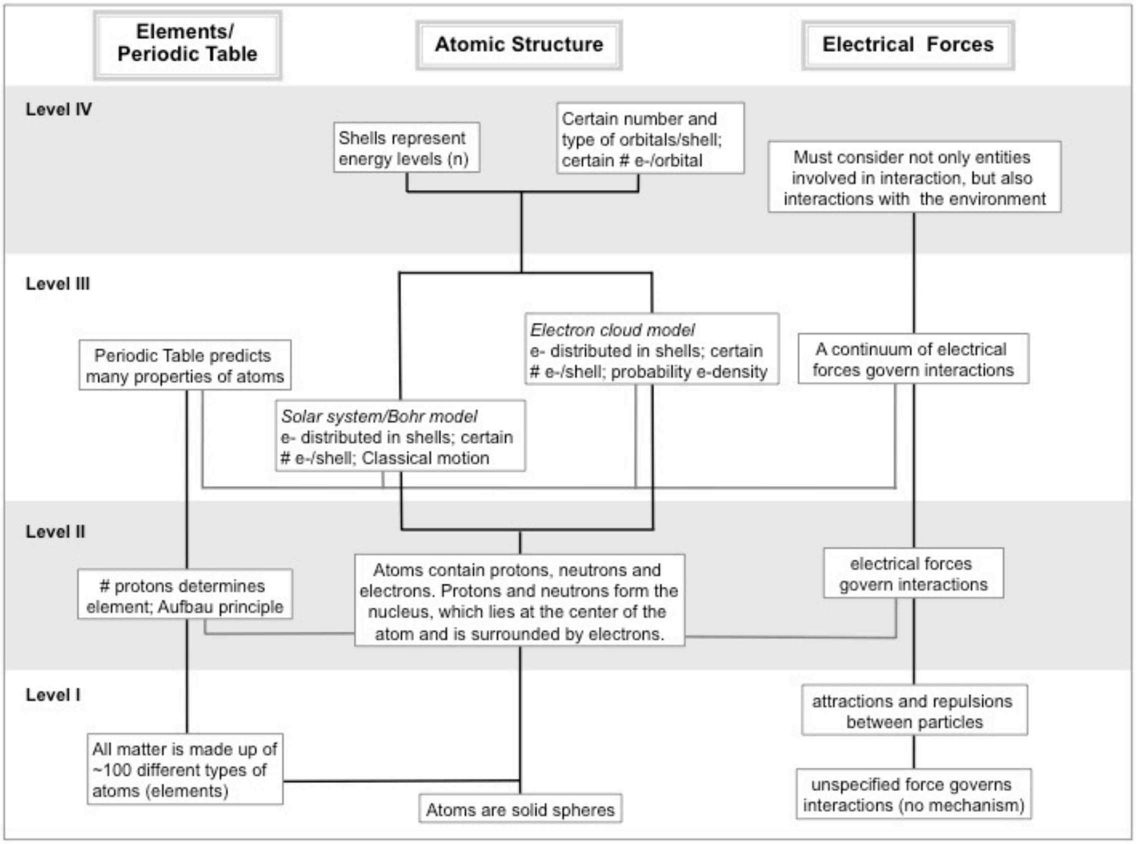

Figure 2. Illustration of three strands of the learning progression for the nature of matter

(Adapted from Stevens, Delgado & Krajcik, accepted)

Assessments to Characterize How Students Understand the Construct

The assessment tasks developed in the task phase were incorporated to design an interview protocol for assessing grade 7-14 students to better characterize how students develop understanding of concepts related to the nature of matter following the current curriculum in schools (see Task column in Table 2). Although much progress has been made in the field, numerous holes still exist in the research literature related to student learning and understanding of important science concepts. Assessing students across the grade range of the LP with the same instrument provides insight into the points of the LP on which instruction should focus, informs the type of instructional strategies that might help support student learning and support the assessments that will be developed to locate students' positions on the LP on a larger scale.

Instructional Strategies to Support Student Learning

The instructional strategies were developed based on learning research, the potential student difficulties and alternative conceptions (see Table 3 for some examples) identified in the unpacking process. The empirical data collected to characterize how students develop understanding of the construct also provided insight into where and how to focus instruction.

