Developing a Learning Progression for the Nature of Matter as it Relates to Nanoscience

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Learning progressions describe how students gain more expertise within a discipline over a period of time. They illuminate how learners need to develop certain ideas before they develop a more sophisticated understanding of the topic (NRC, 2007). The period of time that a learning progression describes can vary. Wilson and colleagues use embedded assessment in order to track the growth of students' knowledge and understanding within a single unit within a science curriculum (Roberts, Wilson & Draney 1997; Wilson & Sloane 2000; Wilson 2005). However, learning progressions can describe student learning over a much longer period of time. For example Smith and colleagues described a learning progression of how students developing a particle model of matter throughout the elementary grades (K-8) (Smith, Wiser, Anderson, & Krajcik, 2006).

Since the development of understanding depends on many factors, students can follow many paths as they move from novice toward expert understanding (Smith, Wiser, Anderson, & Krajcik, 2006). Two of the most critical factors are the curriculum and instructional practice to which they are exposed. In addition, students have different personal and cultural experiences to the classroom and as such thrive in different environments. However, instructional materials that link to students prior knowledge, actively engage students and take into consideration other factors that promote learning, can promote student learning and engagement in difficult tasks at ages much earlier than previously suspected (NRC, 2007)

The development of learning progressions can inform strategies for both instruction and assessment by providing a systematic measure of what can be regarded as “level appropriate”. Science literacy as defined by the NSES Standards (NRC, 1996) and Benchmarks (AAAS, 1993), contains an extremely broad scope of topics. The NSES standards in particular, do not suggest how ideas within this broad range of topics might be connected, or how they might build upon each other over an extended period of time. In an effort to do this, AAAS created strand maps that suggest a logical sequence of ideas for building understanding within a given topic (AAAS, 2001). However, while some of the sequencing is based upon knowledge of what is level appropriate for learners, much of it was created based on how experts structure knowledge within the discipline.

Learning progressions describe not only how knowledge and understanding develops, but also predict how the knowledge builds over time. Thus, the focus is no longer only on end-product knowledge as characterized by summative assessment, but on how students’ ideas build upon other ideas (NRC, 2007). In addition, a research-based learning progression will identify any common discontinuities in the development of knowledge. These discontinuities can represent gaps in student knowledge, or highlight concepts with which students have difficulty. This knowledge can be used to helpo inform and organize instructional practice. Thus, having a research-based progression of how students develop their understanding of important scientific concepts would be an important step for organizing the science curriculum and aligning instruction and assessment.

The emerging field of nanoscience and nanotechnology promise to greatly impact society by exploiting the unique properties of matter that are found at the nanoscale (10^{-9}-10^{-7} meters). New information and technologies resulting from nanoscience research will have broad societal implications that will be realized in many fields, including health care, agriculture, food, water, energy, and the environment. In order to determine how best to introduce nanoscience into the science curriculum, we are developing a learning progression that describes how some of the core principles, or big ideas in nanoscience might develop over time (Stevens, Sutherland, Schank & Krajcik, 2007).

One of the major challenges to bringing nanoscience and nanotechnology, as well as most emerging science, into the classroom is their interdisciplinary nature. For example, nanoscience and nanotechnology incorporate chemistry, physics, biology and engineering (Roco, 2001). This interdisciplinary nature requires students to be able to integrate ideas from several topic areas in order to explain most nanoscale phenomena. Likewise, building expert level understanding of any big idea in science requires students to draw from, and connect ideas from multiple disciplines. However, students often have difficulty making connections between different scientific concepts and ideas. One big idea necessary to understand nanoscience is the particle model of matter (Stevens, Sutherland, Schank & Krajcik, 2007). However, students often have difficulty applying knowledge from one part of the model to another (Renström, Andersson, & Marton,1990). In addition, students often use models of different levels to describe different concepts related to the structure and behavior of matter. (Harrison & Treagust, 2000).

