Examining learning progressions beyond content: Strands of scientific proficiency

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There has been a recent proliferation of research on learning progressions (LPs) in science education as a way to influence the development of more coherent curricula and assessments. The recent draft of the Conceptual Framework for the New Science Education Standards also employs LPs as an approach to identify and organize the core ideas in science. While many LPs integrate big ideas in science content with cross-cutting themes of scientific practice, they do so in a variety of ways and to various extents. This symposium will examine issues relating to the integration of content-focused and practice-focused LPs with the other strands of scientific proficiency. The strands of proficiency refer to interest development, content learning, learning to reason, developing an understanding of the enterprise, learning to engage in disciplinary practices, and coming to identify with science (NRC, 2007, 2009). Presenters will discuss attempts to integrate different LPs with the strands as well as the theoretical challenges in developing such integrated LPs. Presenters will also address ways that the design of learning environments and associated products (e.g., curriculum, assessments, out-of-school programs) could benefit from attending to learning strands that have typically not been strongly emphasized in LP research and development efforts.

Symposium presented at the annual meeting of the National Association for Research on Science Teaching, Orlando, FL, April 3-6, 2011

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Learning Progressions in Science

One goal of learning progression research is to support the development of research-based standards and curricula that focus on big ideas of science in ways that help students see the major themes and concepts tying phenomena together (Corcoran, Mosher, & Rogat, 2009). Such an emphasis is reflected in the recent work to develop new national science standards: *Framework for Science Education* (NRC, 2010). Learning progression research also provides an opportunity to improve the coherence of science curricula from the time students enter school through graduation, and beyond; researchers have begun to examine how learning progression research can be used to investigate curriculum design (Krajcik, Shin, Stevens, & Short, 2009; Wiser, Smith, Doubler, & Asbell-Clark, 2009) and teacher training (Schneider & Plasman, 2011). Though the field is still negotiating the details of what it means to design, revise, and validate a learning progression in science, there are several commonalities in the approaches taken by researchers who work in this area[1]. Learning progressions describe how learners may grow in sophistication towards a big idea in science (Corcoran, Mosher, & Rogat, 2009; Duncan & Hmelo-Silver, 2009; NRC, 2007). These big ideas describe unifying concepts that help make sense of a broad variety of phenomena, offering robust explanatory power for the world around us (Smith, Wiser, Anderson, & Krajcik, 2006). A learning progression describes how intermediate levels of sophistication can be valued and built upon, rather than only focusing on alternative ideas and scientific ideas. As part of valuing increased sophistication through intermediate levels of understanding, learning progression research focuses on the role instruction plays in moving students from the knowledge they students bring with them to school towards the scientific conception. Further, most learning progressions describe how understanding is developed across many grades, though breadth of the progression and the grain-size of analysis vary between research groups and topics (Heritage, 2008).

Goals for Scientific Literacy: Proficiency in Science

As the researchers continues to examine what it means to define, validate, and use learning progressions, we also consider how the body of learning progression literature and active research programs support the science education community's goals for science education. To frame this question, we consider such research syntheses as National Research Council's *Taking Science to School* (2007) and *Learning Science in Informal Environments* (2009) to provide a framework for science literacy goals. Such a perspective on learning science has also been adopted by the new *Framework for Science Education* (NRC, 2010). *Taking Science to School* describes what it means to be "proficient in science" by recognizing that separating content knowledge and process skills is a false dichotomy. The *Taking Science to School* framework

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[1] More detailed discussions of the methods used in developing and defining learning progressions can be found in Corcoran et al. (2009), Salinas (2009) and the special issue on learning progressions in the *Journal of Research in Science Teaching* (Volume 46).

envisions science as “both a body of knowledge and an evidence-based, model-building enterprise that continually extends, refines, and revises knowledge” (p. 2). *Learning Science in Informal Environments* embraces and extends the previous framework by examining aspects of motivation, engagement, and identity as additional features of what it means to engage in science outside of the classroom. Together, these documents describe six strands that shape a comprehensive goal for science education as these should be considered as interwoven facets of science proficiency. Developing proficiency in science includes (NRC, 2007, 2009):

1. Motivation to learn about science as well as a continued interest in challenging scientific problems. Motivation and interest in lead to persistence in engagement with science across time.
2. Knowledge, use, and interpretation of scientific explanations of the natural world.
3. Engaging in scientific reasoning through the generation and evaluation of scientific evidence and explanations.
4. Understanding that science is a way of knowing. Scientific thinking changes as new evidence emerges and theories are reevaluated through a process of social engagement in the scientific discourse.
5. Participation in a community of scientists though engagement in a social system which includes a common discourse, particular practices, ways of conducting procedures and representing data.
6. Developing an identity as someone who learns about and participates in science.