Table 3

Summary of some potential difficulties and alternative ideas that students may have as they move along the learning progression

Level	Potential Difficulties and Alternative Conceptions
Four	- Students frequently consider only the interacting entities and forget to consider interactions with the particles in the environment. - Students have difficulty applying the concept of polarity (Taber & Coll, 2002)
Three	- Students often rely too heavily on the octet model to explain interatomic interactions. Thus, they have difficulty explaining interactions involving dipoles and induced dipoles (Taber & Coll, 2002). - Students may believe that bond polarity is a secondary property of covalent bonds instead of thinking about a continuum between ionic and covalent bonding (Pallant & Tinker, 2004).
Two	- Students may believe that charge-charge interaction results in neutralization, not bond formation. (Boo 1998; Pallant & Tinker, 2004) - Students often do not know the forces responsible for holding particles together in the liquid or solid state (Stevens, et al., 2007)
One	- Students may use non-scientific language to describe the forces holding particles together.

(Adapted from Stevens, Delgado & Krajcik, accepted)

Table 4 illustrates some potential instructional strategies for helping students move along the portion of the LP that focuses on electrical forces. The strategies include phenomena that will illustrate and perhaps help motivate students to develop understanding of important concepts in the progression. Certain strategies are common to all levels. For example, there is a focus on models–the skill of building, interpreting and using them to predict and explain phenomena throughout the LP. In other cases, the LP suggests instructional strategies unique to developing understanding of a particular concept or set of concepts.

Table 4

Some potential instructional strategies to help students move along the learning progression

Level	Potential Instructional Strategies
Three	Focus instruction on the electrons that mediate interactions—the commonality amongst the different ways in which atoms and molecules interact, instead of categorically differentiating the types of interactions/chemical bonds.

Two	Through experience with real world phenomena (e.g., balloon sticking to the ceiling, plastic comb picking up pieces of paper, charged rod bending a stream of water), students should build an understanding of attractive and repulsive forces. Students should develop an understanding of the dependence of an interaction on charge (positive or negative), the amount of charge, and distance between charged/charged objects by experiencing and working with a variety of phenomena (i.e., Coulomb's law).
One	Develop students' knowledge and skills about modeling by using models and simulations to illustrate the relationship of attractive and repulsive forces on the random motion of the particles (e.g., springs between particles in a solid, magnetic "particles")

Step 6. Review Products

Following the CCD process, we developed three products including a LP, an interview protocol and a set of instructional strategies. For each step of this iterative process, the products were reviewed internally and when appropriate, externally (see Figure 1, step 6). The internal review focused on critique and revision of the products to ensure that they align with the claims and evidence. In addition, the interview protocol were revised to better characterize student understanding of the construct as different sets of students were interviewed through review and revision of the claims and evidence. Likewise, the LP was reviewed using the same criteria. The instructional strategies were revised iteratively based on research and student data from current classrooms using traditional materials. The next step of CCD is to have an external review of these products. External review can include procedures such as receiving feedback from teachers of the target students, receiving feedback from content or assessment experts and conducting pilot tests and field trials with target students. The external review of the LP requires the development of instructional materials based upon the strategies outlined in the LP, followed by classroom tests in order to iteratively refine the LP.

Refining and Empirically Testing the Learning Progressions

An important characteristic of LPs is that there may be many possible pathways to follow from one level to the next along the progression rather than a single defined unidirectional route. Since learning is a complex process, many factors affect the path that students may follow as they build understanding, including the learning context, instructional materials, instruction, and students' prior knowledge and experiences. In addition, students bring different personal and cultural experiences to the classroom and as such may thrive in different environments. Thus, a LP must be revised iteratively based on the empirical research for considering them as a valid representation of how understanding develops in a big idea. In order to refine and test LPs, researchers need to collect evidence from students who experience the instructional materials that were developed following LPs. Since the position of students along the progression is significantly influenced by the previous science instruction that students received (Cobb, 1999), students must have appropriate learning experiences with exemplary curriculum that helps them make connections among the ideas to develop integrated understanding of a science idea. This helps to ensure that students' poor understanding in science is not because of lack of appropriate learning experiences, but because of difficulty with the learning the ideas. Thus, well-developed coherent instructional materials based on a LP should be designed, implemented, and tested iteratively while developing an empirically tested LP.

Because of the scope of the LP, the entire progression cannot be empirically tested simultaneously, but in portions. A learning goal or series of learning goals must be developed that describes how students can progress from one level of the LP to the next. Based upon these learning goals, coherent instructional materials should be developed and tested in the classroom.

From the empirical data collected to characterize how students currently develop understanding of ideas related to the nature of matter, we identified gaps in the development of students' models of the structure of a solid (Stevens, et al., 2007). Although students appear to develop understanding of many aspects of the structure of matter as they move through their curriculum, they did not develop understanding of key ideas including the importance of the arrangement of particles or intermolecular forces. Based on the LP and potential instructional strategies, a coherent instructional unit was developed to help students move along the relevant portion, electrical forces in the nature of matter LP (see Figure 3 dotted lines).

