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PROGRESSION THROUGH ASPECTS OF VARIATION: AN ALTERNATIVE APPROACH TO CONSTRUCT LEARNING PROGRESSIONS

Learning progression is a useful way of describing the development of student understanding. Existing work on learning progression has largely employed the approach of characterizing student thinking using "levels", or placing individual student at a particular level. We argue that this approach does not allow for the multiple conceptions students may hold simultaneously and are likely to reveal in different contexts. As an alternative, we propose the approach of using a typology, which focuses on the individual conception (as opposed to the individual student), and thus may better capture the complexity of student understanding. A typology for the concept of "size and scale" is presented to illustrate our approach. Potential advantages of this approach are discussed at the end of the article.

Su Swarat, Northwestern University
Greg Light, Northwestern University
Denise Drane, Northwestern University
Eun Jung Park, Northwestern University

Learning progressions have gained popularity in science education due to their potential for organizing standards, informing learning assessment and guiding instruction (Catley, Lehrer, & Reiser, 2005; Duschl, Schweingruber, & Shouse, 2007; Smith, Wiser, Anderson, & Krajcik, 2006). Defined as "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (e.g., 6 to 8 years)" (Duschl et al., 2007, p.214), learning progressions describe the development of student understanding not only in terms of isolated knowledge, but also connections between sets of ideas (Stevens, Shin, Delgado, Kracjik, & Pelligrino, 2007).

Empirical studies on learning progressions have been relatively few, but have investigated concepts in various science disciplines including biology (Catley, Lehrer, & Reiser, 2005; Roseman, Caldwell, Gogos, & Kurth, 2006), chemistry (Smith et al., 2006; Stevens et al., 2007), physics (Alonzo & Steedle, 2008; Delgado, Stevens, Shin, & Krajcik, submitted), and environmental science (Anderson, 2007; Mohan, Chen, & Anderson, submitted). Some studies took a top-down approach, where the learning progressions were determined based on experts' knowledge of the concepts. For example, the "conceptual strand map" for the molecular basis of heredity (Roseman et al., 2006) suggested the sequence of ideas to be learned in order for students to understand that DNA determines the characteristics of proteins, which in turn affect organism functioning. Smith and colleagues (2006) proposed what students should know at the k-2, k3-5, and k6-8 level regarding properties of matter and the atomic-molecular theory. A similar approach was taken to unpack existing standards related to evolution into grade-specific “learning performances” (Catley, Lehrer, & Reiser, 2005). Other researchers have complimented this approach with empirical data. Through interviews with middle school and undergraduate students, Delgado and colleagues (submitted) validated a theoretically derived learning progression for “size and scale”. Specifically, they identified six progressive levels based on students’ performances on four tasks — ordering, grouping, relative size and absolute size of objects. Taking a similar approach, a multi-dimensional progression for the structure of matter was developed (Stevens et al., 2007). This learning progression not only suggested the sequence in which less sophisticated ideas lead to more sophisticated ones, but also connections between ideas that are necessary for progression from one level to the next. A hypothesized K-8 learning progression on force and motion was suggested based on science standards and relevant literature, tested using open-ended and multiple-choice questions, and revised into a five-level progression (Alonzo & Steedle, 2008). In contrast, Anderson (2007) took the bottom-up approach in building learning progressions for environmental science literacy, where seven levels of student achievement for the topic of carbon cycle, water cycle, and biodiversity were documented through written assessment and interview data.

Content knowledge is the focus of some learning progressions. For example, the conceptual strand map for molecular basis of heredity (Roseman et al., 2006) denotes the need to understand “An organism’s traits reflect the actions of its proteins” before grasping the idea “The genetic information stored in DNA is used to direct the synthesis of the thousands of proteins that each cell requires”(p.6). Learning progressions like the one for force and motion (Alonzo & Steedle, 2008), on the other hand, describe student thinking: A Level 3 student in this progression “understands that an object is stationary either because there are no forces acting on it or because there is no net force acting on it” (p.15). The majority of learning progressions are described in terms of learning performances. For instance, the levels in the learning progression for “size and scale” (Delgado et al., submitted) are distinguished by student performances in four aspects of the concept — For the aspect of “ordering objects”, a Level 2 student should recognize that atom is the smallest but makes errors in ordering others.

