Chapter 3

Tracking student learning over time using construct-centred design

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Introduction

Rather than investigating learning and context as disconnected entities, learning research should investigate how learning and context work together to understand and predict how people learn (Barab and Squire, 2004). In such research, learning scientists address theoretical questions about the nature of learning in context, developing approaches to the study of learning phenomena in real contexts to produce evidence-based claims for their theoretical questions (Collins, Joseph, and Bielaczyc, 2004). For valid evidence-based claims, researchers should consider students’ learning over an extended period of time in various contexts because learning challenging content may take years to develop and is influenced by many factors, such as classroom contexts, instructional materials, and students’ prior knowledge and experiences (Smith et al., 2006; Guschl, Schweinruber, and Shouse, 2007). Such research involves the development of products (e.g., learning theory, instructional materials and technology tools) and explores the relevance of the products on learning rather than simply examining isolated variables within laboratory contexts (Brown, 1992; Barab and Squire, 2004). Thus, the research programme should be iterative, be process-oriented, and involve design products that work in real contexts. Such programmes of research also need appropriate methodologies. Based on our previous work, we propose using construct-centred design (CCD) as an appropriate methodology (Krajcik, Shin, Stevens, and Short, 2009; Pellegrino et al., 2008).

Because CCD focuses on the construct that students are expected to learn as well as the construct that researchers and teachers want to measure, the CCD methodology provides a flexible and systematic approach for guiding product development, monitoring the development process, and examining the effects on learning outcomes. The aim of this chapter is to illustrate how the CCD process provides a systematic research methodology for learning research using the development of learning progressions (LPs), a new and complex research field in science education, as an example. LPs illustrate students’ conceptual growth across time and guide the alignment of instructional materials, instruction, and assessment in a principled way (see for example Smith et al., 2006; Duschl, Schweinruber, and Shouse, 2007). Although we focus on science learning, the CCD methodology and its form of analysis are applicable to design research for exploring the long-term development of ideas in other disciplines.

Before turning to the specifics of the CCD methodology, we describe the main idea and key characteristics of LPs. Next, we describe the CCD methodology and its relation to other design approaches. Finally, we provide an example to illustrate how CCD can guide the development and refinement of LPs for monitoring students’ understanding across time. We conclude by discussing the strengths and weaknesses of the methodology.

Learning progressions

Learning scientists consider LPs to be a valuable framework for designing instructional materials, instruction, and assessment to support meaningful learning because they organize content to provide a potential path for students to develop understanding of a core idea over time (Duschl, Schweinruber, and Shouse, 2007; NRC, 2006 and 2007; National Assessment Governing Board, 2006a and 2006b). Learning progressions are research-based descriptions of how students build their knowledge and gain more expertise within and across a core idea over a broad span of time (Duschl, Schweinruber, and Shouse, 2007; Smith et al., 2006). Core ideas help explain the major concepts in a domain or may offer insight into the development of the field. Thus, they provide a foundation for future learning. They illuminate how learners can develop and connect concepts within and across disciplines as they progress towards a more sophisticated understanding of the key concepts and skills necessary for developing core ideas. As such, they can provide a guide for tracking student learning over time.

There are three key factors to an LP: a lower and an upper anchor to define the range of content within a core idea and defined levels of understanding (Smith et al., 2006; Stevens, Delgado, and Krajcik, 2009). Based upon learning and cognitive research, the lower anchor explicitly defines the knowledge that students must have before they can begin to develop understanding of concepts contained in the learning progression. The upper anchor describes the knowledge and skills that students are ultimately expected to hold at the end of formal instruction corresponding to the LP.

Because meaningful learning can be defined as the ability to connect related ideas and apply knowledge to new situations (Bransford, Brown, and Cocking, 1999), 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 related ideas. An LP does not describe a linear, one-dimensional path towards greater understanding that historically has often been assumed. Instead, the levels of an LP specify the connections between related ideas that students should be able to make, and identify and characterize not only the ways in which students can develop understanding of the important concepts under the umbrella of the core 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
an LP contains a progression of sets of ideas within and among topics 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 and how students should select and combine ideas and apply them to new problems.