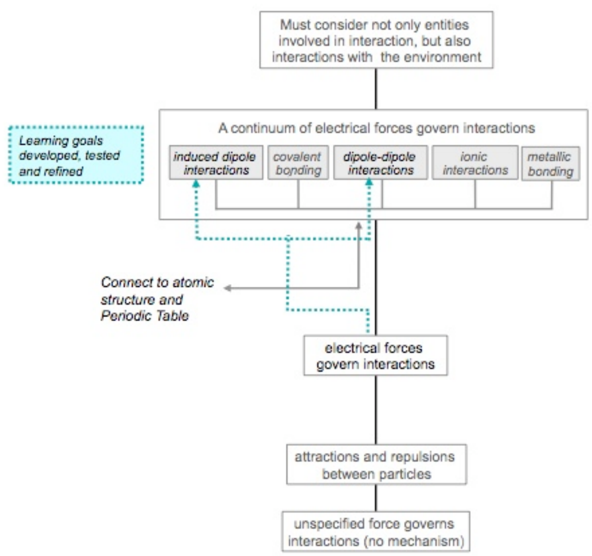

Figure 3. Illustration of the process of empirically testing a portion of a LP

Note: The levels are more explicitly defined, but simplified for this figure (Stevens, Delgado & Krajcik, accepted).

Developing Coherent Instructional Materials based on Learning Progressions

CCD also proposes guidelines of necessary design features to support the development of instructional materials and assessments based on a small portion of LPs. For instructional materials to support student learning, CCD is used in a similar way as in developing LPs. However, unpacking process focuses on specific learning goals based on the small portion of a LP, based on expert knowledge and research in the discipline. As the CCD process was designed to ensure the alignment of the development of instructional materials, instruction and assessment, we used the design process to develop coherent instructional materials to empirically test a portion of the LP related to the development of students' understanding of intermolecular forces. In the case of an instructional unit, the construct is a learning goal:

Students will explain macroscopic phenomena by citing the electrical forces and interactions, which occur between subatomic particles, atoms, and molecules within matter.

These instructional materials were designed to help students relate their knowledge of atomic structure, molecular geometry, and electrical forces in order to help students develop conceptual understanding. The unpacking process focuses on specifying the science content that is contained in the learning goal, which is a small portion of a LP. In this example, the claims relate to electrical forces. Table 5 provides an example of the claims, evidence, assessment task and learning task linked to the instructional unit on intermolecular forces. When developing the learning tasks that correspond to the claims and evidence, there are several important design features to consider when developing coherent instructional materials for students and teachers.

Contextualization

The instructional materials should connect the science content with the real world. This may be done through a unifying phenomenon where instruction focuses on building understanding of science content in order to explain the phenomenon. Alternatively, a driving, or focus, question can be used to guide instruction (Krajcik & Mamlok-Naaman, 2006). The driving question "*How do geckos stick*?" was used to contextualize the instructional unit on intermolecular forces for high school chemistry students (Short, Lundsgaard, & Krajcik, 2008). Research has shown that students are interested in this phenomenon (Hutchinson, 2007).

Learning Tasks

Learning tasks are the parts of the instructional materials that will build upon students' prior knowledge and experiences to help them develop the knowledge and skills necessary to understand the phenomena and respond to the driving question. They will incorporate relevant phenomena, technology (animations and simulations) and hands-on activities, and will use multiple formats (e.g., text, discussion, modeling) to support and scaffold student learning.

In designing the instructional unit on intermolecular forces, principles of project-based science (PBS) were used (Krajcik & Blumenfeld 2006; Krajcik & Czerniak 2007) to allow students to generate hypotheses about the potential mechanisms for gecko adhesion based on their prior knowledge and experiences. Throughout the curriculum, students test some common initial hypotheses (e.g., claws, suction cups, glue or other sticky medium). For example, students are asked to test whether geckos have glue on their feet. They use transparent tape as a model for the gecko foot and test how the dirtiness of a surface affects the force required to remove a piece of tape from that surface. Students are left on their own to determine levels of dirtiness, set up their experiment, and organize and represent their data. They then compare their results to the experimental results related to gecko adhesion to a dirty surface. This provides students with the opportunity investigate the validity of their own explanations in a scientific way.

Table 5

Example of one claim for electrical forces, the associated evidences, and the task used to illicit such evidences.