We believe that these learning progressions provide promising starting points to map out the trajectories students need to go through in order to fully understand the corresponding science concepts, and they provide valuable information to material, curriculum, and assessment design. However, all of them choose individual student as the unit of analysis – that is, their ultimate goal is to place individual students at certain levels of the progression. Our work on “size and scale”, though not starting with the goal of building a learning progression, indicates that this strategy may not be effective, particularly in characterizing students who hold inconsistent mental models of the same concept, a phenomenon frequently observed in our data (Light, Swarat, Park, & Drane, 2008).

We propose here an alternative way of framing a learning progression – to view the space of student understanding as consisting of individual exhibitions of student conceptions as opposed to individual students. That outcome space, then, is comprised of the different ways in which students conceive a particular phenomenon. In other words, the same student can have multiple incompatible understandings that are represented in multiple locations of the learning progression. These conceptions are not defined by content or learning performances specific to certain assessment tasks, but by the structure of student reasoning or thinking behind the exhibited conceptions. Unlike existing learning progressions that end with student thinking, we unpacked students' thinking in terms of *aspects of variation*, a central idea borrowed from Variation Theory (Marton & Booth, 1997). Variation Theory views different conceptions as "defined in terms of increasing complexity, in which the different ways of experiencing the phenomenon in question can be defined as subsets of the component parts and relationships within more inclusive or complex ways of seeing the phenomenon" (p.125). One could describe the different ways or the *variation* in how students experience or learn a concept in terms of *dimensions or aspects of variation* —"the different ways of experiencing something are different ways of experiencing the same thing, the variation in ways of experiencing it can be described in terms of a set of dimensions of variation" (Marton & Booth, 1997, p.108).

To illustrate, in the remainder of the paper we will provide an example of a typology for undergraduate students' conceptions of "size and scale". We will briefly describe the studies, explain the resulting typology, and conclude with a discussion of what advantages this approach of mapping student understanding might hold.

Study overview

We chose the concept "size and scale" as the focus of our studies because it holds great importance in students' learning of nanoscience. Identified as one of the "big ideas" of nanoscience (Stevens, Sutherland, Schank, & Krajcik, 2007), "size and scale" is fundamental to students' learning of size-dependent properties that are at the core of nanoscience. Students, however, have been shown to have considerable difficulty with this concept, both at the K-12 (e.g. Tretter, Jones, Andre, Negishi, & Minogue, 2006), and undergraduate level (Drane, Swarat, Light, Hersam, & Mason, 2009). The typology reported here is based on our work in exploring undergraduate students' conceptions of this concept, particularly how they apply numerical scales to compare and represent objects' size differences in the nano-context.

Our research consists of three studies, all involving students enrolled in engineering or materials science courses with a special focus on nanoscience at a single research intensive institution in the midwest. The first two studies took the approach of task-based, think-aloud interview. They both were exploratory in nature, and involved a small number of students from diverse demographic and academic background (n=12 for the first interview study, and n=20 for the second study). In the first interview study, the participants were asked to order a list of objects of widely varying sizes (football field, elephant, typical science textbook, human hair, bacterium, virus, and atom) along a line, and then apply a numerical scale to represent their size differences. Students were prompted to verbalize their reasoning as they completed the task. Building upon students' responses in the first study, the second interview study provided interviewees with example responses, and asked students to evaluate their appropriateness. A set of multiple-choice assessment items aimed at probing student understanding of numerical scales were developed based on the results of the interview studies. These items were administered in the third study to a larger sample of students (n=111), who were asked to not only complete the items but also provide written justifications for their answers.