Smith and colleagues proposed a research approach that is grounded in students' progressive understanding of a core concept and can inform the development of LPs for all disciplines. In this approach, a coherent set of core ideas was defined, clarified, and elaborated based on the research on students' understanding of associated concepts. Next, they combined the key concepts related to each core idea with scientific practices (e.g., modelling and scientific explanations) to develop 'learning performances' (Krajcik, McNeill, and Reiser, 2008: 9), which are referred to as the articulation of the cognitive tasks that describe how students should be able to make use of the knowledge. From these efforts, they defined levels for each grade range that are suitable for the experiences, knowledge, and cognitive ability of students at that level in order to describe how students can develop understanding of the core idea over time. Finally, the concepts from each level were used to develop an LP and generate assessment items that link to the learning performances. The assessments focus on measuring complex learning skills in a progressive way to place students along the LP. This approach offers promise for improving large-scale and classroom assessment by focusing on students' conceptual growth to monitor their understanding of a core idea across time instead of a one-time measurement using low-level tasks (e.g., description and recall).

The key aspect of LPs and the approach used by Smith and colleagues is the grounding in research and empirical evidence on student learning and understanding of core ideas. Empirical learning research should guide the selection and description of the lower and upper anchors, and the levels of the LP. However, although much progress has been made in the field, numerous unanswered questions still exist in the research literature related to the design and empirical testing of LPs and how they can guide student learning across time. Developing well-grounded LPs requires thorough, longitudinal studies related to how student learning of core ideas develops in a diverse set of contexts. A principled research methodology such as CCD (Pellegrino et al., 2008) is necessary to guide the complex, iterative process of developing and refining an LP and assessments based upon the LP. In the section that follows, we describe the founding of CCD and present how the CCD methodology can apply to the development of LPs.

**Foundation of construct-centred design**

A research methodology to guide learning research and the development of products should be flexible enough for (1) mapping out the constructs associated with core ideas and (2) developing assessments and instructional materials that support and measure how students' understanding develops over time. By modifying and adapting the learning goal driven (LGD) design process for developing curriculum materials (Krajcik, McNeill, and Reiser, 2008) and the evidence-centred design (ECD) model for developing assessments (Mislevy at Riconoscere, 2008), the CCD process (Pellegrino et al., 2008) provides such a model.

**Learning-goal-driven design**

The LGD design model builds upon and extends the backward design approach presented by Wiggins and McTighe (1998) and current instructional design frameworks (Gagné, Wager, Golas, and Keller, 2005) to provide an approach for the development of coherent instruction materials (Krajcik, McNeill, and Reiser, 2008). This process begins by defining the focus of the instructional materials based on national, state, or local standards. The next step is the unpacking process, which involves explicitly specifying the content contained in the standard of interest as identifying necessary prior knowledge, potential student difficulties and alternative conceptions, and strategies for representing content to engage students in meaningful ways. Learning performances that describe what students should be able to do with the knowledge are then developed based on the concepts identified during the unpacking process and the results of learning research related to student learning of the relevant content. The development of learning performances is critical step that defines the cognitive tasks for students to accomplish. The learning performances then guide development of learning and assessment activities.

**Evidence-centred design**

ECD is a powerful and flexible framework for organizing content and developing assessments grounded in the principles of evidentiary reasoning (Mislevy at Riconoscere, 2008). A key to this approach is the focus on defining evidence which describes 'what behaviours or performances should reveal' whether students have the desired knowledge (Messick, 1994: 16). In light of this perspective, the ECD approach answers three questions: (1) Exactly what knowledge is critical an should be assessed? (2) What does it mean to understand that knowledge, and how should students be able to use the knowledge to demonstrate the understanding? and (3) What particular tasks, questions or situations will bring about the appropriate type of response? Within the context of the ECD approach, the content of a domain must be clearly and completely defined. An important part of the ECD process involves specifying what students should be able to do with their knowledge and the practice in which they should engage with the knowledge, which is called a 'claim'. The evidence defines the features that student work is expected to exhibit in a given situation to provide support that the student has met the claim. The evidence provides a detailed description of the precise level-appropriate knowledge and skills that students should exhibit to illustrate their understanding. The process also defines what tasks or situations should elicit evidence of student understanding of the claim or part of a claim.
Construct-centred design process

