The Knowledge Integration Perspective: Connections Across Research and Education

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**Abstract.** This chapter highlights the knowledge integration perspective and its implications for education in light of connections to other research on conceptual change. We focus on synergies and affordances across perspectives to (a) better account for the data collected across studies in the conceptual change literature and (b) more fully consider their implications for learning and education. We outline our perspective on knowledge integration in light of core contemporary issues in conceptual change including knowledge structure coherence, learning trajectories, and curricular design. We also discuss implications for research and future investigations.

Introduction

Vosniadou et al. (2008) discuss intersections between their framework theory perspective and other conceptual change perspectives in their chapter from the first edition of this handbook. The current chapter builds on that excellent foundation by outlining and discussing our knowledge integration perspective in light of other elemental perspectives (that emphasize the diversity of student ideas) and framework theory perspectives (that emphasize the coherence of student ideas). The goal of this chapter, as with Vosniadou et al.’s original chapter, involves moving beyond a focus on differences between conceptual change perspectives to instead focus on similarities, synergies, and affordances in hopes of better addressing core theoretical and practical questions central to learning and education.

Knowledge Integration Perspective

An examination of the diverse, creative, and unique ideas that students formulate has led researchers to argue for a constructive process of knowledge generation and change. When students are asked to explain scientific phenomena in an abstract de-contextualized frame, they often respond quite differently from when asked to explain an observed phenomenon. Analyzing the conceptual change processes involves explaining how students take advantage of their ideas when they encounter a new situation. Students’ methods for grappling with new observations reveal that they engage in a creative process of trying to make sense of their world (Hatano & Inagaki, 2003).

Many researchers have focused on the diversity and character of student ideas. These ideas have been referred to as “misconceptions,” “alternative conceptions,” “beliefs,” “intuitive ideas,” and “constructed ideas.” Any theory of conceptual change needs to explain the emergence of these views, as well as their role in conceptual change. Researchers have compiled the varied ideas that students generate in a wide assortment of scientific domains (Pfundt & Duit, 1994). This large body of evidence has developed an image of students constructing multiple, contradictory, and fragmented ideas that stem from their interactions with the material and social world (Clark, 2006; diSessa, 1988; A. Howe, 2002; Linn & Hsi, 2000; Metz, 2000; Siegler, 1996). Many researchers have shown that the ideas students generate arise from observations, analogies with related events, cultural practices, or colloquial uses of language.

The knowledge integration perspective on conceptual change has emerged from a series of empirical studies. It was spurred by evidence of the impact of context on student reasoning (Linn, 1983). It celebrates the ideas students generate and views these ideas as intellectual accomplishments rather than intellectual constraints (Linn, 1995; Linn, Davis, & Bell, 2004; Linn & Hsi, 2000). Important evidence for this view comes from a longitudinal study carried out over five years that gives insight into student lifelong learning (Clark, 2006; Clark & Linn, 2003; Lewis 1996; Linn & Hsi, 2000).

This longitudinal study illustrated how students maintain conceptual ecologies involving multiple conceptual elements and ideas at various levels of sophistication, connection, and conflict. These conceptual elements and ideas include cultural and observational information and beliefs spanning both epistemological and ontological aspects of knowing and learning. Examples include, but are not limited to, nominal and committed facts, experiences, intuitive conceptions such as phenomenological primitives (diSessa, 1988), narratives, epistemological elements, mental models (Gentner & Stevens, 1983), and concepts (Carey, 1985) at various stages of development (Clark, 2006; Linn et al., 2004). As with Vosniadou et al.’s (2008) framework theory perspective and diSessa’s knowledge in pieces perspective (1988), the knowledge integration perspective acknowledges that ideas can be introduced (through schooling and other experiences) that result in fragmentation, conflicts between ideas, and/or synthetic models. Learning occurs through a process of restructuring and reorganizing new and existing ideas.

Our own work (Clark, 2006; Clark & Linn, 2003; Linn & Hsi, 2000) identifies these ideas through the explanations and causal descriptions that students express in interviews and other assessments (e.g., “metal things are colder than wood things” or “the metal attracts heat”). These explanations and causal descriptions point to underlying (although often unarticulated) views that shape students’ thinking, explanations, and predictions. Students use these multiple ideas to interpret the phenomena they encounter in their everyday lives. The particular ideas students consider and connect depend on contextual cues. Some connections arise from experience (e.g., metals feel cold), some connections are situation-specific and less broadly useful (e.g., cooling on the stove is different from heating), some are imported from another domain such as electricity and may or may not be useful or accurate in the new domain (e.g., glass is not a conductor of electricity so it will be a poor thermal conductor), and some have their roots in classroom instruction (e.g., metals have heavier molecules). Some connections that students make are spontaneous and ephemeral; some are much more durable and persistent. Some spontaneous ideas and connections may not persist beyond that occasion. Some ideas and connections become more established and strengthened over time, resulting in systematic predictions and explanations.

