Chapter 18
Development of Understanding in Chemistry

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1 Introduction

Considerable research in science education in Europe and the United States (USA) in recent years has been focused on studying how students' understandings of core ideas in science develop over time. This work goes by many names, including "learning progressions" and "learning trajectories" in the USA and "teaching sequences" and "teaching experiments" in Europe. In this chapter, we mostly consider work associated with the "learning progressions" perspective. Learning progressions (LPs) describe successively more sophisticated ways of thinking about a topic (Corcoran et al. 2009; NRC 2007) and are based on research about how people learn as well as on the critical analysis of the structure of the associated disciplinary

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knowledge. To date, educational researchers have developed LPs in science for diverse topics such as atomic-molecular structure (Smith et al. 2006), properties of matter (Smith et al. 1985), carbon cycling (Mohan et al. 2009), and force and motion (Alonzo and Steedle 2009). Much current thought on LPs is collected in a recent volume (Alonzo and Gotwals 2012). However, there is still ample debate on issues such as what constitutes progress in a given area (Foster and Wiser 2012), how more sophisticated ways of thinking are characterized (Mohan and Plummer 2012), and whether progress can adequately be described as a series of successive levels of understanding (Sikorski and Hammer 2010). There are also discussions about how to apply findings from LP research to the development of standards (Foster and Wiser 2012), to curriculum development (Wiser et al. 2012), and to assessment design (Alonzo and Gotwals 2012).

The promise of LPs lies in the potential to guide the coordination of teaching practices, instructional resources, and assessment tools with students' cognitive, metacognitive, and sociocultural resources so that learning builds coherently. However, much work needs to be done to fulfill such promise. Thus, in this chapter we highlight critical issues in the development of LPs that can actually serve as effective curriculum models and assessment frameworks in the teaching of chemistry across educational levels and in diverse contexts. In particular, we underscore the need for better understanding (a) how students' reasoning evolves with training in the discipline, (b) what assessment frameworks can better uncover actual progression in understanding central concepts and ideas, and (c) what instructional sequences are likely to foster development of more sophisticated ways of thinking about core topics. To frame these discussions, in the following section we analyze critical aspects of recent research in the area of LPs in chemistry.

2 Learning Progressions

A recent paper by Duschl et al. (2011) provides an analytical review of LP research in science education, with connections to learning trajectories work in mathematics education, across work occurring in the USA and Europe over the past decades. This comprehensive review focused on how LPs are being created and how they are being validated and described. In particular, the authors isolate four major aspects in which existing LPs tend to vary.

First, Duschl et al. find that LPs tend to focus either on scientific knowledge without integrating science practices or on science practices without integrating domain knowledge. Where there is integration between concepts and practices, there is variation as to how LPs are constructed. Some LPs treat concepts and practices separately and then merge the two; a second set stresses science content over practices, while a third strand embeds or situates science practices into domain-specific contexts.

Second, Duschl et al. find that how lower and upper levels or stages of an LP (also called the lower and upper anchors) are defined tend to vary. The idea of lower and upper levels is based upon research on the differences of expert and novices. While some LPs provide explicit definitions of a lower anchor (novice), others do so more implicitly. For example, lower anchors may be expressed as descriptions of students' intuitive accounts of familiar events. Upper anchors of LPs are defined more clearly in most LP work, corresponding to descriptions of scientific knowledge and practices that students are expected to master.

A third variation in LPs relates to how intermediate levels of understanding are studied, described, and related to instruction. Some authors, for example, describe intermediate levels as a linear sequence of steps somewhat disconnected from instruction (Alonzo and Steedle 2009). In other cases, intermediate levels are described as "stepping stones" in students' learning which represent productive ways of thinking that may support important reconceptualizations with proper instruction (Smith et al. 2010).

Finally, the fourth variation identified by Duschl et al. refers to the explicit or implicit model of conceptual change associated with the LP. In particular, the authors describe two classes of conceptual change models, which they identify as the misconception-based "fix it" view and the "work with it" view. These two classes correspond to two types of LPs described by the same authors: validation LPs, which tend to view learning as a linear and rather predetermined path toward canonical forms of scientific understanding, and evolutionary LPs, which conceptualize learning as developing productive networks of conceptual knowledge. Lower and intermediate levels of progression in validation LPs often seek to elicit and confront students' misconceptions, while evolutionary LPs seek to identify productive ideas or ways of reasoning that can be used to bolster meaning making.