Similar to the LGD and ECD processes, the CCD process begins with specifically defining the focus of the construct. We define the construct as the core ideas that students are expected to learn and that researchers and teachers want to measure (Messick, 1994; Wilson, 2005). Because the foundation of the process focuses on the definition and explicit specification of content that lies within constructs, the process is termed a 'construct-centred design'. In describing the process, we do not mean to imply that this is a linear process. In practice, the process is interactive and highly recursive, with information specified at one stage clarifying, and often modifying, what was specified earlier. Figure 3.1 illustrates the CCD process and the relationship between CCD and the development of LPs. A detailed description of each step follows.

Step 1: Select the construct

The first step in CCD is to choose the construct and define the target learners (see Figure 3.1, step 1). The construct is essential as it identifies the 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 define the construct appropriately and also guides preparation of level-appropriate instructional materials, instruction, and assessment.

Step 2: Define the construct

The next step is to define the construct based on expert knowledge of the discipline and related learning research (see Figure 3.1, step 2). This process, called 'unpacking', involves defining the ideas contained within the construct. By 'unpacking', we mean breaking up the construct into smaller components to explicitly specify the concepts that are crucial for developing an understanding of the construct. Being related to the construct is not enough; the concept must be necessary for building understanding of the construct. The depth of understanding that is expected from students is also clearly defined in this step. 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 includes identifying potential difficulties students might have learning the content; providing possible instructional strategies that may help student learning; and identifying strategies for effectively representing the concepts based on previous learning research to engage students in a meaningful way.

Step 3: Create claim(s)

A set of claims is generated based upon the unpacked construct. Claims specify the nature of knowledge and understanding regarding a particular concept that is expected of students (see Figure 3.1, step 3). In constructing a claim, vague terms like 'to know' and 'to understand' should be avoided. Rather, claims should specifically define what students would be able to do with their knowledge using terms that describe the cognitive behaviours you want students to engage in (e.g. Bloom’s taxonomy; Bloom, 1956). For example, students should be able to provide examples of phenomena, use models to explain phenomena, or construct explanations, or develop test hypotheses. An important part of student learning involves the ability to connect related ideas and apply knowledge to new situations (Bransford, Brown, and Cocking, 1999). Therefore, it is important that the claims specify how students should be able to connect ideas both within individual topics and among related topics in order to describe how students build integrated understanding of the construct.

Step 4: Specify the evidence

The evidence specifies the aspects of student work (e.g. behaviours and performances) that would be indicative of a student who has the desired knowledge to support a specific claim or set of claims (see Figure 3.1, step 4). In particular, this step helps to explicitly define the expected level and depth of understanding.
that the target learners should demonstrate. Based upon the unpacked construct and a set of claims, evidence for the relevant content for a construct is specified. The understanding defined by the evidence provides 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 3.1, step 5). The tasks can be either learning products that will help learners develop the knowledge in the claim or assessment products 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 may be necessary to assess a single claim. A single task or set of tasks can be associated with a claim or a set of claims assigned to multiple levels on the LP. An individual claim, its evidence, and its corresponding task may link to a single level on the progression.

**Step 6: Review products**

For each step within this iterative process, the products must be reviewed internally and, when appropriate, externally (see Figure 3.1, step 6). The internal review focuses on critique and revision of the products to ensure that they align with the claims and evidence. External review can include feedback from teachers of the target students or from content or assessment experts. Conducting pilot tests and field trials with target students is an essential component that provides invaluable information of the products. In sum, the CCD process provides a systematic and principled way to iteratively develop and revise all aspects of an LP, and ultimately to design associated research, instructional materials, instruction, and assessments for monitoring student understanding of a core idea over a long time period.