*Reorganizing and reconnecting ideas*

As students learn, they reorganize, reconnect, and sort through their ideas. Some ideas become central and pivotal as students use them as focal points around which to integrate other ideas, while other ideas are demoted in priority and centrality. Promoting ideas involves increasing the centrality of an idea in its connections to other ideas and across multiple contexts. Conversely, demoting involves decreasing the centrality of an idea in its connections to other ideas and contexts. Thus promoting and demoting involve creating and modifying connections as well as broadening or narrowing the reach of the idea. Promoting and demoting are similar to increasing and decreasing cueing and reliability priority (diSessa, 1988).

Students also combine and refine ideas between their conceptual ecologies. Integration involves creating or reinforcing the connection between two ideas (as when students identify insulation across materials). Coalescence involves a related process through which two ideas are actually merged (e.g., combining heating and cooling into a thermal equilibrium model.) Differentiation involves the reverse process, wherein one idea splits into distinct components (e.g., differentiating heat energy from temperature.) Students can also reassess and reanalyze ideas and their basic structure, as suggested by Carey (1985) with her example of Newton’s realization that weight is a relation between objects rather than the property of a single object. Not all integrations, coalescences, differentiations, and reassessments necessarily result in more normative accounts from a formal scientific perspective (e.g. students may argue that metal is an insulator and a conductor). Sometimes changes made to address a specific conflict (i.e., a conflict in the student’s repertoire within the given local context or explanation) may result in other local or global conflicts (i.e., a conflict between two or more ideas in a student’s repertoire that are not connected within the single local context). Local and global conflicts may or may not be recognized by the student.

*Distinguishing ideas to achieve coherent understanding*

The knowledge integration framework emphasizes creating opportunities for students to distinguish among their ideas to achieve conceptual change and coherent understanding. This process can be supported in students of all ages. Linn and Eylon (2011) describe a five-year-old making sense of ideas about dinosaurs. Researchers have shown that the ideas students articulate to make sense of school and everyday situations reflect their capability to sort out confusing observations, rather than illustrating developmental constraints (e.g., Gilbert & Boulter, 2000). For example, students often argue that metal must be a naturally “colder” material because metal feels cold at room temperature. These efforts can be seen as evidence for powerful reasoning ability that can be guided by instruction (e.g., diSessa, 2008; Linn & Hsi, 2000). More specifically, when students make an effort to sort out ideas, even if the view they formulate is not supported by all the empirical data, they are engaging in the sort of reasoning that can lead to understanding.

For example, we traced the progress of a student in one study who focused on holes in materials to explain insulation and conduction (Linn & Eylon, 1996). Initially this student argued that materials with holes are poor insulators, using evidence that heat can flow through openings like doors. In later interviews, this student noted that holes like those in sweaters may have a different role. The student mentioned that holes may trap air and thus offer insulation by saying, “air pockets make heat energy not go.” (Linn & Eylon, 1996, p. 599).

To promote productive distinguishing of ideas, students need to appreciate the connections among their ideas. When students distinguish between science class ideas and ideas developed by interacting with the world they may not recognize the connections (e.g., Gilbert & Boulter, 2000). This can occur when school ideas consist of abstract principles and formulas such as “objects in motion tend to remain in motion.” Curricula that do not provide much opportunity for students to explore how to use these abstract ideas in varied everyday problems can contribute to students’ propensity to separate school ideas from personal experience. And, in this case, to argue that, “objects in motion come to rest on the playing field.”

For example, many science courses define heat and temperature in terms of units of measurement (temperature as degrees on a thermometer and heat as calories) or in terms of molecular kinetics. Students rarely study how to explain situations such as wilderness survival, predicting and measuring the temperatures of metal and wood objects that feel differently at room temperature, or estimating the cooling curves for metal and pottery objects removed from a warming oven. As a result, students have no opportunities to reconcile abstract ideas with everyday situations. Furthermore, science courses typically spend little time on connections and self-monitoring. They often isolate topics using abstract definitions, rather than showing the benefit of explanations that connect topics. Thus, typical instruction may inadvertently deter students from using their reasoning abilities to link ideas and bridge disciplines (Linn & Hsi, 2000).