Typology of undergraduate students' conceptions of "size and scale"

A typology of undergraduate students' conceptions of "size and scale" (Figure 1) was constructed based on combined findings of the three studies (for details, see Light, Swarat, Park, & Drane, 2007, 2008; Swarat, Light, Park & Drane, submitted). The typology describes four main categories (Fragmented, Linear, Proportional, and Logarithmic) and eight sub-categories (1a-1b, 2a-2b, 3a-3b, 4a-4b) of conception revealed by our data.

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Categories of conception (Structure of Scale)		**Fragmented** Scale is viewed as a fragmented structure, unable to connect different "worlds"		**Linear** Scale is understood as having a linear structure representing direct observation or experience		**Proportional** Scale is understood as having a "semi-logarithmic" structure representing proportional differences		**Logarithmic** Scale is understood as having a logarithmic structure representing "powers of 10"-based differences	
Aspects of variation		**4b**	**4a**	**3b**	**3a**	**2b**	**2a**	**1b**	**1a**
1st	**Integration of numbers**	Scale orders detached "worlds" qualitatively without numbers	Understands scale as ordering or connecting phenomena of different "worlds" using numbers						
2nd	**Continuum**		Scale orders detached "worlds" with numbers	Understands scale as a continuum linking phenomena of widely varying sizes					
3rd	**Log scale awareness**			Linear scale with no reference to log scale components	Understands scale as incorporating certain log scale components (e.g. terminology, visual representation, basis of construction)				
4th	**Proportion**				Linear scale with no indication of proportion-based thinking	Understands scale as based on proportion or ratio			
5th	**Powers of 10 (P10)**					Scale based on proportion-based comparisons without a common factor	Understands proportion in terms of P10		
6th	**Equally spaced intervals**						Scale based on P10-based comparisons, without equally spaced intervals	Understands equally spaced intervals in terms of P10	
7th	**Epistemological integration**							Log scale viewed as "unreal", whereas linear scale as "real"	Understands all scale types as "real" created tools
									Understands all scale types as "real" created tools

Figure 1. Typology of undergraduate students' conception of "size and scale"

A fragmented conception describes the view that objects belonging to different "worlds" (i.e. the macro-, micro-, and nano-world), due to their dramatic size differences, cannot be represented on a continuous scale; that is, they need to be represented using separate scales. Within the fragmented category, sub-categories 4a and 4b are distinguished by whether the demonstrated conception reveals an awareness of integrating numerical measurements with the understanding of scale. A linear conception indicates a belief that a scale based on absolute size differences (i.e. by using subtraction) is most appropriate to represent objects of widely varying sizes as those given in our studies. Within the linear category, sub-categories 3a and 3b are distinguished by whether an awareness of some components of logarithmic scale is demonstrated. A proportional conception represents the thinking that objects differing much in size should be compared using their relative size differences (i.e. by using division), and the scale should reflect such comparisons. Both sub-categories 2a and 2b recognize the importance of scale based on proportional differences, but they differ in that students with 2a conceptions calculated the proportional differences based on a common factor of 10, whereas 2b conceptions did the proportional calculation by using simple divisions. Lastly, a logarithmic conception represents a scale of choice with logarithmic features. Within the logarithmic category, sub-categories 1a and 1b differ in whether an awareness of the applicability and epistemological equivalence of both the logarithmic scale and the linear scale (though viewing the former as more advantageous and appropriate in the context of our studies) is developed, with 1a conception understanding when and why to apply each scale, and 1b conception viewing the logarithmic scale as an "artificial" invention suited for scientific purposes only and the linear scale as the "real" scale.

The order in which the categories are arranged (i.e. 4b at the left end to 1a at the right end) corresponds to a hierarchical progression of less to more sophisticated understanding. The advance in sophistication is described by the increased complexity of student understandings in terms of their awareness of the aspects of variation (shown in the first column of the typology) that differentiate the categories of conception. That is, the more aspects of variation students become aware of, the more sophisticated their conception is likely to be.