**Application of construct-centred design**

In this section, we describe the process of developing an LP that focuses on the development of grade 7–14 students’ understanding of a core idea (i.e. the nature of matter) to illustrate how the CCD methodology can generally inform the development and refinement of LPs. Since the goal of this chapter is to show how the CCD approach provides a principled and systematic methodology for developing LPs, we limit the discussion of the science content, however more detail can be found elsewhere (Stevens, Delgado, and Krajcik, 2009).

**Select and define the construct**

The nature of matter is a broad topic that includes the structure, properties, and behaviour 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. To help define the range of content that needed to be unpacked, the lower and upper anchors for the LP were defined. In this case, the lower anchor was defined using 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 nanoscale science and engineering learning for grade 7–12 students (Stevens, Sutherland, and Krajcik, in press) and current learning research related to those expected understandings.

The concepts within the two constructs were then unpacked to define what it means to understand them at levels appropriate for grade 7–14 students. In this example, we unpacked the constructs of atomic structure and electrical forces to identify and describe the concepts crucial for developing an understanding of the constructs. The depth of understanding that is expected from students at the upper anchor is also clearly defined in this step. Table 3.1 illustrates the science content related to atomic structure incorporated into the LP. The unpacking process also includes identifying potential difficulties that students may have learning the content, providing possible instructional strategies, specifying the prior knowledge needed to build understanding of the content, and identifying phenomena to help effectively represent the content based on previous learning research.

**Create claims, specify evidence, and design tasks**

A set of claims, and the related evidence and tasks, were developed for the relevant content for the two constructs. The development of the claims and evidence were informed by the national standards documents (AAAS, 1993; NRC, 1996) and the learning research literature. Table 3.2 provides an example of a claim and its corresponding evidence and tasks. Based upon the claims and evidence, we developed an LP.

**Develop a learning progression**

The claims and evidence specify how students should be able to connect ideas both within individual topics and among related topics in order to describe how students build integrated understanding of the constructs. The claims and evidence can be used to refine the levels according to learning research and the logic of the discipline. Figure 3.2 illustrates part of 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 constructs. The sets of ideas within a level connect.
Table 3.1: Unpacked science content lying between the upper and lower anchors for the learning progression for atomic structure

Atomic structure

Atoms consist of electrons, neutrons, and protons.  
Protons have a positive charge, electrons a negative charge, and neutrons are neutral.  
The number of protons defines the type of element, and represents the atomic number on the Periodic Table.  
Neutral atoms of an element have the same number of protons and electrons, but not necessarily the same number of neutrons.  
Different numbers of neutrons for a given number of protons create different isotopes of the same element.  
Protons and neutrons have similar mass, but electrons have a much smaller mass.  
The nucleus takes up only a very small percentage of the volume of an atom, but makes up the vast majority of the atomic mass.  
The electrons are distributed in 'shells' that surround the nucleus. These shells represent energy levels (n).  
The inner shells plus the nucleus make up the atomic core.  
The outer shell of electrons is different from the inner shells of electrons.  
The configuration of the outermost electrons determines how an atom can interact with other atoms.  
There are a certain number of orbitals in each shell or level (e.g. 1s, 2s, 2p, 3s, 3p, 4s, 4p, 5s, 5p, 6s, 6p) of an atom.  
The Pauli Principle predicts that only two electrons can be in a single orbital. Each electron has a different spin (i.e. ±½).  
The solar system model does not describe electron distribution within an atom well; the electron cloud model, which describes the electron probability density, provides a better model.  
Electrons exhibit both particulate and wavelike behavior.  
The Heisenberg Uncertainty Principle states that the position and momentum of an electron cannot be determined simultaneously.  
Only energy changes in certain (quantized) amounts are observed in isolated atoms, molecules, or other confined systems.  
Different energy levels are associated with different configurations of atoms (and molecules).  