These strands represent a vision for the ways in which science education can support students’ development both in and out of school. They describe goals for what students will be able to do as scientifically literate members of society. Further, given the interrelated nature of the strands, they should be considered as an integral component of learning science rather than separate goals. Songer, Kelcey and Gotwals (2009) point out that supporting students in developing more sophisticated ways of thinking about science “must include both the increasingly more sophisticated sequence of content topics and the increasingly more sophisticated progression of inquiry reasoning skills, also called scientific practices (NRC, 2007), over time (p. 611).” Given this description of what it means to participate in science proficiently, and our overall learning progression framework described above, this symposium begins to examine: What ways can we use learning progression research to understand how students develop proficiency across all the strands of scientific proficiency? And, to what extent has learning progression research examined ways that students develop in sophistication across these strands?

We begin to answer this question by considering first consider examples of learning progression research to uncover the ways in which the strands of science proficiency have been emphasized in the literature. The majority of existing learning progressions focus on scientific content as the big idea: Strand 2 (explanations of the natural world). This initial focus on content-based learning progressions is reflected in *Taking Science to School* which defines learning progressions as “sequences around important disciplinary specific core ideas (p. 221)” while also point out that developing students’ knowledge and practice around a scientific topic will ultimately involve all four of the strands of scientific proficiency included in the report. Content-focused progressions include matter and atomic molecular theory (Merritt, Krajcik, & Shwartz, 2008; Park, Light, Swarat, & Drane 2009); Smith et al., 2006; Stevens, Delgado, & Krajcik, 2010), celestial motion (Plummer & Krajcik, 2010), energy (Lee & Liu, 2009), evolution (Catley, Lehrer, & Reiser, 2005), force and motion (Alonzo & Steedle, 2009), genetics (Duncan, Rogat, & Yarden, 2009), and magnetism (Sederberg & Bryan, 2009).

Other researchers have developed learning progressions that do not set a specific content area (Strand 2) as part of the big idea but rather, they address aspects of Strands 3, 4, and 5 by examining how proficiency in science progresses in scientific reasoning and knowledge of what it means to participate in science. The MoDeLs project has developed a learning progression describing how students learn the elements of modeling practice as well as the metamodeling knowledge, which describes understanding the nature and purpose of modeling (Schwarz et al., 2009). Berland and McNeill (2010) developed a learning progression for argumentation; three strands of argumentation are unpacked using disciplinary (science) knowledge and empirical evidence to illustrate how students grow in sophistication across the instructional context, argument product and argument process. Sikorski, Winters, and Hammer (2009) have begun to consider the organization of a learning progression around scientific inquiry for students and teachers.

Other research groups have begun to investigate what it might mean to develop a learning progression that demonstrate increasing sophistication across scientific explanations integrated with other strands of science proficiency. Songer, Kelcey, and Gotwals (2009) point out that “defining a learning progression as only content knowledge without consideration of inquiry reasoning is problematic” (p. 611). Therefore, they chose to investigate biodiversity in tandem with evidence-based explanations, thus integrating core ideas from Strands 2 and 3. Their results illustrate a robust method for assessing student development along the *evidence-based explanations in biodiversity* learning progression and highlight problems with standardized testing that do not consider complex reasoning as an assessment variable. The *Environmental Science Literacy* project includes the development of learning progressions around: carbon (Mohan, Chen, & Anderson, 2009), water (Gunckel, Covitt, & Anderson (2009), and biodiversity (Wilson, Tsurusaki, Wilke, Zesaguli, & Anderson, 2007). These progressions include aspects of Strands 2, 3, and 5 as core ideas of their environmental literacy learning progression. First, the authors consider developing sophistication in environmental literacy to be the product of acquiring control over a secondary discourse – a way of using language, of thinking about the world, and acting in response to the environment. They further describe the ways in which students master this secondary course through scientific practices: “*developing and using accounts of carbon cycling to explain and predict* different situations and events” (Mohan, Chen, & Anderson, 2009, p. 676, italics in original). Finally, they point out the key scientific concepts necessary for students to engage in scientific reasoning about carbon cycling in socio-ecological systems.