In addition to the characterization by Duschl et al. (2011), other attempts to describe differences among approaches to developing LPs exist. Furtak (2009) observed two types of LPs: Type 1 are sequences of correct ideas organized in a logical order deriving from consultation with experts and/or standards documents, and Type 2 are maps of student ideas bounded by naïve pre-instructional ideas about the natural world on the lower end and by scientifically accepted explanations on the upper end. Wiser et al. (2013) described two views of LPs in terms of their "knowledge paths" based on how they use empirical data on students' ideas and what students can do and by the relationships between the knowledge paths and curriculum. The first view is based on cross-sectional studies of students of assessment data, without establishing a relationship to curricula. For example, Liu and Lesniak (2005) analyzed responses to TIMSS items that assess students' understandings of different aspects of matter – structure, conservation, and change – to identify waves of understanding in students as they progress from grade 3 to 12. The second view includes relating students' beliefs longitudinally to the curriculum that students are experiencing and seeks to uncover paths of learning as series of conceptual changes bringing students' structures of knowledge more in line with scientific theories. The primary difference between these two views, then, is the question of whether LPs and curricula are distinguishable.

Our view is that LPs cannot exist outside of the conditions of student learning. However, we recognize that LP research is complex and demands comprehensive attention over long periods of time. Thus, there are multiple entry points to the development of an LP, as exemplified by existing investigations on LPs for different topics in chemistry such as atomic-molecular structure (Smith et al. 2006), properties of matter (Smith et al. 1985), the concept of substance (Johnson and Tymms 2011), and the nature of matter (Stevens et al. 2010). In this chapter, we seek to contribute to the knowledge base in the field by describing three particular approaches to the development of LPs in chemistry that emphasize different aspects of learning and teaching. The first of these approaches highlights the need for better characterizing how implicit cognitive constraints may guide and limit student reasoning at different learning stages. The second approach stresses the importance of developing a coherent content framework to track progression in conceptual understanding. The third approach challenges the dominant content-focus view in LP research by concentrating attention on instruction that motivates and engages students in purposeful activity in relevant contexts. All three approaches can lead to LPs that describe pathways of how student understanding develops over time and the conditions that optimize students' progression through these pathways. All three approaches require assessment of student understanding as part of iterative cycles of validation of the LP, moving from hypothesis of the LP, to assessment of student understanding, to interpretation of student data that revises the LP.

3 Mapping Cognitive Constraints

The development of LPs could be facilitated if we had a more extensive and thorough understanding of how students' ideas and ways of reasoning are likely to evolve with training in a discipline. Talanquer (2006, 2009) has proposed that student reasoning in chemistry seems to be guided by implicit assumptions about the nature of chemical substances and processes. These assumptions act as cognitive constraints that guide and support but also limit student reasoning. Specifically, cognitive constraints help students make decisions about what behaviors are possible or not and about what variables are most relevant in determining behavior. These constraining ideas also support the development and application of dynamic mental models of systems of interest.

A variety of researchers have identified diverse implicit cognitive elements that seem to guide, but also constrain, students' reasoning in different domains. They have referred to them in different ways, such as implicit presuppositions (Vosniadou 1994), ontological beliefs (Chi 2008), and phenomenological primitives (diSessa 1993). However, there is considerable debate on the extent to which these types of cognitive elements form coherent integrated knowledge systems or more fragmented collections of cognitive resources. It is likely that their level of integration may vary depending on the nature of the knowledge domain and the prior knowledge and experiences of each individual. The nature of constraining cognitive elements can be expected to change over time with development and learning; some of these constraints may lose or gain strength depending on existing knowledge and perceived salient cues and goals of a task. From this perspective, defining progress in understanding, or LPs, may be facilitated by first mapping the landscape of cognitive constraints that most commonly guide student reasoning when engaged in learning a given topic.