Lifelong learning requires that students extend scientific ideas to new situations and new science topics. For example, students might initially study energy in isolated areas – learning how plants get and use energy, how humans get and use energy, how energy is generated and used to power an automobile, or how energy is released in an earthquake. For many students, these are quite distinct domains that never get connected. Yet, sophisticated understanding of science requires combining these situations and developing a coherent or integrated view of concepts like the nature of matter, energy, or evolution. Designers of curricula can add effective ideas such as pivotal cases or intermediate models, as we discuss later, that may prove more tractable for integration with students’ everyday lives. These intermediate models can serve as a catalyst for connecting everyday and abstract formal ideas. For example, research shows that heat flow ideas were more generative for middle school students than molecular kinetics ideas for understanding thermal equilibrium, heating and cooling, insulation and conduction, direction of heat flow, and specific heat among middle school students (Linn & Muilenburg, 1996).

*Designing productive ideas*

Abstract scientific ideas have great power for experts wishing to organize their knowledge across varied contexts (Larkin & Reif, 1979). Efforts to identify ideas that play a similar role for students have demonstrated the value of pivotal cases or intermediate models that serve as a catalyst for connecting everyday and abstract formal ideas.

Studies demonstrate the importance of identifying pivotal cases to coalesce disparate ideas. These cases help students critique their own ideas and embrace normative views (Linn & Eylon, 2011). For example, to help students integrate the disparate idea that “metals feel cold so they must make things cold” with “metals are conductors,” one teacher added a pivotal idea comparing two contexts – the beach on a hot day and the mountains on a cold day. Students were asked to compare how metal and wood objects feel in those two contexts. This pivotal case helped students integrate their ideas about the conductivity of metal and wood objects because it drew on evidence from personal experience, involved a controlled experiment, could be easily discussed with other students, and involved two familiar contexts they did not spontaneously connect.

These findings reveal a promising approach for designing inquiry activities to promote knowledge integration (Linn & Eylon, 2011). To succeed, inquiry activities need four processes: First, elicit the ideas held by the student so they can be analyzed. Second, add well-designed normative ideas that form pivotal cases to stimulate comparisons among ideas and promote normative views. Third, encourage distinguishing among ideas using valid evidence. Finally, enable reflection on the repertoire of ideas that leads to a coherent account of the scientific phenomena.

The Web-based Inquiry Science Environment (WISE) offers students and teachers units developed following this pattern. WISE has specific features that both support learning and reveal the process of knowledge integration that students follow. Inquiry activities engage learners in investigations of personally relevant questions such as “How can a picnic container be designed to keep food cold?” or “What human activities contribute to increases in greenhouse gases?” WISE features such as the Idea Basket and Explanation Builder (see Fig. 1) support students to generate ideas, keep track of their ideas, organize their ideas, and create explanations. (McElhaney, Matuk, Miller, & Linn, 2012).

Figure 1. The Idea Basket and Explanation Builder support students to keep track of their ideas and organize them into arguments: WISE (http://wise.berkeley.edu).

*Summary: Knowledge integration*

In summary, the knowledge integration framework calls for design of inquiry science activities that capitalize on students’ ability to make sense of scientific phenomena across contexts. Students generate a broad range of ideas about any scientific phenomenon. These ideas represent multiple types of explanations, vary across contexts, and may not be recognized as applying to the same topic. The knowledge integration framework takes these ideas as building blocks and mobilizes the same processes that generated them to focus instructional design and student investigations on coherent understanding. This approach is captured in the knowledge integration pattern. By inspecting their own ideas, considering new ideas, distinguishing among existing and new ideas, and reflecting on their investigations, students are encouraged to promote the most promising ideas and articulate a coherent account of the topic.

Coherence versus Fragmentation

As discussed in diSessa’s (2008) chapter in the original version of this handbook, there has been a long running debate in the conceptual change literature between framework theory perspectives and elemental perspectives on conceptual change. Much of this debate has focused on whether students’ understandings in science are better characterized as a coherent unified scheme with a theory-like character (e.g., Carey, 1985; Gopnik & Wellman, 1994; Ioannides & Vosniadou, 2002; McCloskey, 1983; Vosniadou, 2002; Vosniadou & Ioannides, 1998; Wellman & Gelman, 1992; Wiser & Carey, 1983) versus an ecology of quasi-independent elements or ideas (e.g., Clark, 2006; Clark, D’Angelo, & Schleigh, 2011; diSessa, 1988; diSessa, Gillespie, & Esterly, 2004; diSessa & Sherin, 1998; Dufresne, Mestre, Thaden-Koch, Gerace, & Leonard, 2005; Parnafes, 2007; Hammer & Elby, 2003; Harrison, Grayson, & Treagust, 1999; Hunt & Minstrell, 1994; Linn, 2006; Linn & Hsi, 2000; Linn, Davis, & Bell, 2004; Minstrell, 1982; Özdemir & Clark, 2009; Thaden-Koch, Dufresne, & Mestre, 2006; Wagner, 2010). The comparison above simplifies the actual theoretical perspectives, which are considerably more nuanced. Proponents of framework theory perspectives, for example, do not argue that students’ knowledge is theory-like to the degree that scientists’ knowledge is theory-like (e.g., including meta-conceptual awareness or availability to hypothesis testing), nor do proponents of elemental perspectives propose that students’ understanding involves random interactions of independent elements.