Our review of the literature suggests that while many of the existing learning progressions have a content focus, a few research groups have begun to look for ways to consider an integrated approach to the strands; we found progressions that integrate two or more of Strands 2-5. These are the aspects of science proficiency examined in *Taking Science to School*. Strands 1 and 6, those that appear in *Learning Science in Informal Environments*, were not found to be part of the core descriptions of the body of learning progressions reviewed here.

Implications for Curriculum and Instruction

Learning progression research is intimately tied with curriculum design and instructional practices, through attempts to empirically validate learning progressions and through the possibilities implicit in using learning progressions to develop science curricula. Students' progress along the learning progression is not developmentally inevitable; rather, it is dependent on experiencing appropriate instruction, which is dependent on the student's level of prior knowledge. Therefore, understanding how a learning progression can describe a potential pathway towards achievement of a big idea in science involves examining how instruction can support student achievement and considering whether the validity of the learning progression is dependent particular instruction or can be generalized across instructional conditions. Understanding the role of the curricula in students' progress along a given learning progression, and the use of those student learning outcomes to revise or validate the learning progression, may be limited due to students' lack of prior knowledge (Krajcik, Shin, Stevens, & Short, 2009; Plummer, 2011). Learning progression research also relies on the existence of appropriate environments to test learning progression hypotheses. Several learning progression researchers have identified the need to create or revise curricula in order to empirically validate their learning progressions, including content-focused and scientific practice-focused progressions (e.g. Duncan, Rogat, & Yarden, 2009; Plummer, 2011; Schwarz, Reiser, Acher, Kenyon, & Fortus, 2011). Efforts to empirically test learning progressions using design-based research with targeted curricula may be difficult given the challenges posed by resistance by students' and teachers' beliefs about the nature of schooling (Schwarz et al., 2009) and limited occurrences of scientific practices, such as modeling or argumentation, in typical classrooms (Berland & McNeill, 2010; Schwarz et al., 2009). The symposium will consider how such challenges impact the development of learning progressions across the strands of science proficiency.

Learning progression research also offers an opportunity to develop coherent curricula. A coherent curriculum is designed around supporting students through a purposeful alignment of instruction that is organized to develop an integrated understanding of a small set of big ideas with (Schmidt, Wang, & McKnight, 2005; Schwarz et al., 2009). Coherence of the curricula has been found to be a major factor influencing student achievement (Schmidt, Wang, & McKnight, 2005). A learning progression can be a “template for the development of curriculum assessment products” that promotes successively more sophisticated ways of being proficient in an aspect of science (Songer, et al., 2009, p. 612). Krajcik and colleagues (2009) suggest that designing curricula based on learning progressions allows for explicit linkage between big ideas and instruction thus providing the necessary coherence that is currently missing from most science curricula. Researchers should include descriptions of instructional strategies capable of moving students to a more sophisticated level on the learning progression by allowing students to make sense of content, uncover connections between concepts through experience with appropriate phenomena (Krajcik et al., 2009). As part of the symposium, we address ways that the design of learning environments and associated products (e.g., curriculum, assessments, out-of-school programs) could benefit from attending to the strands of scientific proficiency that may not have been emphasized in LP research and development efforts.

Overview of the Symposium

This symposium provides a forum for discussion of issues relating to the possibilities and challenges in developing learning progressions across the strands of science proficiency and examines implications for the design of learning environments, curricula, and assessment. The presentations will be guided by the following set of questions though individual presenters will focus on those areas most pertinent to their work:

1. What ways can we use learning progression research to understand how students develop proficiency across all strands?
2. What are gaps in the current research on learning progressions, specifically considering the problem of integrating content-focused learning progressions with the other strands of scientific proficiency?
3. In what ways has current research approached integrating content with other aspects of the strands of scientific proficiency?
4. Are all of the strands important for consideration in learning progression development?
5. How can the connections between instruction and learning progressions be expressed and what should the “final product” of research on learning progressions be?