3.1 Goals and Methodology

In recent years, Talanquer (2006, 2008, 2009) and colleagues (Maeyer and Talanquer 2010) have carried out research guided by the following overarching questions:

- What central assumptions and reasoning strategies constrain students' ideas and reasoning about chemical entities at various learning stages?
- What does this set of cognitive constraints reveal about characteristic LPs for core chemical ideas and ways of thinking?

The search for answers to these questions has been pursued using different research strategies that include analysis of prior research studies in the field, paying particular attention to longitudinal and cohort studies that explore students' ideas at various grade levels, open questionnaires, and individual interviews. These latter research projects have involved college students enrolled in first- and second-year chemistry courses. In general, data analysis has used iterative constant comparison methods in which common assumptions and reasoning strategies are identified within each question or interview task. The analytical process seeks to identify (a) types of agents invoked in building explanation or making predictions (e.g., active, passive), (b) types of properties noted (e.g., compositional cues, explicit structural factors, implicit molecular properties), (c) explanatory mechanisms indicated (e.g., centralized causal, teleological), and (d) conditions judged to be relevant in explaining properties and behavior (e.g., external vs. internal factors, single vs. multiple variables). These different elements are used to build hypotheses about core implicit assumptions and reasoning strategies underlying students' explanations and predictions.

3.2 Illustrative Findings

To illustrate results generated by the studies described above, Table 18.1 summarizes some of the core implicit assumptions derived from the analysis of students' alternative conceptions about the structure of matter (Talanquer 2009). The assumptions are arranged along different dimensions (e.g., properties, structure) to indicate the possibility of semi-independent evolution with learning or development. Although the representation is linear, it does not imply that learning follows a linear path, that all individuals move sequentially through every stage, or that old assumptions fully replace new ones. The representation implies, for example, that naïve chemistry students can be expected to think of a piece of matter as a "continuous" medium that can be divided into smaller pieces that have the same properties as the original part ("inheritance" assumption). With training in the discipline, many students begin to assume that a substance is made of a collection of particles ("corpuscularity") embedded in some sort of material medium ("embedding" assumption), but many of them still consider that these particles have the same properties as the macroscopic sample.

Table 18.1 Progression of a subset of implicit assumptions that seem to constrain student reasoning about the structure of matter at different learning stages (Talanquer 2009)

Dimension	Progression			
	Naïve	*Novice*		*Expert*
Structure	Continuity	Granularity Embedding		Corpuscularity Vacuum
Properties	Inheritance			Emergence
Dynamics	Static	Causal-Dynamic	Contingent-Dynamic	Intrínsic-Dynamic

In general, the results of these types of investigations suggest that students' ideas about chemical entities are constrained by sets of implicit assumptions that evolve with learning by addition, coalescence, differentiation, and reorganization of the core elements. Although many implicit assumptions seem to be interrelated, some of them lose or gain strength independently from one another (with age and experience some assumptions may be activated more or less frequently). Overlapping or competing assumptions about the properties of chemical substances and processes are able to coexist at any given time, particularly at intermediate learning stages. The activation of certain cognitive constraints seems to be highly dependent on judgments of similarity among systems or tasks, cognitive availability, and framing of the task based on salient cues and perceived goals.

3.3 Application

The analysis of students' assumptions and reasoning strategies about chemical entities and processes indicates that it is possible to identify a number of cognitive constraints that seem to guide student thinking in different areas and learning stages. Constraint maps, such as that illustrated in Table 18.1, can then be used to design assessment instruments to diagnose and place students along the different dimensions in the progression and also to revise the framing of the LP. As an example, Stains et al. (2011) have applied this cognitive framework to the development and validation of a survey, the Structure and Motion of Matter (SAMM) survey, designed to assess students' understanding of diffusion. Data collected from 485 students from grade 8 (age 13) to upper-level undergraduate (fourth year of university) indicate that an approach based in the identification of implicit assumptions is fruitful in characterizing progression in understanding along three relevant progress variables: (1) structure of solute and solvent substances in a gas solution, (2) origin of the motion of gaseous solute particles, and (3) nature of particle trajectories (Sevian and Stains 2013). As students apply underlying assumptions to the phenomenon of diffusion in a gas, the first progress variable appears to depend on assumptions in the structure dimension (see Table 18.1), the second upon assumptions in the dynamics dimension, and the third upon combinations of assumptions in both dimensions. However, these studies also underscore the complexity of tracking the evolution of students' ideas across many grade levels, in diverse school contexts, and with different curricula. For example, grade 8 students learning through a half-year curriculum that required them to reason using more sophisticated assumptions about structure, but not about dynamics, consistently demonstrated thinking patterns in the first and third progress variables that were more advanced than those expressed by students at grades 9–12 and university levels in which the curriculum did not explicitly require reasoning using sophisticated assumptions about structure.