While the debate has tended to focus on the polarity of these differing positions rather than searching for commonalities, both perspectives propose systematicities in student ideas. Framework theory perspectives propose an overarching hierarchical conceptual structure with theory-like properties that constrains a student’s interpretation of subordinate models and ideas. Elemental perspectives suggest that systematicities arise as elements interact with each other in an emergent manner where the combinatorial complexity of the system constrains students’ interpretations of phenomena. Detailed descriptions are included in the original version of this handbook for the framework theory perspective (Vosniadou et al., 2008) and the knowledge in pieces perspective (diSessa, 2008). We would propose, as did Vosniadou et al. (2008), that the perspectives are complementary in many ways. Vosniadou et al.’s chapter, for example, highlighted several similarities between their perspective and elemental perspectives:

1. Framework theory and elemental perspectives both describe systems that are “not static but constantly developing and evolving influenced by students’ experience and information they receive from the culture” (p. 22).
2. Neither the framework theory perspective nor elemental perspectives describe “unitary, faulty conceptions” but instead describe “complex knowledge system[s] consisting of presuppositions, beliefs, and mental models” that “provide explanation and prediction” (p. 22).
3. Framework theory and elemental perspectives both propose that “learners use additive, enrichment types of learning mechanisms to assimilate the new incompatible information to existent knowledge structures” (p. 15).
4. Framework theory and elemental perspectives both propose that “the process of learning science and mathematics is slow and gradual and characterized by fragmentation, internal inconsistency and misconceptions” (p. 15) that result in “internally inconsistent responses or in the formation of synthetic models” (p.15) when students’ everyday understandings meet with formal ideas from instruction.
5. The perspectives agree that accounts of knowledge acquisition should capture “the continuity one expects with development” and have “the possibility of locating knowledge elements in novices’ prior knowledge that can be used to build more complex knowledge systems” (p. 22).
6. The perspectives agree that accounts of knowledge acquisition should “move from single units of knowledge to systems of knowledge that consist of complex substructures that may change gradually in different ways” (p. 15).

We propose that further similarities between the perspectives emerge when we look at elements and theories from two perspectives. First, it is helpful to consider a graduated spectrum for the magnitudes of influence that elements may exert on one another. Second, “zooming” out to a broader view of the conceptual landscape further clarifies common aspects of these views.

*Magnitude of influence of ideas*

Framework theory perspectives focus on the organizing role of a small number of key ontological and epistemological ideas (which they describe as framework theories). Students interpret observational and cultural information and beliefs (which they describe as specific theories) in light of these key ideas to create functional models for operating in the world. Vosniadou et al.’s (2008) chapter illustrated the framework theory perspective as shown in Figure 2.

Elemental perspectives tend to focus heavily on the interaction of many individual ideas. While elemental research has often focused on unarticulated explanatory primitives (e.g., phenomenological primitives, diSessa, 1988; diSessa & Sherin, 1998), elemental research also acknowledges the presence and role of other components in a student’s conceptual ecology, which include, but are not limited to, nominal and committed facts, experiences, narratives, epistemological elements, mental models, and concepts at various stages of development and sophistication (Carey, 1985, Clark, 2006; diSessa, 2008; Linn, Davis, & Bell, 2004). While some elemental research has examined the interaction of elements to support higher levels of systematicity (e.g., diSessa & Sherin, 1998; Thaden-Koch, Dufresne, & Mestre, 2006; Wagner, 2010), the primary focus of much elemental research has explored the interactions among individual ideas.

Figure 2. Hypothetical conceptual structure underlying children’s mental models of the earth from Vosniadou et al. (2008)

The ideas in a student’s conceptual ecology have many sources and influences. Linn et al., (2004) discuss three key categories of these sources and influences in terms of deliberate efforts, cultural experiences, and interpretations of phenomena that parallel Vosniadou et al.’s (2008) typology of ideas in Figure 2 as well as diSessa’s (1996) description of the range of components in a student’s conceptual ecology. As Linn, et al. (2004) explain, some ideas come from *deliberate* efforts of students to interrogate the world such as when they plant tomatoes in sun or shade, break open a rock, or test whether objects sink. Others come from students’ *cultural* experiences, such as beliefs held in their communities, family hobbies, dinner table conversations, and interactions with relatives. Some ideas are based on students’ *interpretations* of the phenomena they encounter such as when they argue that a fire is alive because it moves or consumes plants.