Source: Adapted from Stevens, Delgado and Krajcik, accepted

Table 3.2: Examples of the claims, evidence, and tasks for the atomic structure construct

<table>
<thead>
<tr>
<th>Claim</th>
<th>Evidence</th>
<th>Task</th>
</tr>
</thead>
</table>
| Students should be able to draw and explain a functional model of the atom. (What is functional depends on their level and the level-appropriate phenomena they need to explain.) | Level 1: The student model of an atom should include:  
- Atoms (no components) | - Draw a picture of what you think an atom would look like (your model of an atom) and explain it. |
| 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, mass of electrons is much smaller. | | - (If appropriate) Tell me about the protons, neutrons, and electrons in your model. How do they compare to each other? |
| 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. | | - Clarify their ideas of electron motion. For example, ask, “Do the electrons orbit around like planets?” (or whatever is appropriate from their drawing). |
| Level 3b: The student model of an atom should include:  
- Level 2 evidence +  
- Electrons are in constant motion, but unlike macroscopic objects, they do not have a trajectory.  
- The Heisenberg Uncertainty Principle indicates that it is impossible to predict where an electron will be based upon where it has been.  
- 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 in the atomic models represent energy levels. | | |
Table 3.2 continued

<table>
<thead>
<tr>
<th>Claim</th>
<th>Evidence</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Only certain amounts (quanta) of energy will move electrons to another level.</td>
<td>- Electrons are distributed in orbitals that surround the nucleus. Only a certain number of electrons (two) are allowed within each orbital (Pauli Principle).</td>
<td>- A certain number of orbitals is contained within each level (shell).</td>
</tr>
</tbody>
</table>

Source: Adapted from Stevens, Delgado, and Krajcik, 2009

![Image](image.png)

**Figure 3.2 Illustration of three strands of the learning progression for the nature of matter**

Source: Adapted from Stevens, Delgado, and Krajcik, 2009

Data collection: characterizing how students develop understanding of the nature of matter

To help fill gaps in the learning research related to the two constructs, an interview protocol was developed based on the CCD claim and evidence phases to characterize how ideas related to the nature of matter developed as grade 7–14 students passed through the current curriculum (see, for an example of an interview protocol, Stevens, Delgado, and Krajcik, 2009). 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 students develop understanding, and supports the development of assessments that can be developed to locate students’ positions on the LP on a larger scale.

Participants and procedure

A cross-sectional sample of students representing the range of grades covered by the LP was interviewed. In this case, grade 7 students and high school students (one set had not taken a chemistry course and another set had) from the same district or school system were individually interviewed. At each level, the students who were interviewed were chosen to provide a mix of gender and to represent a range of achievement levels. A 20–30-minute semi-structured interview was performed with individual students to characterize student understanding of all of the topics contained in atomic structure. The interview questions required students to apply their knowledge to explain real-world phenomena. The interviews were conducted in several phases. After each phase, student responses were evaluated and the protocol was revised to better characterize student understanding of the constructs.

Coding scheme

The data collected from the interview was coded following a coding scheme based on Minstrell’s (1992) ‘FACETS’ approach. Each concept from the unpacked construct was unpacked further into small, independent ‘facets’. This approach helps prevent predisposition towards predefined models and ensures that all student models can be accommodated. A code of ‘Y’ was used to signify that the facet was included in the student response while a code of ‘N’ indicated that the idea was not communicated by the student (see Figure 3.3 for a coding example). Student ideas not included in the coding scheme were coded ‘other’. The responses in the other category provide further information on alternative ideas and difficulties students may have learning the content. As such, they inform the instructional strategies that may help students move along the LP. If a question was inadvertently omitted or the interviewer strayed too far from the interview protocol, the code was ‘NA’. To achieve inter-rater reliability, one researcher coded
Atomic composition and structure