4 Assessing Conceptual Progression

The development of LPs also requires the creation of coherent content frameworks to track progression in conceptual understanding. Such was the goal of the ChemQuery assessment system developed to measure and describe how students learn chemistry around the big ideas in the discipline (Claesgens et al. 2009). This project led to the development of the "Perspectives of Chemists" framework, which is built on the theoretical idea that school chemistry is largely based on three core conceptions: *matter* (matter is composed of atoms arranged in various ways), *change* (change is associated with rearrangements of atoms), and *energy* (energy is associated with changes that occur). In terms of measurement, these conceptions are considered progress variables that help characterize how far students progress in their conceptual understanding of a topic. The framework then can be used to (i) measure students' understandings in reliable and valid ways, (ii) explicitly identify relationships between the explanatory models that facilitate student understanding in chemistry and discrete standards that instructors must teach, (iii) make the goals of instruction clear enough to facilitate students' participation in regulating their own understanding, and (iv) yield information helpful to understanding how pacing, sequence, and structure of learning activities might improve student-learning outcomes.

4.1 Goals, Methodology, and Framework

The Perspectives of Chemists framework focuses on describing and mapping student conceptual understanding in chemistry. The goals are to describe what chemistry students actually learn at different educational stages and to characterize what successful learning looks like. The approach to assessment and measurement is comprised of various steps and methods. The process begins with qualitative analysis of student work through classroom observations, cognitive task analysis, and phenomenography, to elicit patterns in student response data. Scoring and quantitative data are then used to reveal additional complexity in student learning. These areas of complexity are further explored using qualitative research methods such as interviewing, verbal protocol analysis, and continued classroom observations. The approach to measurement is based on a partial credit item response that generates validity and reliability evidence, as well as estimates of how precise a student score is likely to be (Claesgens et al. 2009).

The Perspectives of Chemists framework emerged from many iterative rounds of qualitative and quantitative data collection, analysis, and interpretation of findings by groups of experts. During this process, patterns in student responses were identified, and answers were grouped to reflect similarities in thinking approaches and strategies. Construction of performance levels for different progress variables followed a generalizable pattern somewhat similar to concepts associated with the SOLO taxonomy (Biggs and Collis 1982). This taxonomy allocates student responses on assessment tasks to a hierarchy of stages. In the case of the Perspectives of Chemists framework, it included five levels:

1. *Prestructural*: Student answer is an irrelevant response to the assessment task.
2. *Unistructural*: Student response focuses on a single aspect of the information available.
3. *Multistructural*: Student response uses multiple aspects of the information available.
4. *Relational*: Student takes the information available and relates it to aspects of external information in one or more other structures, schemas, or scripts.
5. *Extended abstract*: Student response draws on and relates structures to additional information and concepts.

The ChemQuery assessment system developed as part of the research project consists of detailed descriptions of the progress variables and a scale of progression in understanding across each variable, illustrated in Table 18.2 for the “matter” variable. The system includes over 20 open-ended items associated with each progress variable, scoring rubrics, and item exemplars (Scalise et al. 2006). This system has been used to map student performance in chemistry across high school and university levels. Data were collected from 418 high school students (ages 14–17) after 1 year of chemistry instruction and from 116 university students (ages 18–20) after they completed college-level introductory chemistry. In the following subsection, results of applying this approach to the development of progression along the “matter” variable are summarized.