We can clarify the relationships between framework theory and elemental perspectives by envisioning a more extensive and graduated spectrum for the magnitudes of influence that elements may exert on one another. Framework theory suggests that elements exert high magnitude influence on the interpretation of a “specific theory,” which in turn exert high magnitude influence on the construction of mental models. In line with diSessa’s and our own elemental perspectives, however, Vosniadou et al. (2008) propose that the connections between ideas can be disrupted through schooling or other experiences, resulting in conflicts or fragmentation in the coherence of students’ explanations. All of the perspectives agree, therefore, that the influence of ideas on one another is neither necessarily unidirectional nor complete. Instead the differences are in the degree of magnitude of influence that certain ideas exert on other ideas. All of the perspectives thus acknowledge that (a) different ideas in a student’s conceptual ecology exert different magnitudes of influence on other connected ideas, (b) connections, ideas, and their magnitudes of influence may change over time, and (c) this can result in inconsistencies, fragmentation, and synthetic models.

Essentially, the perspectives differ in their predictions about the scope and direction of influence of elements on one another. One main distinction resulting from this involves the degree of consistency that each perspective predicts in terms of students’ explanations across contexts. None of the perspectives predict absolute consistency or randomness, but higher degrees of consistency are predicted by framework theory than by elemental theory perspectives. This distinction between perspectives focuses theoretically on the core high magnitude ontological and epistemological ideas that organize students’ thinking on scientific phenomena they encounter in their everyday lives.

Vosniadou et al. explain their perspectives on this coherence on page 16 of their chapter. Our own work suggests that students across countries and cities tend toward the middle of this scale. Thus, Özdemir and Clark (2009) studied 32 students across four age groups in Turkey; Clark, D'Angelo, and Schleigh (2011) studied 201 students across four age groups in Mexico, China, the Philippines, the United States, and Turkey; and Clark, Menekse, D’Angelo, Özdemir, and Schleigh (submitted) studied 124 students across four age group in two cities and across three high school tracks in Turkey. All of these studies compare interview protocols and coding methodologies developed in Ioannides and Vosniadou (2001) and diSessa, Gillespie, and Esterly (2004) to analyze the consistency and types of force meanings that students of different ages expressed in interviews. All three of these studies document both systematicity and fragmentation in students' explanations of force across the interview contexts. These studies reveal fragmentation that is consistent with elemental theories. They also document the prevalence of specific ideas as posited by framework theories.

The distinction in terms of levels of consistency predicted by framework theory and elemental perspectives is strongest in terms of young students. Both framework theory and elemental perspectives predict that the introduction and reinterpretation of ideas (particularly from instruction) can fracture coherence for older learners. Framework theory perspectives propose that, prior to schooling, students’ naïve framework theories will exert exceptionally high influence in constraining specific theories and mental models to the degree that young students will typically be highly consistent in their explanations across contexts, while elemental perspectives predict less consistency for young children. Even for young students in the Clark studies, consistency in responses was rather uncommon. However, methodological issues in interviewing young children have muddied explorations on this (e.g., diSessa, Gillespie, & Esterly, 2004). Future investigations across research groups should explore the structure and relationships of ideas that have a higher magnitude influence to refine our understanding of their import.

Essentially, framework theory perspectives have focused primarily on the relationships of ideas in terms of magnitudes of influence while elemental perspectives typically focus instead on more fine-grained descriptions and phenomena (often in the domain of physics phenomena). While research from elemental perspectives acknowledges ranges in magnitude of the influence that elements can exert on one another (e.g., Clark, 2006; diSessa, 1993), the ranges of magnitudes often appear to be relatively small compared to the range of magnitudes inherent in Vosniadou et al.’s framework theory perspective (more along the lines of a single order of magnitude rather than multiple orders of magnitude). Thus, while Vosniadou et al.’s, diSessa’s, and our perspectives all predict that elements influence each other at various magnitudes, framework theory perspectives focus on the high magnitude of influence that certain elements exert on surrounding elements, while the elemental perspectives focus more on the dynamics of contradiction and fragmentation that occur when students encounter new ideas in various contexts. These contradictions and fragmentations are especially apparent when student responses are analyzed at a fine-grained level. Furthermore, at the fine-grained level, the potential benefit of encouraging comparisons of ideas becomes compelling.