<table>
<thead>
<tr>
<th>Facet</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atoms are spherical</td>
<td>Y</td>
</tr>
<tr>
<td>Atoms are made up of components</td>
<td>Y</td>
</tr>
<tr>
<td>Atoms contain protons (p⁺)</td>
<td>Y</td>
</tr>
<tr>
<td>Atoms contain electrons (e⁻)</td>
<td>Y</td>
</tr>
<tr>
<td>Atoms contain neutrons (n⁰)</td>
<td>Y</td>
</tr>
<tr>
<td>p⁺ are positively charged</td>
<td>Y</td>
</tr>
<tr>
<td>e⁻ are negatively charged</td>
<td>Y</td>
</tr>
<tr>
<td>n⁰ are neutral</td>
<td>Y</td>
</tr>
<tr>
<td>Nucleus lies at the center of the atom</td>
<td>Y</td>
</tr>
<tr>
<td>p⁺ and n⁰ at the corner (nucleus)</td>
<td>Y</td>
</tr>
<tr>
<td>e⁻ in outer portion of atom</td>
<td>Y</td>
</tr>
<tr>
<td>Nucleus takes up small percentage of atomic volume</td>
<td>N</td>
</tr>
<tr>
<td>Electrons in shells</td>
<td>N</td>
</tr>
<tr>
<td>Certain number of n⁺ allowed in each shell</td>
<td>N</td>
</tr>
</tbody>
</table>

Electrons in cloud 'bounding around'

Nucleus contains positively charged protons and neutral neutrons

Figure 3.3 Coding example

Source: Adapted from Stevens, Delgado, and Krajczik, 2009

100 per cent of the data. A second independent rater coded 10 per cent of the data that was selected at random. We achieved a correlation greater than 95 per cent between the two raters.

Data analysis and results

We performed a Guttman analysis (Guttman, 1944) to characterize how students typically develop ideas related to the construct. First, we grouped the individual facets into the original unpacking of the construct and then we sorted the coded data using a Guttman scale. As shown in Figure 3.4, a progression consists of six progressive levels of facets including ABCDEFG. The scale illustrates that a student who understands D also understands ideas A, B, and C, but not necessarily E or F. The scale structure can be used to describe the progression of how students' understanding develops.

For testing the significance of each level along the Guttman scale, we used the McNemar test of 2 x 2 tables using the MH Programme (Uebensax, 2006). The McNemar technique provides a simple way to test marginal homogeneity, which implies that row totals are equal to the corresponding column totals. In this study, a statistically significant difference indicates an ordered connection. In Figure 3.4b, 17 students understand B and C, one student discussed C but not B, nine students discussed B but not C, and eight students discussed neither. The McNemar test showed a significant difference for the step from B to C at p = 0.0114, suggesting that this is an ordered connection. In contrast, the step between D to E did not show a statistically significant difference, which indicates that the step is not an ordered connection (see Figure 3.4).

The resulting scales provide information about how students develop understanding of the constructs. For instance, Table 3.3 illustrates how students do not move directly (and cleanly) from Level One to Level Two of the LP for the atomic structure construct. Instead, they often have incomplete knowledge of the composition and basic structure of an atom.

The development of an empirical progression that describes how students may develop understanding of the assessed concepts is an important part of the empirical testing and revision of a LP. It is important to realize that this first empirical progression describes the state of student learning using current instructional materials. However, it does not tell us what might be possible given better designed materials. In subsequent iterations, when the LP is being empirically tested using instructional materials designed to support the learning described by the LP, the empirical progression will inform the revision of the LP and associated instructional materials.