4.2 Summary of Results

The application of the Perspectives of Chemists framework revealed that most high school students in the sample were moving from a “notions” level as described in Table 18.2 to beginning to describe and explain properties of matter at a particulate

Table 18.2 Assessment framework: perspectives of chemists on "matter"

Levels (low to high)	Essential questions and big ideas	Description of level	Examples
1. Notions	*What do you know about matter*? Matter has mass and takes up space. It can be classified according to how it occupies space	Students articulate their ideas about *matter* and use prior experiences, observations, logical reasoning, and knowledge to provide evidence for their ideas. The focus is largely on *macroscopic* descriptions of *matter*	Students describe and explain materials or activity based on observable properties
2. Recognition	*How do chemists describe matter*? Matter is categorized and described by various types of subatomic particles, atoms, ions, and molecules	Students begin to explore language used by chemists to describe matter. They relate *atomic structure* and *motion* to *composition* and *phase*. Ways of thinking about matter are limited to relating one idea to another at a simplistic level of understanding	Students represent matter through arrangements of atoms as discrete particles
3. Formulation	*How can we think about interactions between atoms*? Composition, structure, and properties of matter are related to how electrons are distributed among atoms	Students are developing more coherent understanding that matter is made of *particles* and the *arrangements* of *particles* relate to *properties of matter*. Student reasoning is limited to causal instead of explanatory mechanisms	Students recognize that matter has characteristic properties due to the arrangement of atoms into molecules and compounds
4. Construction	*How can we understand composition*, *structure*, *properties*, *and amounts*? Structure and properties of matter are explained by varying strengths of interactions between particles and by particle motion	Students reason using normative *models* of chemistry and use these models to *explain* and *analyze* the *phase*, *composition*, and *properties of matter*. They use appropriate chemistry models in explanations and understand assumptions used to construct the models	Students explain molecular behavior and properties in terms of stability and energies involved in intra- and intermolecular bonding
5. Generation	*What new experiments can we design to gain a deeper understanding of matter*? Bonding models are used as foundation for the generation of new knowledge	Students are becoming experts as they gain proficiency in generating new understanding of *complex systems* through the development of new instruments and new experiments	Students design experiments to explore the structure-property relationships in macromolecular systems

level (Claesgens et al. 2009). For example, many students were starting to relate numbers of electrons, protons, and neutrons to atomic properties (e.g., identity, mass) and arrangements and motions of atoms to phase behavior. In general, high school students could articulate their ideas of matter, using prior experiences and logical reasoning to justify their thinking, but much of the evidence they provided was out of scope, off-topic, or distant from normative models of chemistry. Many students seemed to answer questions and solve problem based on hybrid mental models that merged learned chemistry concepts with intuitive understandings about chemical systems.

The results of the field study indicated that after 1 year of high school and 1 year of college chemistry, most university students scored in the range of recognition of basic models of matter (upper region of Level 2 and lower region of Level 3 in Table 18.2). Only a small fraction of students demonstrated sound conceptual understanding of multi-relational interactions in chemical systems and ability to generate accurate causal mechanisms. Many college students tended to overgeneralize the application of concepts and ideas as they engaged in problem-solving. These results indicate that many students at this level should not be expected to effectively build models relating physical and chemical properties to molecular structure (Formulation level in Table 18.2).

4.3 Conclusions and Implications

The Perspectives of Chemists framework is an illustration of how a generalizable conceptual construct calibrated with item response modeling can be used to characterize progress in the understanding of core ideas in chemistry. The described approach can be used to reliably measure student learning conceived not simply as a matter of acquiring more knowledge and skills, but as progress toward higher levels of competence and knowledge integration. The results suggest that it takes substantial time for students to achieve conceptual understanding of chemistry. However, many students seem to be able to significantly improve their thinking given time and opportunity. This progress seems to require extensive opportunities to explore, use, and recreate the language and models of chemistry. Understanding how students transition between different levels along each progress variable may help us identify more effective instructional strategies that support student learning by taking advantage of the somewhat incorrect, but often productive ways of reasoning that many students develop.

5 Engaging in Purposeful Activity

LPs are frequently conceived as descriptions of progression of conceptual understanding toward specified big ideas (upper anchors) over extended periods of time. Many studies in this area seem then to be constrained by the following assumptions:

- LPs are to be considered through a lens of development of conceptual understanding.

- Teaching influences the development of conceptual understanding by carefully planned confrontation with a certain sequence of pre-established concepts.

However, it could be argued that there may be alternative guiding premises for the elaboration of LPs. In particular, one could assume that:

- LPs should be considered through a lens of development *in activity*.
- Teaching influences the development of conceptual understanding by carefully planned confrontation with a certain sequence of *types of activity*.