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An Intimate Intertwining of Content and Practices: A Learning Progression for Climate Change Biology

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Research in science education consistently demonstrates that as early as the onset of formal elementary-age schooling, American students are capable of sophisticated scientific thinking such as constructing explanations about focal science content (NRC, 2007; Metz, 2011). Many recent American policy documents describe the importance of age-appropriate, critical thinking in elementary school that builds a strong foundation for additional critical thinking and problem solving in later years (e.g., NRC, 2007). In one new research specialty, the area of learning progressions (e.g., NRC, 2007; Songer, Kelcey and Gotwals, 2009), research studies and policy documents describe the value in systematically mapping science conceptual knowledge development as it might progress over six or more years (e.g., two or more age bands). In the work of learning progressions, researchers and curriculum developers map out a template of knowledge goals that (a) builds on what is known about how children learn over time, (b) incorporates what we know about common misconceptions and errors, and (c) leads to a template for the guided development of critical thinking in particular focus topics (Corcoran, Mosher and Rogat, 2009; Songer, Kelcey and Gotwals, 2009).

One of the controversial aspects of learning progressions work is the nature of the knowledge that is represented in these progressions. Drawing from research in the literature and represented in policy document such as *Taking Science to School*, our work firmly takes the stance along with Duschl and colleagues that, "scientific reasoning is intimately intertwined with conceptual knowledge (NRC, 2007, p. 129). As a result, our learning progressions necessarily have both content and practice components that are (a) represented in learning progressions, and (b) fused into learning goals associated with each curricular activity. Figure 1 illustrates a portion of our learning progression associated with climate change biology for middle school students that includes both content and practices. Figure 2 presents sample learning goals that demonstrate the fusion of content (BE3) and practices (prediction making).

In summary, this short paper will conclude with a short discussion addressing tow of the symposia overview questions.

<u>1. What ways can we use learning progressions research to understand how students develop proficiency across all strands?</u>

The strength of the four strands is their interconnectedness with each other and the structure they provide for the systematic development of learning progressions, assessment instruments, curricular units and professional development modules. In addition, the interconnectedness of the four strands reinforces the necessary fusion we see between content and practices in order to foster deep conceptual understandings of focal science content. We can use learning progression research as helping us to empirically evaluate our age-appropriate scaffolds and sequence to guide the development of these fused content and practices leading to deep conceptual understandings of focal content.

<u>2. What are the gaps in the current research on learning progressions?</u>

The largest gap is in the area of assessment design and assessment evaluation. To put it bluntly: we do not have the assessment instruments we need to evaluate learning progression research. We need to work together to design, and evaluate, the validity and reliability of assessment instruments that are both instructionally sensitive and focused on deep conceptual understandings of focal content.