Claim	Evidences	Task
Students explain attraction between two objects in terms of the production of opposite charges due to imbalance of electrons.	*Student work product will include:* - Students explain the production of charge by describing that only electrons move from one object to another object. - Students describe that neutral matter normally contains the same number of electrons and protons. - Students describe that electrons are negative charge carriers and that the destination object of the electrons will become negative, as it will have more electrons than protons. - Students recognize that protons are positive charge carriers and that the removal of electrons causes the remaining material to have an imbalance in positive charge. - Students cite the opposite charges of the two surfaces as producing an attractive force that hold the two objects together.	*Learning Task:* Students are asked to predict how pieces of tape will be attracted or repulsed by each other. *Assessment Task:* Students are asked to explain why the rubbing of fur against a balloon causes the fur to stick to the balloon.

Instructional Sequence

The instructional materials should follow a logical and coherent progression of sub-learning goals that help students develop the knowledge described by the learning goal. Instructional sequences provide the learning tasks and phenomena that students need to experience in order to build understanding of the learning goals.

In this Gecko unit, the use of inquiry methods guides the design of the instructional sequences. In order to determine the mechanism of gecko adhesion, the students investigate the common hypotheses for the adhesion. In small groups, students explore one mechanism at a time, designing and executing investigations to test each mechanism's viability for explaining gecko adhesion. The sequence of investigations largely mirrors the path that scientists followed as they investigated gecko adhesion.

Assessment Strategies

The instructional materials should provide suggestions for formative (e.g., discussion questions) and summative assessment that enable teachers to gather rich information rather than superficial feedback about student learning. Throughout the instructional unit, students are prompted to make sense of their experiences and data by producing both oral and written explanations about gecko adhesion, which allows learners to construct artifacts that represent their emerging understandings. Teachers can use the artifacts (e.g., homework assignments, storyboards, and lab reports) as embedded assessments to provide direct evidence of learning. The assessment tasks culminate in a final essay in which students are asked to make sense of data on gecko adhesion from both the scientific literature and their own investigations and discussions from class.

Use of Learning Technology

Because some science phenomena can only be experienced through the use of technology (e.g., animation, simulations), multiple representations of phenomena can help students develop deeper understanding of the scientific concepts underlying the phenomena. For example, students interact with several computer simulations to help make sense of electrical attraction and repulsion at the molecular level, something they cannot see with their naked eye. They also use simulations that bridge the gap in scale between a macroscopic phenomena and its underlying microscopic causation (PhET, 2007)

Key Scientific Practices

Constructing and evaluating scientific explanations is an important part of inquiry-based instruction as it requires students to use evidence, reasoning and scientific ideas to support claims (McNeill & Krajcik, 2007). This Gecko unit emphasizes the production of scientific explanation as students are repeatedly asked to take data and produce claims that are justified by scientifically sound reasoning. Students must justify their claims using data and elaborate why this evidence applies to their claims.

In addition, it is especially important that the instructional materials support students in developing the skills of working with and, where feasible, of building models. Throughout the instructional unit, models and analogies were employed to help students test hypotheses about gecko adhesion. Students also evaluate data and observations, as well as produce models of observed phenomena—such as gecko adhesion—to create representations of the ideas they are studying.

The instructional unit was enacted in one of elective high school chemistry course. The unit lasted approximately 4 weeks. The data were collected from 11^{th} and 12^{th} grade students (N=28) enrolled at a high school in a diverse, low-SES public school district in a large, economically depressed Midwestern city. The results of pre- and posttest tests show significant gains ($p<0.001$, $ES>1.48$) (Short, Lundsgaard & Krjcik, 2009). The study also reveals that the instructional unit has a limitation in supporting student learning sub-idea of electrical forces. The designers revised the unit based on the results and teacher and student feedback. The revised unit was again implemented in the same school to investigate whether the problem of student learning in the topic is from the difficulty with the learning the ideas, or lack of appropriate learning experiences from the instructional materials. This information will help in refining the LP. In sum, this study shows that an instructional material based on the LP guidelines can support students develop their understanding in an advanced chemistry content. The LP should be refined based upon the results of the testing. Results from refining the LP should flow back into the revision of the instructional materials. The CCD process provides a systematic and principled way to develop and revise all aspects of a LP iteratively. The same process guides the empirical testing of the LP.

Challenges

There are still several challenges to overcome in the process of developing and refining LPs to build a coherent science curriculum and the associated assessment. We view a longitudinal study as the ideal way to empirically test and refine the entire suggested learning path of a LP. However, a more realistic way of empirically testing a LP is through testing a series of smaller pieces of the LP. Subsets of LPs specifically define the learning tasks and instruction that will help students move along the relevant portion(s) of the LP. One or several learning goals in series may describe how students can progress between the levels of the LP. Empirically testing a LP requires developing and testing an *entire* series of learning goals that describe specifically how to move students toward conceptual understanding of the big idea in science. Thus, the process of empirically testing the LP ultimately leads to curriculum materials that are coherent over a broad time span.