In this section we elaborate on this alternative conceptualization to the development of LPs.

5.1 Activity as a Basis for Learning

Conventional LPs tend to pay close attention to the sequencing of concepts and ideas from more simple to more complex. For example within the area of "matter and materials," a suggested LP may start by focusing on understanding what objects are and then proceed to substances, to elements, and then introduce modeling using the particulate model of matter. Both the content-focused tradition, which pays close attention to the conceptual "architecture" of expert understanding, as well as the cognition-focused tradition, which attends to the cognitive "architecture" of the mind of learners, tend to prioritize the learning of content. Instructional planning under these educational paradigms focuses thus on the analysis of whether component X of the targeted content area should be taught before or after component Y. However, this approach to the development of LPs does not create opportunities for learning to be regulated by the students' own motives. In this regard, context-based approaches to chemistry education (Gilbert 2006) may provide insights into how to open spaces for student self-regulation of their own learning progress. A key element in context-based approaches to teaching and learning is the engagement of the learner in purposeful activity. Luntley (2008) describes this as follows:

> We need a notion of a kind of purposeful activity with respect to things that … captures the idea that [a] subject is putting her life in order in acting with respect to X and yet lacks concepts for discriminating X. If both conditions are met [purposeful activity with respect to X and the lack of concept X], there will then be scope for explaining the conceptual development of acquiring a concept for X out of this more basis purposeful activity. (Luntley 2008, p. 7)

This way of describing conceptual development stresses the idea that it is the motives, the affective components, the purposefulness, and the usefulness of an activity (as behavioral environment) that drive the progression of learning.

5.2 LPs as a Sequence of Purposeful Activities

According to activity theory, activity is a cultural-historical phenomenon in which human beings master their world by purposefully changing natural and social reality (Vygotsky 1978). In order to observe progression in learning over a certain time span, there needs to be a motive for this progression. Involvement and meaningful participation in purposeful activity is a critical condition for learning (Luntley 2008). From this perspective, one can argue that the planning of learning tasks should be situated within authentic social activity (Bulte et al. 2006; Gilbert 2006, Gilbert et al. 2011). Consequently, LPs should require student involvement in different types of activities with increasing levels of complexity, mimicking authentic human practices in a way that acknowledges what lies within the students' zone of proximal development.

If an activity as focal event can successfully serve as a context for learning, we should identify authentic practices within each discipline that can be adapted for educational purposes. Then, we need to sequence such activities in such a way that progression in learning can take place over time with a clear purpose and direction. Given the focus of this chapter, let us consider how one could accomplish such task in the case of teaching and learning chemistry, from primary education until the level of tertiary education.

In our complex societies, chemists engage in different types of activities, including production of food and goods, evaluation of the quality of such products, and conceptual design of new substances and processes. These can be characterized by a set of actions in diverse behavioral environments. Engaging in the activities requires developing understanding about the composition and behavior of chemical substances and processes. How could students be engaged in these types of activities to help them develop more complex or sophisticated ways of understanding? For example, one could propose the following progression:

A. *Production*: At a first level, one could work with students guided by the overarching idea that in our society we deal with all kinds of consumer products: foods and goods. Within this scenario, a variety of essential questions could be posed: What are these products good for? What are they made of? Looking for answers to such questions opens a path for constructing central ideas about *objects and materials*.
B. *Evaluation of quality*: In a next stage, the following questions may be posed: What is the quality of these products? What does it take to evaluate whether a product is good for use or consumption? Answers to these questions could be explored in different relevant contexts such as evaluating the quality of products for personal hygiene. While engaged in these activities, discussions could focus on identifying the main components of a product or on quantifying their amounts. Central ideas about chemical composition in terms of *substances and mixtures* and *elements and compounds* could come into focus for students to make sense of practical activity at this level.
C. *Conceptual design*: The evaluation of the quality of chemical products could naturally lead students to wonder about issues related to the synthesis of new substances and the production of materials. Questions such as "How is this product made?" and "How do we prepare an alternative product that better satisfies our quality criteria?" could help engage students in a next set of activities

involving the design of desired products. For example, the cleaning agents for a shampoo or a washing powder. At this stage, concepts and ideas related to the *atomic-molecular theory of matter* come into focus as powerful tools for explanation, prediction, and decision making.