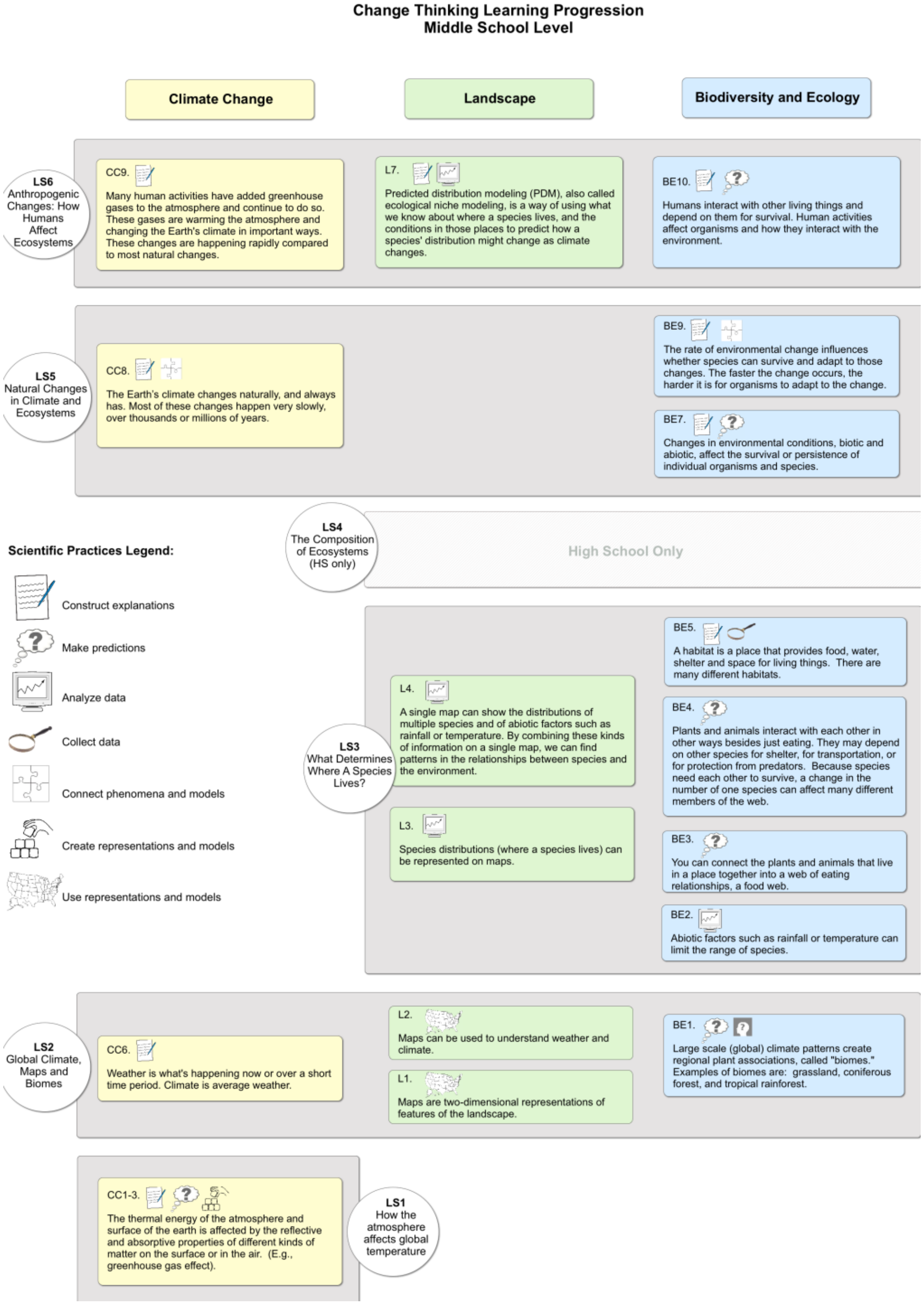

Figure 1: Content (colored boxes) and Practices (with icons) for a middle school unit on Climate Change Biology.

Content (from progression): *Biodiversity and Ecology 3: You can connect the plants and animals that live in a place together into a web of eating relationships, a food web.*

Practice (underlined): *Create a justified prediction about natural phenomena and justify it with scientific evidence, theory or models.*

Learning goal: Students create a justified prediction about what will happen to a focal species if one of their prey is eliminated.

Figure 2: Sample Sixth Grade Content and Practice Progression Sections Fused into Learning Goal

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Examining Learning Progressions Beyond Content: Strands of Scientific Proficiency

Dilemmas of integrating Scientific Content and Practices in Learning Progressions

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Several recent policy reports (NRC, 2005; NRC, 2007), as well as the current efforts to develop a conceptual framework for the new science education standards (Board on Science Education, 2010), have pointed to learning progressions as a potentially useful approach for guiding the development of new standards, curriculum, and assessment in science education. Learning progressions (LPs) embody a developmental approach to learning by describing hypothetical paths that students might take as they develop progressively more sophisticated ways of reasoning about scientific concepts and practices in a domain over extended periods of time (Corcoran, Mosher & Rogat, 2009; Duncan & Hmelo-Silver, 2009; NRC, 2007; Smith, Wiser, Anderson & Krajcik, 2006). LPs focus on a small set of core ideas and practices in a domain and therefore provide an alternative to the vastly criticized “mile wide and inch deep” science curriculum in the U.S. (Valverde & Schmidt, 2000). Moreover, many of the proposed progressions (e.g. Carraher, Smith, Wiser, Schliemann, & Cayton-Hodges, 2009; Mohan, Chen & Anderson, 2009; Songer, Kelcey, & Gotwals, 2009) are rooted in a view of practice and content as intrinsically linked and mutually necessary for science literacy; virtually all of the existing examples of LPs in science include some aspects of content and practice.