However, this strategy of empirically testing LPs can be limiting due the lack of students' prior knowledge and experiences necessary to build understanding of the desired content within a particular trajectory. The lack of students' conceptual understanding in science (Delgado et al., 2007; Stevens et al., 2007) is likely not only due to the difficulty of the material, but also because the learners have not had appropriate learning experiences to help them develop understanding of the ideas. If students have an exemplary curriculum that helps them make connections among ideas to develop integrated understanding of a science topic, a different picture of student learning might emerge. As such, when we test LPs using student data from current classrooms using traditional materials, it is unclear if lack of appropriate learning experiences or challenges in learning the ideas themselves leads to students' poor performance on assessments. We take the stance the learning is tied to the curriculum and instruction that students experience (in addition to other factors such has home life) and as such, a different picture of student learning would emerge if students experienced curriculum based on what we know promotes learning. Thus, it may be necessary to empirically test an entire LP from the beginning and to the end of student understanding in a big idea as it may not be possible to successfully validate instructional strategies associated with the middle of the progression if the students have not already developed the integrated knowledge described by the earlier levels of the LP.

Another challenge we face as a field is the development of valid assessments to measure the level of student understanding along LPs. The typical assessment approach generates mainly information about whether a student possesses certain knowledge or not in order to inform teachers and researchers about student achievement. The major criticism of this approach is the weak connection between assessment items and the developmental progress of student understanding, as these instruments do not illustrate students' conceptual growth for monitoring of their understanding over time. The science education community has struggled to design instruments to track student understanding of a big idea. Recently, educators have begun to focus on the potential for using LPs to develop meaningful assessment as a way of tracking how understanding develops of a big idea over time (NRC, 2006 & 2007; National Assessment Governing Board, 2006a, 2006b; National Assessment of Educational Progress, 2009). Prior to using this approach, quality, extensive research is needed to validate assessment items.

Conclusion

To support all learners in developing integrated understanding of big ideas, instructional designers and researchers need to take a developmental approach to the design of instructional materials in a coherent manner. Lately educational researchers began working to create a knowledge base for developing LPs to provide support in designing a coherent science curriculum, and guide the alignment of instructional materials, instruction and assessment development. Researchers should empirically test LPs using the evidence collected from students who experience coherent instructional materials that were developed based upon a LP: however, the process is iterative in nature with results from empirically testing the LPs feeding back to improve coherence and alignment of materials. Such work makes substantial advancement in moving forward the ideas expressed in Taking Science to School (Duschl, Schweingruber & Shouse, 2007) and in Learning Progressions in Science: An Evidence-based Approach to Reform (Corcoran, Mosher & Rogat, 2009) about building coherent curriculum and assessment systems that align with each other. The Corcoran, Mosher and Rogat document illustrates researchers in the field are not applying similar procedures for designing and aligning of LPs and instructional materials (2009). Research-based guidelines and a principled approach are needed to guide researchers for building their LPs and the associated coherent instructional materials and assessments. The CCD and the proposed guidelines offer a systematic approach for the development of such products. Although this approach will need refinement and further development, it provides beginning place for others to start designing and developing their LPs and aligned instructional materials.

In this paper, we proposed set of guidelines that researchers can use to build LPs based on essential characteristics of coherence and LPs. The work we describe extends the approach of Wilson and colleagues (Wilson, 2005; Wilson & Berenthal, 2006) beyond aligning assessments with how ideas develop over time to include the design, development and refinement of instructional materials that align with LPs across years. The work also extends that of Smith and colleagues (2006) in providing an approach, CCD, that other researchers in the field can use to build LPs and instructional materials in a principled and systematic manner. We apply CCD to building and refining LPs and instructional materials taking into consideration a set of guidelines that provide guidance in 1) organizing the content around big ideas, 2) identifying critical concepts within a big idea, 3) specifying prior knowledge, experiences, and potential difficulties, 4) specifying how students use and build understanding of a big idea, 5) providing instructional strategies, and 6) providing assessment. Our experiences and research in building LPs and coherent curricula illustrate that the proposed guidelines and the iterative CCD process can improve the quality of the development of LPs and the coherence of the associated instructional materials. Although the development of empirically tested LP is extremely time-intensive and requires substantial resources, the potential outcome could be of a great value in helping learners developing integrated understanding of big ideas.

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