D. *Research/inquiry*: The proposed sequence of activities would gradually lead to analysis of difficulties that chemists encounter to accomplish their goals: What if we cannot synthesize what we want? What if we need to explore new types of chemical substances or alternative synthetic routes? These questions could be used to motivate students to become involved in research projects that demand the development of *models* and engagement in *scientific argumentation*.

The sequences and examples of activities described above exemplify how to enact LPs through a lens of development in activity and how to facilitate the development of conceptual understanding by carefully planned confrontation with a certain sequence of types of activities. While we do not report here on results of using this approach to elucidate an LP, other studies that approach LP research through designing purposeful activities that deliberately promote a particular sequence of reconceptualizations have done so (e.g., Wiser et al. 2013).

6 Final Comments

The research endeavors described above highlight different critical aspects in the research and development of LPs. First, there is a call to more thoroughly understand implicit cognitive elements that may constrain student reasoning at different stages in development and training in a domain. The construction of detailed constraint maps like those described in Sect. 3 has proven to be useful in the design of assessment instruments that effectively diagnose students' places along a given progression. Second, there is an invitation to more clearly define and characterize what it means to advance in conceptual understanding of big ideas in a discipline. These conceptual frameworks are needed to generate coherent assessment systems that can be used to map student performance across different educational levels. Finally, there is a call to review and expand current conceptualizations of LPs to recognize the central role that engagement in purposeful activity plays in the development of meaningful understandings. From this perspective, the separation that is frequently made between learning and instruction in current LP research needs to be challenged.

Although very different in their perspectives, the three approaches to LP work described in this chapter suggest a similar progression in the understanding of core ideas about the structure of matter. This progression is visualized in Table 18.1 (Sect. 3), in the assessment framework presented in Table 18.2 (Sect. 4), and in the sequence of types of activities described in Sect. 5. In all these examples, student understanding moves from stages in which explanations and predictions are based on perceptive cues and macroscopic conceptualizations of matter, to levels in which macroscopic and particulate ideas are either merged or selectively used depending on the context, to stages in which properties, chemical entities, and processes are explained using atomic-molecular models of matter.

However, the three types of studies summarized in this chapter also elicit tensions to be navigated. The development of LPs demands the identification and definition of variables along which progress of learning can be characterized. These progress variables must be measurable. The three measurable progress variables described in Sect. 3 – structure, origin of motion, and particle trajectories – may or may not overlap well with the *matter* variable of Sect. 4. Additionally, how student understanding is intended to be measured in Sect. 3 differs from how it is measured in Sect. 4. To measure student understanding according to the LP described in Sect. 3, measurements must be designed to identify the implicit assumptions that guide student reasoning (e.g., Stains et al. 2011). However, in Sect. 4, assessment instruments are framed in terms of what students can do with their chemical knowledge (i.e., performance assessments).

The curriculum approach described in Sect. 5 provides students with purposeful practices through which they can reconceptualize their understanding. However, the opportunities for reconceptualization should ideally derive from the results of formative assessment employed by the teacher, as facilitator of student learning. Formative assessment derived from the LP study should provide the teacher with a means for creating learning opportunities that challenge students at the proper zone of proximal development. Thus, the development of teaching tools and strategies depends on the cognitive or conceptual framework that is used and on how student understanding is actually measured.

These different tensions raise a larger challenge: a need for better integration of different perspectives in the development of LPs. Attempts have been made to propose hypothetical LPs that merge findings from various LPs covering overlapping science content and age ranges (e.g., Rogat 2011). However, such a merger overlooks inconsistencies in theoretical assumptions about how cognitive constraints evolve, how students represent understanding, and how activity motivates students and fosters understanding and ability to use knowledge productively.

Notwithstanding the challenges involved, further understanding of students' development along LPs should inform the coordinated development of curricula and assessments that scaffold student learning in chemistry. Only then will LPs be more likely to achieve the promise of guiding the coordination of teaching, instructional resources, and assessment tools with students' cognitive and metacognitive resources so that learning builds coherently.

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