*Zooming in and out*

The impact of frameworks become clearer as we “zoom out” to a broader view of the conceptual landscape. Essentially, while elemental perspectives acknowledge that some elements in students’ conceptual ecologies are more prominent than others and exert disproportional influence on surrounding elements, these studies (e.g., Clark, 2006) are so “zoomed in” that they do not emphasize the broader relationships between elements. In contrast, studies from Vosniadou et al.’s framework theory perspective are “zoomed out” to a medium distance, highlighting a more hierarchical arrangement among elements for a single domain (e.g., Figure 2’s representation from Vosniadou et al. of children’s understanding of the shape of the earth). From the perspective of Figure 2, there appears to be a hierarchical up-down relationship between elements. We propose that by “zooming out” to an even greater conceptual distance at the scope of multiple domains, the relationships take on yet an additional dimension. Essentially, if we expand our focus to include not just a student’s thinking about the shape of the earth but also the larger set of phenomena that the student would consider to be part of the natural world and universe, the diagram in Figure 2 would add many more elements at each level of magnitude (i.e., framework theories, specific theories, and mental model levels) within the various categories suggested at each of those levels (e.g., epistemological and ontological categories for framework theory elements or information and beliefs for specific theory elements).

We propose that the independent nature of the ideas at each level would become clearer in this envisioned “zoomed out” perspective if students were asked to explain several different phenomena across the domains. This type of research would reveal how students use ideas for varied, relevant phenomena (i.e., individual ideas could be marshaled for explanations of more than one phenomena or they could be marshaled independently of one another depending on the nature of the domain, explanation, and context). For example, the set of ontological, epistemological, observational, and cultural ideas and beliefs listed in Figure 2 would not be exclusively paired with one another for a single domain. An explanation in another related domain might draw on some but not all of these ideas and connect them to other ideas not included in Figure 2 to address the new question and context. Certain elements might have dramatically disproportionate influence, as suggested by framework theory perspectives, in terms of the organizing role they played and the magnitude of influence exerted. Yet, individual elements could be recruited independently into configurations specific to different phenomena and contexts.

Thus we might visualize the synergies in these perspectives by looking at the relationships among element in two ways. Framework theory perspectives emphasize the magnitude of influence that an element can exert on other elements, while elemental perspectives emphasize the ways that multiple elements interact and are recruited depending on domain and context. What needs to be explained by all conceptual change perspectives is the nature of the connections between ideas that exert high-magnitude influence on other ideas in a context. Do they have any other characteristics or relationships to one another besides the fact that they each exert high influence in that context? By integrating ideas of magnitude and scope into research about conceptual ecologies we might thus better explain and model observed systematicities and fragmentation that are evidenced in data collected across studies.

Learning Trajectories and Productive Curricular Sequences

The development of learning progressions builds on work in science education to establish standards for different grade levels and to define the scope and sequence for the curriculum. The learning progression efforts make hard decisions about which of the very abstract standards ought to be elaborated in the curriculum and about the expected trajectory students will follow. Learning progressions can be strengthened by incorporating core ideas about the processes of conceptual change outlined here. Specifically, the distinction between framework and elemental perspectives raise issues about learning trajectories and productive curricular sequences. From a zoomed-in view, students typically bring a wide variety of elements to science class and may follow idiosyncratic trajectories, consistent with the knowledge integration perspective. In class students generally encounter more sophisticated accounts of phenomena for the first time. The challenge and opportunity is to help students make productive connections between their everyday ideas and more formal causal and mechanistic ideas. Researchers studying learning progressions seek to characterize student progress to give structure to instruction but have to contend with the variations in student ideas.

Several research groups have begun to identify progressions of understanding in specific topic areas. The AAAS Atlas (AAAS, 2001) identifies sequences of topics and suggests appropriate grade level goals. By identifying a sequence of accomplishments or understandings that students might achieve, researchers seek to clarify how students could progress in complex topic areas (such as genetics, force and motion, or evolution) in order to end up with generative, useful, and sound understanding of the key ideas and concepts. The success of this endeavor depends, in part, on the nature of the elements of student knowledge. If students hold very different ideas they may follow distinct paths. Finding a common instructional focus to help students advance along distinct trajectories is an exciting challenge.

As we argued for framework and elemental perspectives, characterizing learning progressions depends on “zooming out” to locate a common path to understanding a discipline. This may deter instructional designers from considering the richness and variety of ideas in students’ conceptual ecologies. “Zooming in” may ultimately reveal multiple paths of conceptual change. Recent theoretical and empirical work has begun to integrate insights from conceptual change into learning progressions (e.g., Duncan & Hmelo-Silver, 2009; Lehrer, Kim & Schauble, in press; Wilson, 2009).