The empirical progression also provides some insight into instructional strategies that might help students move along the LP by identifying difficulties and alternative ideas students may have regarding the content (for example, see Table 3.4). Understanding students' ideas is critical in the development of instructional materials and in determining when and how it might be appropriate to introduce the concepts to students. In addition, knowledge of student misconceptions aids the development of assessments that measure students' progress in understanding the ideas in the LP.
### Table 3.4 Example of potential instructional strategies to help students move along the learning progression

<table>
<thead>
<tr>
<th>Level</th>
<th>Potential instructional strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four</td>
<td>Link the quantum effects to more familiar phenomena in addition to or in lieu of the historical phenomena (e.g., conductive to insulator transition vs. photoelectric effect).</td>
</tr>
<tr>
<td>Three</td>
<td>Both the solar system, or Bohr model and the electron cloud model of the atom should be introduced, but with an emphasis on the fact that each are models and that each can or are better for explaining certain phenomena than the other. Students should be able to apply each model of atomic structure to explain phenomena (e.g., properties of many types of materials and trends of the Periodic Table and justify their choice.</td>
</tr>
</tbody>
</table>
| Two   | The exploration and characterization of chemical reactions creates a need for students to develop an understanding of elements and the Periodic Table, which in turn drives a need to develop a model of atomic structure that allows them to answer questions such as:  
- What is different about each element?  
- Why is it that atoms of certain elements combine and others do not?  
- Why do elements combine in only certain combinations?  

The idea that atomic structure is described through models, and the nature of models, should be emphasized. |
| One   | Develop students' knowledge and skills about modeling with a focus on connecting the macroscale and atomic scale to explain a range of familiar phenomena (e.g., smells traveling across the room and phase changes).  

Do not introduce the details of atomic structure. |

### Source:
Adapted from Stevens, Delgado, and Krajcik, 2009

### Refining and empirically testing the learning progressions

Following the CCD process, we developed two products, including an LP and an interview protocol. For each of the steps of this iterative process, the products are reviewed internally. The interview protocol and LP are revised to better characterize student understanding of the construct, based upon the iterative review and revision of the claims and evidence and multiple rounds of student interviews. The next step of CCD is to have external review of the LP, followed by the empirical testing. This requires the development of instructional materials based upon the strategies outlined in the LP, followed by field trials, including pilot and classroom tests in order to iteratively refine the LP.

An important characteristic of LPs is that students may follow different possible pathways 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, they may thrive in different environments. Thus, in order to refine and test LPs, empirical data should be collected from students who have experienced curriculum materials that were developed following LPs. Since the position of students along the progression is significantly influenced by the previous instruction that students received (Cobb and Bowers, 1999), students must have appropriate learning experiences with an exemplary curriculum that help them make connections among the ideas to develop integrated understanding of a topic described by an LP. This helps us to make sure that students' poor understanding is not because of a lack of appropriate learning experiences, but because of the developmentally challenging ideas to the students. Thus, well-developed, coherent curriculum...
materials based on an LP should be designed, implemented, and tested iteratively throughout the process of empirically testing and refining an LP.

A longitudinal study is the ideal way to empirically test and refine learning paths of an LP. However, a more realistic way of empirically testing an LP is through testing a series of smaller pieces of the LP. The use of relatively large grain-sized LPs, as proposed by Smith and colleagues, helps define and organize the important concepts in a core idea and is therefore a useful first step in the development of a coherent curriculum (see Figure 3.5a). Testing the LPs empirically requires an instructional sequence that describes how to support students in developing understanding of a portion of the LP. One or several learning goals may describe how students can progress between the levels of the LP (see Figure 3.5b). Based upon these learning goals, instructional materials and assessment are developed to follow how students develop understanding of key concepts of the learning goals in the course of instruction.

The instructional sequences should also be developed following the CCD process. A series of learning goals that will help students to develop the desired understanding should be carefully defined. The learning goals are then unpacked to specify the content students are to learn, the difficulties they may have learning the content, and any alternative ideas they may have related to the content. A set of claims and the corresponding evidence is developed based upon the unpacking. In turn, the claims and evidence guide the design of learning tasks and instruction and associated assessment tasks. In order to empirically test the LP, assessment items that are independent of the instructional materials are developed. The CCD process is also used to develop assessment items that place students along the LP. Thus, the same design model is used for all phases of the development, refinement, and empirical testing of this complex research product: the LP.