However, the ways in which LP scholars have treated the relationship between content and practice in their proposed progressions varies significantly. Some progressions foreground practice (Schwarz et al., 2009), while others foreground content (Alonzo & Steedle, 2008; Duncan, Rogat, & Yarden, 2009). Even among those progressions that intertwine content and practice (e.g. Mohan et al., 2009; Songer et al., 2009) there are differences in the ways in which practices are defined and used, and in the descriptions of how growth along one dimension (content or practice) is related to growth along the other (Lehrer & Schauble, 2009; Sikorski & Hammer, 2010). The ways in which content and practice are related are also reflected in how progress is perceived- that is, what it means to develop “more sophisticated” ways of reasoning. Is progress measured in terms of acquiring more sophisticated and accurate content understandings, or is it measured in terms of developing more sophisticated epistemologies and inquiry practices? For example, a student may provide a well-reasoned and evidence-based explanation of a phenomenon that is not aligned with canonical understandings in the domain; the value of such a response depends on how the LP defines progress. Thus the issue of how the learning of content and practice are represented in the LP, and how they are presumed to be related, raises some interesting theoretical and practical challenges.

I discuss some of these challenges in the context of two alternative progressions proposed in the domain of genetics (Duncan et al., 2009; Roseman, Caldwell, Gogos & Kurth, 2006). The motivation for developing LPs in genetics stems from the increasing demands for genetic literacy placed on the public as more genetic technologies gain entry into the public realm (genetic engineering, cloning, stem cell research, etc). This increase in literacy expectations is juxtaposed against research findings showing that high school graduates do not have the necessary understandings of genetics for such personal and civic engagement (Bates, Lynch, Bevan & Condit, 2005; Jallinoja & Aro, 2000; Kindfield, 1992; Lanie et al., 2004; Lewis & Wood-Robinson, 2000). Current instructional practices in genetics tend to focus on memorization of terms and processes rather than on core ideas and underlying mechanisms (Duncan & Reiser, 2007; Kurth & Roseman, 2001; Venville & Treagust, 1998). In order to foster more meaningful and useful understandings of genetics we need to focus curriculum, instruction, and assessment on the core ideas and practices in this domain, and begin developing these ideas in earlier grades.

The Alternative Genetics LPs

The genetic LPs both span grades 5-10 and reflect different assumptions about how knowledge develops in genetics and thus describe different learning paths. The alternative progressions in genetics are both content focused and do not explicitly address scientific practices. However, both implicitly emphasize the importance of developing of mechanistic models of genetic phenomena, an important aspect of scientific inquiry in genetics (Stewart, Cartier & Passmore, 2005).

The two LPs in genetics provide hypothetical models of how students' understandings of genetics can be developed from late elementary through high school. They are grounded in a view of knowledge for genetics literacy as composed of three interrelated conceptual models (Stewart et al., 2005): (1) the inheritance model, which explains the probabilistic patterns of correlation between genes and traits; (2) the meiotic model, which explains the cellular processes that allow for the transfer of genetic information from one generation to the next; and (3) the molecular model, which explains the cellular and molecular mechanisms by which genes bring about their physical effects within an individual. Taken together these models embody the conceptual knowledge that is the basis for reasoning in genetics.

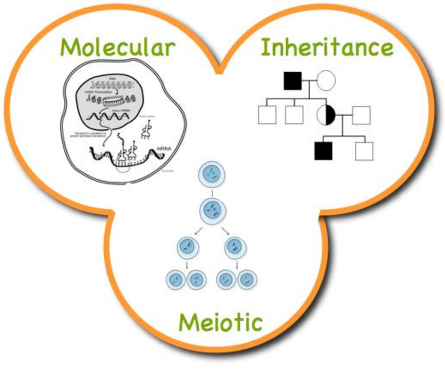

Figure 1. Genetics literacy framework

The progression proposed by Roseman et al. (2006) is organized around the two main functions of DNA: (a) determining the characteristics of organisms, and (b) passing the genetic information from one generation to the next. The Roseman et al. LP differs from current instructional practice in two ways. First, it emphasizes the functional products of genes- proteins- before discussing the structure and function of DNA. The idea that proteins do the work of the cell and thus are the biological mechanisms that bring about the physical traits is central to the molecular model of genetics (Duncan, 2007; Duncan

& Reiser, 2007; Lewis & Kattmann, 2004). Roseman et al. (2006) argue that understanding the role and importance of proteins is a precursor to understanding the function of DNA as determining traits. Second, the progression introduces the molecular model before discussing the meiotic or inheritance models. The argument here is that the concepts of genes, chromosomes, and alleles (part of the inheritance and meiotic models) are rather abstract for students and can be better understood once students have a firm grasp of the structure and function of DNA and proteins (molecular model).