Duncan, Rogat, and Yarden (2009), for example, identified a learning progression based on the big ideas in genetics. They then deconstructed the big ideas into a series of levels in their theoretical paper. They based this deconstruction on prior empirical research on learning genetics (e.g., Duncan, 2007) and on a systematic analysis of the field. Duncan et al. (2009) acknowledged that their theoretical account of the learning progression is abstract and incomplete in some ways since many of the questions relevant to this sequence have not yet been answered, but the learning progression specifies deep understanding across three levels, a goal that has rarely been achieved in textbooks and other curriculum materials. Shea and Duncan (2010) then tested the progression in a two-year long empirical investigation involving detailed analysis of interviews with students. They determined whether students expressed the ideas identified as big ideas in genetics and whether students went through the levels of understanding articulated in the learning progression. Their study explored discrepancies between the hypothesized sequence of understanding and the observed responses of individuals, while documenting the conceptual ecologies students develop and the idiosyncratic sequence of understanding that each student follows. Through this process, Duncan and colleagues illustrated how the variety of student ideas and the variation in student trajectories contributed to the actual processes of conceptual change in their learning progression.

This research on the varied paths for development of student understanding of genetics resonates with the results from our own longitudinal analysis of fifty students’ conceptual change in an eighth-grade thermodynamics curriculum. We interviewed students across a semester and again preceding their tenth and twelfth-grade years to follow their subsequent progress (e.g., Linn & Hsi, 2000; Lewis, 1996; Clark, 2006).

Clark (2006), for example, first analyzed the full cohort of fifty students and then analyzed two fairly successful and two less successful students in greater detail. Clark’s analyses clarify the multiple conceptual change paths, sequences, and processes through which students’ understandings of thermal equilibrium evolve from disjointed sets of context-dependent ideas toward, if not achieving, greater integration, normativity, and cohesiveness. Figures 3 and 4 show how students’ explanations were cataloged and coded for the connections that students made. The analyses also highlighted the centrality of certain high-magnitude ideas (which varied across students) in students' explanations and processes of reorganizing and refining the other ideas and connections within their conceptual ecologies. Clark outlined the implications of these results for curricular sequences in terms of (a) depth of coverage, (b) support for normative connection of ideas rather than simply adding more ideas, (c) increased opportunities to compare non-normative and normative ideas in contexts that cue the non-normative ideas,(d) support for multiple conceptual paths through the curriculum, (e) consideration of the pedagogical trade-offs in choosing specific accessible intermediate models, and (f) re-explanation of disruptive experientially-supported ideas to support school-instructed ideas.

Our research and other recent research on conceptual change illustrates that students’ learning processes involve multiple paths. Learning progressions and curricular sequences will be most successful if they “zoom in” to support these paths as well as “zooming out” to consider overall goals. To support multiple paths, curriculum designers need to make choices about which scientific models and explanations to incorporate into instruction (such as which abstractions and pivotal cases to select) as discussed briefly in the knowledge integration overview. National and international assessments demonstrate that few citizens master causal explanations for most scientific phenomena (Schmidt, Raizen, Britton, Bianchi, & Wolfe, 1997). Choosing appropriate forms of explanation is therefore challenging but critical.

Some problems benefit from multiple explanations. White and Frederiksen (1998) report, for example, that students understand electricity better when they learn a series of explanations going from descriptive to causal. Students might start with descriptive explanations or mechanistic accounts and then learn molecular theories (Linn & Muilenburg, 1996). The molecular kinetic account of heat transfer, for example, draws on unseen processes and may be less generative than the heat flow account for students who are also struggling to understand the particulate nature of matter (Nussbaum, 1985). Furthermore, researchers have pointed out that students’ descriptive views can interfere with understanding of causal or atomic explanations (Chi, 2005; Vosniadou, in press). Others argue that many causal or atomic explanations are challenging to apply to everyday events and should be added to science courses judiciously (Linn & Hsi, 2000). This research shows that students need both to distinguish between the types of explanations encountered and to learn how to make links across these explanations.

Figure 3. Condensing and placing an interview segment in an explanation map from Clark (2006)

Figure 4. Coding and placing an interview segment into an element map from Clark (2006)

One curriculum (Linn & Hsi, 2000) addressed this goal by having students explore everyday situations and then synthesize their findings in pragmatic principles. On the topic of thermal equilibrium, for example, the curriculum focused on the following pragmatic principle: “if all the objects are in the same surround and none of them produce their own heat, then they will all come to the same temperature.” Pragmatic principles like this one offer students an abstract, accessible explanation. They allow students to connect class experiments, everyday situations, and more abstract ideas about scientific phenomena.