Seven aspects of variation describe and distinguish the conception categories and sub-categories. The first aspect "Integration of numbers" describes whether students are able to integrate numerical measurements of object sizes with the scale of choice. The second aspect "Continuum" describes whether students perceive that objects of dramatic size differences (e.g. an atom vs. a football field) can be represented on a continuous scale. The third aspect "Log scale awareness" describes whether the scale or the understanding behind it indicates an awareness of the logarithmic scale and its components. The fourth aspect "Proportion" refers to the construction of a scale based on proportional comparison of object sizes, as opposed to absolute differences calculated through subtraction. The fifth aspect "Powers of 10 (P10)" refers to the use of common factor 10 in comparing size differences. The sixth aspect "Equally spaced intervals" describes whether students could translate the P10-based comparison into appropriate representation on a log scale (i.e. the equal spacing between adjacent powers when labeled on a log scale). The last aspect "Epistemological integration" describes whether students were able to draw a meaningful connection between linear and log scales, in terms of viewing both as "real" representation tools that hold advantages in different situations.

As mentioned above, the hierarchy of the categories is determined by the aspects of variation that define each category or sub-category. For example, conception 4b, the least sophisticated conception category, describes the view that scale orders detached "worlds" in a fragmented fashion, but with no actual numbers associated with such ordering. This conception contrasts with the other categories in terms of the first aspect of variation "Integration of number" — All categories except for 4b exhibit the awareness of this aspect; in other words, all the other categories recognize the integration of numbers with scale (regardless of the type of scale chosen). Similarly, the aspect of variation "Proportion" sets apart categories up to 3a from categories 2b and above in that the conceptions in latter categories all exhibit the awareness of the role of proportion in the understanding of scale, whereas the former do not. Thus categories 2b and above are considered more advanced than categories 3a and below in the hierarchy. The 1a conception sub-category, the most sophisticated conception in the typology, displays an awareness of all seven aspects of variation.

Discussion

The "size and scale" typology is a representative example of our approach to characterizing student conceptions. One might argue that the typology is merely a different version of a learning progression, particularly one centered on student thinking (e.g. Alonzo & Steedle, 2008). However, we view the difference as more substantial than visual representation alone.

First, the typology can be used in two different ways to describe students' learning progressions. One way of doing so is similar to the use of "levels" in the existing learning progression work. That is, individual students, based on their revealed conceptions, can be placed into certain conception categories (e.g. sub-category 3b) according to the criteria specified in the typology. For example, in the context of our studies, a student who exhibited a fragmented conception at an earlier point could be said to have improved his or her understanding if a more advanced conception (linear, proportional, or logarithmic) is demonstrated after instruction.

Alternatively, the unique feature of our typology whereby it describes distinct conceptions rather than individual students allows it to characterize learning progressions based on the conception, not the student. That is, the characterization of an individual student is no longer limited to one point of the progression. Instead, multiple expressions of conception from the same student can be mapped at different points in the typology. This is useful when students exhibit different conceptions, which often occurs when they are assessed with items situated in different contexts (Light et al., 2008). For instance, in our research, we have seen students who can produce and explain the log scale well when asked to place objects that vary dramatically in size along a scale of choice, but reveal a fragmented understanding when asked in general about the commonalities and differences between objects belonging to the different "worlds" (e.g. macro-, micro-, and nano-worlds). In a typical learning progression, these students are likely to be labeled either as understanding the log scale or holding the fragmented conception depending on the judgment criteria, which obviously does not accurately capture the inconsistencies within their understanding. Using the typology, however, these students can be simultaneously mapped in two categories (category 1 and 4), which indicates the lack of integration between the model of log scale (most likely acquired through instruction) and the model of separated worlds (most likely developed based on visual experiences).