The Duncan et al. (2009) progression takes a different approach, arguing that all three genetic models should be introduced, in some simple form, from the beginning and developed throughout the middle and high school years. Progress is defined as the development of deeper understandings of each model as well as the interrelationships among them. According to this progression students should be capable of reasoning about some concepts in the inheritance and meiotic model even before they understand the molecular model in its entirety. The Duncan et al. progression differs from current instruction in that it too proposes an earlier introduction of the role of proteins as the mediating mechanisms of genetic effects, as well as an emphasis on the relationships among the three genetic models.

In essence the difference between the two progressions hinges on the conjectures regarding the accessibility of each of the three genetic models and the conceptual dependencies, or contingencies, between them. Duncan et al. propose that understanding genetic phenomena entails coordinated reasoning across all three models and thus simplified versions of each model are introduced simultaneously and developed throughout the course of the progression. The Roseman et al. progression involves the more stringent requirement that the molecular model be taught first, because understanding the meiotic and inheritance models is contingent on a deeper understanding of the molecular model. According to their progression those models should be taught in later grades, with the meiotic model taught first and the inheritance model taught last as it is the most abstract.

The discrepancies between the learning paths proposed by the two progressions stem, at least in part, from the gaps in the current research base, particularly the lack of research about middle and high school students' ability to reason about the molecular model. Very few studies examined student understanding of these ideas given specific instruction designed to support such learning (Duncan & Tseng, 2010; Gelbart & Yarden, 2006; Rogat & Krajcik, 2006). Research about students' understanding of the inheritance and meiotic models is somewhat more robust, with several studies of learning environments targeting these concepts (e.g. Buckley, et al., 2004; Jungck & Calley, 1985; Cartier & Stewart, 2000; Tsui & Treagust, 2003). There are hardly any studies in which students were engaged in learning all three models. Cartier and Stewart (2000) did include some instruction about the molecular model, in a unit focused primarily on the inheritance and meiotic models, but did not assess students' ability to develop explanations using that model. Thus the research base used to develop the two progressions does not provide sufficient evidence to rule out either of the conjectural learning paths proposed.

Scientific Practices and the Two LPs

As noted earlier many of the science LPs include elements of scientific practices as part of the big ideas around which the LP is organized. In these cases there are differences in the ways the relationships between content and practices are viewed and represented in the LP. Neither genetics progression includes practices as part of the big ideas; however, both include dimensions of scientific practices as part of the learning performances that operationalize student understandings at each level of achievement (NRC, 2005; Reiser, Krajcik, Moje & Marks, 2003). These learning performances are essentially a composite of content and practice. For example, the development of a mechanistic explanation of how a change to a gene (mutation) can result in a change to the observed trait. In this case the content is an understanding of genes, mutations, and the various biological components across organization levels that link genes to their observable effects (like proteins, cells, tissues). The practice is one of developing a mechanistic explanation or model that tracks a causal chain linking the starting conditions (mutation in the gene) to the outcome (change in trait). Many of the learning performances in the genetics LPs focus on the practice of developing mechanistic accounts of genetic phenomena. These accounts draw on mechanisms embodied in the three genetic models. The development of mechanistic accounts is a central practice of modern science (Westfall, 1986). Promoting this practice is an integral part of inquiry-based instruction and the development of students' scientific reasoning in general (Russ, Scherr, Hammer, & Mikeska, 2008; Southerland, Abrams, Cummins & Anzelmo, 2001; Tamir & Zohar, 1991) and in genetics (Buckley et al., 2004; Cartier & Stewart, 2000; Stewart et al., 2005; Stewart, Hafner, Johnson & Finkel, 1992).