Conclusion

A number of learning scientists have discussed the value of a research program that is iterative, process-oriented, and involves designing products that work in real contexts that extend our understandings of the nature and condition of learning and development, as well as promote student learning (Barab and Squire, 2004; Brown, 1992; Collins, Joseph, and Bielaczyc, 2004). The typical strategy for this type of learning research employs naturalistic methodologies to investigate how learning occurs and the product development process for building evidence-based claims (Barab and Squire, 2004).

A fundamental challenge for such research is the extensive quantity of qualitative and quantitative data that must be collected and organized in order to provide appropriate evidence to support the research claims (Collins, Joseph, and Bielaczyc, 2004). Based on our previous work, we believe that CCD can become a valuable methodology for learning research that may overcome this challenge. In particular, the CCD approach focuses on clearly defining the construct to focus the research and development strategies. Another critical characteristic of CCD is the explicitly specified evidence based on the unpacking of the construct that links directly to the claims. Specifying the claims and evidence supports the development and alignment of a range of products. Following the systematic process outlined by CCD provides guidance for the collection and organization of data by defining what data are essential for supporting the claims. The CCD process ensures that the design of research and development products is generated in a credible and principled way to meet the needs of learning research and classrooms.

In summary, the CCD approach extracts and expands aspects of the LGD (Krajcik, McNeill, and Reiser, 2008) and ECD (Mislevy and Riconscente, 2005) design frameworks to provide a research methodology for aligning learning research and development. CCD is a flexible process that can support a broad range of complex design research and development products, such as the development, refinement, and empirical testing of LPs, as illustrated in this chapter. As such, CCD provides an important methodology for other researchers interested in developing LPs. Because CCD is a new approach, it can be considered as a component of an iterative development process that is constantly being refined and revised to accommodate the needs of learning researchers. We still have much work to accomplish to make CCD a usable methodology for other researchers. We need to further develop the guidelines and examples for each step of CCD to provide guidance on how researchers can use CCD to accomplish a variety of design-based research goals. To do this, researchers need to apply the CCD process to design various research, instructional materials, learning progressions, and
assessments tasks in order to articulate the subcomponents of the various CCD steps more clearly. As we and other researcher use CCD to guide a greater number of research and development products, the process will become better articulated. Design research, along with developing instructional materials, instruction, and assessment, are challenging and time-consuming work. However, if we hope to make progress on promoting the development of meaningful learning, we need to undertake complex research and development.

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References

Chapter 4

Analysis of interview data using the constant comparative analysis method

Nicos Valanides

The purpose of this chapter is to show how qualitative data can be dissected, conceptualized, and put back together in new ways, using the constant comparative analysis method (CCAM) or grounded theory (GT). The different coding procedure steps, which constitute the heart of the method, will be described and exemplified. In addition, appropriate ways of quantifying the qualitative data for statistical analyses will be also presented. For this purpose, we use interview data generated by primary school children as they investigated the functioning of a device. The interviews adopted the ‘think aloud’ technique and the interviews were tape-recorded and transcribed later. Using the CCAM scoring, rubrics were developed for identified variables and their constituent parameters.

Constant comparative analysis method

Glaser and Strauss (1967) developed the constant comparative analysis method (CCAM) or grounded theory (GT). It is a methodological approach that follows a cyclical process of induction, deduction, and verification and a set of specific strategies for analyzing qualitative data, such as interviews, that can improve not only the reliability of the data, but also the theoretical depth of analysis. The CCAM involves inductive category coding and comparison of observed behaviours across categories (Goetz and LeCompte, 1981). As a consequence of this categorization, patterns are gradually revealed and constantly refined throughout the data collection and analysis process (Dye, Scharz, Rosenberg, and Coleman, 2000). Glaser and Strauss (1967) describe the constant comparison method as following four distinct stages:

1. comparing incidents applicable to each category;
2. integrating categories and their properties;
3. delimiting the theory;
4. writing the theory.

CCAM (or GT) is not a descriptive method because it attempts to extend beyond any accurate description of a set of data. CCAM attempts to generate...