Instructional designers need sensible ways to help students link varied types of explanations and ideas to achieve coherent understanding. Research programs have identified benchmark lessons (diSessa & Minstrell, 1998), bridging analogies (Clement, 1993), animations (Holyoak & Thagard, 1995), and argumentation and explanation approaches with simulations and games (Clark & Sampson, 2007; Clark, D’Angelo, & Schleigh, 2011; Clark, D. B., Martinez-Garza, M., Biswas, G., Luecht, R. M., & Sengupta, P., in press; Clark, Nelson, Chang, D’Angelo, Slack, & Martinez-Garza, 2011).

Promising instructional approaches structure learning in multiple ways rather than leaving students to unguided exploration (diSessa et al., 1991; Klahr & Nigam, 2004; Linn & Hsi, 2000). Effective instruction offers each student well-designed views of scientific phenomena such as pivotal cases or intermediate models that advance their reasoning (Edelson, 2001; Linn & Eylon, 2011; White & Frederiksen, 1998). Such instruction also ensures that students encounter multiple contexts, take advantage of social interactions, and explore alternatives (Linn & Eylon, 2011; Quintana et al., 2004). As discussed above, research on promising instructional sequences, such as the knowledge integration pattern, shows that some patterns are more effective than others in terms of helping students link explanations (Linn & Eylon, 2011; Linn & Songer, 1991). To take advantage of well-designed ideas, patterns encourage students to reflect and to monitor their own progress (Davis & Linn, 2000; Chi et al., 1994; Vosniadou et al., 2008). Productive patterns respect and leverage the many ideas students generate about scientific situations rather than trying to confront them or eradicate them (Chi, et al., 1994; diSessa, Hammer, Sherin, & Kolpakowski, 1991; Linn & Eylon, 2011; Siegler, 2000; Smith, diSessa, & Roschelle, 1993/1994; Vosniadou, 2002). These promising instructional ideas are captured in the knowledge integration pattern: the pattern combines the process of eliciting the full range of student ideas, adding pivotal cases or intermediate models, encouraging students to compare, contrast, and sort out ideas, and enabling students to reflect on their efforts to articulate explanations (Linn & Eylon, 2011)

Conclusions

Synthesizing Vosniadou et al.’s framework theory perspective with the knowledge integration perspective and other elemental perspectives reveals overlaps and consistencies. In particular, the explorations of this chapter emphasize how the magnitude of influence of certain ideas from framework theory perspectives can mesh well with the focus on the rich interactions within conceptual ecologies highlighted by elemental perspectives. By considering the focus of research in each theory, common findings become apparent. These synergies clarify and strengthen the accounts of conceptual change collected across studies. This synergistic perspective also supports the value of instructional sequences, such as the knowledge integration pattern, that scaffold students in refining and consolidating their conceptual ecologies around productive focal ideas (pivotal cases). Essentially, highlighting the magnitude of influence of certain ideas in students’ conceptual ecologies explains systematicities in student explanations while still respecting the rich range of ideas and interactions between ideas that lead to idiosyncratic trajectories. Striking a balance between idiosyncratic and high magnitude ideas is also central to effective design of learning progressions. This approach sheds light on the difficulties students have when grappling with the abstract formal ideas introduced in science classes.

This chapter thus elaborates on the proposition common across perspectives that variability in student ideas is a fundamentally valuable feature. Curricula designed to capitalize on the variability and the creativity of student ideas can facilitate conceptual change. The knowledge integration, framework theory, and knowledge in pieces perspectives all argue that understanding how students generate and reconcile new ideas in a specific domain governs important and essential curricular design decisions. Two areas where curricular design is particularly important involve (a) determining which new focal ideas may prove most productive for students and (b) determining sequences of instructional activities to scaffold students’ integration of their ideas as they develop more coherent understandings.

Characterizing students’ conceptual ecologies and adding the right ideas to those ecologies has the potential of dramatically increasing the efficiency and effectiveness of instruction. The sheer numbers of sources of ideas in students’ conceptual ecologies underscores the scope of this task. The diverse range of cultural impacts combined with the broad range of students’ metacognitive skills guarantees that learners will follow many different paths as they make sense of abstract school science ideas. This requires flexible curricula that support multiple paths of conceptual change. It is our claim, as is claimed by Vosniadou et al. (2008), that advancing this agenda will depend as much on exploring synergies and affordances across conceptual change perspectives as on exploring the impact of the distinctions among perspectives.

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