Another example we have seen in our data is that some students exhibit the linear conception and the log conception depending on the assessment items. Most of these students have quite sophisticated understanding — namely they hold solid understanding of both scales, and know when and why to use them. Similarly, if using a traditional learning progression, these students are likely to be placed at one level (linear or log) only. But such placement does not reflect the connections they have established between their mental models of the linear and the log scale. The typology, on the other hand, can easily do so, and thus distinguish these students from those who understand the linear or the log scale only.

Using the typology, learning is considered to have taken place when students who previously exhibited conflicting conceptions (e.g. both fragmented and proportional conception, which disagree regarding the continuous nature of the scale) develop consistency in their understanding. The consistency here is not limited to referring to the use of the same conception in all contexts. In fact, as indicated in our typology (e.g. the aspect of variation "epistemological integration"), a coherent demonstration of knowing what scale is most appropriate in different contexts is perhaps the most desirable learning outcome.

These two ways of describing learning progression offer flexibility in instructional design. Using the typology as the guide, teachers can set learning goals in the same hierarchical order as depicted in the typology, and aim at helping students move from less to more sophisticated categories. Alternatively, the instructional focus can be centered on developing awareness of key aspects of variation (Pang & Marton, 2005), rather than moving along the "levels" or categories. As discussed above, the inconsistencies within students' conceptions reveal a lack of awareness of some of the aspects of variation. Teachers thus can use the typology as a guide in diagnosing the aspects of variation that students are struggling to grasp, and subsequently develop instructional activities to help students develop full awareness of these aspects. Furthermore, aside from diagnosing student understanding, an examination of the particular assessment items or contexts in which inconsistent conceptions were elicited could provide valuable information regarding what aspects of the context triggers (or inhibits the triggering of) certain conceptions. Such triggering factors could subsequently be made salient in instruction (e.g. through contrasting different contexts) to help students become more aware of the aspects of variation, and thus be able to transfer their conception to different situations. The success of this approach has been reported by Pang and Marton (2005) in the context of teaching the economic concept of how a product's demand and supply affect its market price.

Second, unlike learning progressions centered on student thinking, each conception in the typology does not have one corresponding descriptor. Instead, all conceptions are described by a set of aspects of variation, and what distinguishes each conception is their relationship to the individual aspects of variation. As the aspects of variation are specific, we avoid the problem of defining the conceptions with vague descriptors. Furthermore, replacing a single descriptor with a set of aspects of variation lends fluidity to the typology in terms of revision or expansion. Newly discovered conceptions could be easily incorporated by adding the aspects of variation which constitute them, without having to reconstruct and redefine the levels in a typical learning progression.

Third, learning progressions are often built based on student performances in certain assessment tasks, thus they may not be valid when different assessment tasks need to be used. The aspects of variation in our typology are not direct descriptions of student performances, but are synthesized from student reasoning behind their performances. Therefore, our typology can be used to guide the design of assessment tasks appropriate for the particular student population or instructional purposes, as long as they reflect the aspects of variation that set the conceptions apart. In fact, we encourage the use of different assessment items, which as discussed earlier, can help reveal inconsistencies in students' understanding.

Lastly, while the conceptions in our typology are hierarchy related, they do not denote various learning stages that students have to go through. Consistent with Variation Theory (Marton & Booth, 1997) that learning occurs when students become aware of the aspects of variation, we are not concerned with describing how people move through stages. Rather, we are concerned with their progression of awareness — what paths they take to realize the aspects of variation they were not aware of before, and more importantly, how learning environments can be structured to help build these paths and thus facilitate learning. Along these lines, we have developed an intervention for "size and scale" that aimed at making salient the key aspects of variation in the typology. The intervention has been piloted in two different undergraduate courses, and the data are currently being analyzed to see if the intervention is effective in heightening student awareness of the aspects of variation, and thus progressing towards more sophisticated conception.

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