It is plausible to develop a genetics LP that explicitly addressed the practices of developing, critiquing and revising mechanistic models in the domain. How would the learning of practice and content differ if this modeling aspect was integrated into each of the two existing LPs? Clearly content learning would differ as hypothesized by the specific LP. However, it may be that driving the learning of content in a particular path may impede or interfere with growth along the practice dimension. For example, learning concepts related to the more readily observable inheritance patterns may be more conducive to initial development of causal explanations because students likely have more experiences they can draw on to explain patterns of traits they can see. However, if the progression began with concepts in molecular genetics (e.g. the role proteins) students may struggle to make progress in modeling because they have limited experience with molecular entities and processes. Thus one progression may facilitate the learning of content better than the other, but the trend may be reversed for the learning of modeling. It does not follow that an effective progression for concept understanding is going to foster the development of practices equally well. Current research has yet to fully examine the likely reciprocal interactions between the learning of content and practice.

Along with the potentially conflicting developmental sequences for content and practice, assessments may yield conflicting diagnoses of students' level of ability on content and practice dimensions. Imagine an assessment item that requires student to provide a hypothetical model of a given genetic phenomenon in plants, versus another item that requires students to predict how changes to a gene may affect a subsequent phenotype in humans given one or more models. Even if the genetics principles (content ideas) are essentially the same in both tasks, the phenomenological context (plants versus humans) and nature of the practice involved (developing models versus interpreting them and making predictions) differ. A student who knows the genetics principles may be able to apply them in the human context but not in the plan context. The student may also provide evidence of more sophisticated content understandings in the modeling versus prediction task. It becomes challenging to figure out what level of understanding a student has achieved in terms of content, practices, and the integration of both while problem solving. In order to tease apart the effects of multiple variables, assessments for LPs that integrate content and practice will need many more items, and items of different types in order to adequately diagnose student abilities. The issue of context of tasks (e.g plant versus human) further muddies the water, however, this problem exists regardless of the nature of the LP and needs to be considered in validation studies of any type of LP. The two genetics progressions offer an interesting context to investigate issues related to the development of content and practice, and in future research I hope to begin addressing questions related to how the sequencing of content may impact the development of practice (and vice versa). Understanding these interactions in LPs is important if our ultimate goal is to foster understandings of both (NRC, 2007).

A Few Additional Thoughts About Instruction and LPs

An additional feature of LPs is that they are not developmentally inevitable (Corcoran et al., 2009; Duncan & Hmelo-Silver, 2009); rather students progress is mediated by carefully designed curriculum and instruction. Some have argued that defining instructional conditions and strategies is part and parcel of an LP (Lehrer & Schauble, 2009). Others have developed LPs based on cross-sectional data of students who exposed to existing instructional conditions and thus argue that LPs themselves can be viewed as stand-alone theoretical models of learning and that they can be operationalized through a variety of instructional means (Mohan et al., 2009). The relationship between instruction and LPs raises a practical dilemma as well. Given that to study an LP one needs to develop instruction that instantiates the LP model, how can one know if subsequent failures in student learning are a result of a faulty theoretical model (LP) or a problematic instructional design? Even if substantive learning did occur as a result of the designed instruction, it is impossible to know if instruction based on a different LP would have yielded better results. Moreover, the kinds of studies that would shed light on this conundrum are conceptually and logistically complex.

This theoretical dilemma is compounded by a practical one- how can LPs be made useful for teachers and students in real classroom contexts? Even if one accepts that LPs can be developed from cross sectional studies, in order to study such an LP it would have to be instantiated through curriculum and instruction. The argument is that good instruction would move students faster and more effectively through the levels of the progressions as derived from analysis of cross-sectional data. Thus from a practical standpoint LPs must include information about both instruction and assessment to be practically useful. Many of the current descriptions of LPs, including the genetics LPs, do not offer much in the form of instructional resources. Along with instructional guidance the LP approach will entail extensive professional development. A developmental of learning and teaching, that takes a multi-grade perspective, is not currently common practice. Shifting curriculum and instruction in ways that align with such a long-term view is going to require a concerted that blends professional development, instructional materials and strategies, as well assessments. This is a tall order for the relatively young scholarship of LPs. However, LPs do hold much promise and the investment seems worthwhile. Further research will provide more conclusive evidence about the theoretical and practical validity of this approach.

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