The integration of knowledge is made more difficult by typical large-scale and classroom assessments ostensibly based on the standards that focus on low levels understanding such as describing and recalling. These assessments commonly focus on targeted, isolated topics that do not require students to connect currently taught concepts with concepts from other science areas that were previously learned (NRC, 2001; 2005). Instead, these assessments encourage teachers to focus on isolated bodies of knowledge that ultimately results in compartmentalized application of science concepts. As a result, the traditional curriculum often compartmentalizes the various aspects of the study of matter (e.g. structure of matter, conservation of matter, chemical reactions, phase changes). Thus current assessment and instruction practices can largely be described as linear in nature. A representation of this manner of instruction and assessment is depicted in Figure 1.

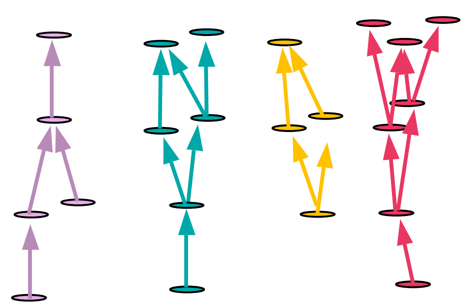


Figure 1. Representation of the isolated manner in which topics are typically introduced to students in the classroom. Each color represents a different, but related topic (e.g different chapters in textbook). The arrows indicate progress towards a more sophisticated understanding of the topic.

In order to make progress towards building students' understanding of science and scientific practice, it is necessary to begin thinking about learning with a multi-dimensional model. Conceptual understanding infers that students have the ability to transfer knowledge and apply it to related problems and to make connections between related ideas (Bransford, Brown & Cocking, 2000). The ability to make connections and apply knowledge is especially important as students build understanding within the ‘big ideas’ of science in general. The very nature of big ideas means that they encompass knowledge from a variety of disciplines, that the ideas can explain a host of phenomena, and that this knowledge must be built up over a number of years (Smith, Wiser, Anderson, & Krajcik, 2006). Thus, a learning progression for a ‘big idea’ in science should describe a progression of *sets* of ideas instead of isolated strands of knowledge (Figure 2). Therefore, it is important to identify and characterize not only the ways in which students develop understanding of the important concepts within individual, related topics under the umbrella of the big idea, but also how they connect ideas between the related topics.

The authors of documents such as Benchmarks for Science Literacy (AAAS, 1993) and the National Science Education Standards (NRC, 1996) suggested connections between key concepts among multiple disciplines in the sciences. However, these connections have not been borne out in most science curricula nor are they a part of typical assessment practices. Thus, in order to generate literacy in emerging sciences, school curricula must begin to emphasize not only the learning of individual topics, but also the connections between them and assessments must be developed to support such a curriculum. We aim to identify these sets of ideas in the arena the big ideas of nanoscience and characterize them.

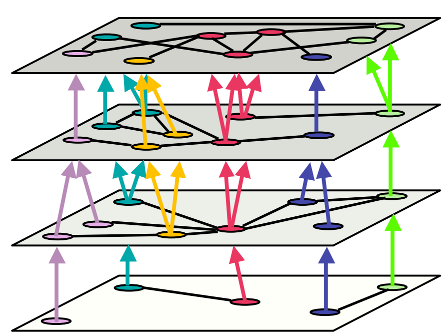
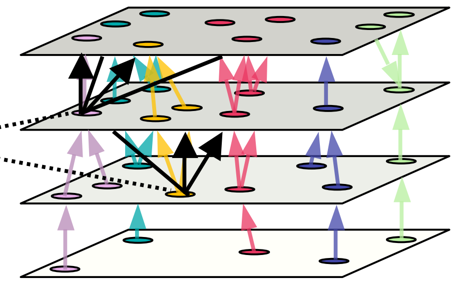


Figure 2. A representation of a progression of sets of ideas within a group of related topics. Each color represents a different topic within the nature of matter. The colored arrows depict progress towards better understanding along a single strand. The black lines represent the connections between the ideas that students should be able to make. The planes designate the sets of ideas in the progression towards building conceptual understanding.

In addition, we hope to identify any critical points along the progression that are required for progress toward a deeper level of understanding of the nature of matter. These critical points may not only be crucial for progress within a single strand, but for building understanding in other related strands (Figure 3). Identification of these points would be especially informative for organizing science instruction.

Figure 3. Certain ideas may be critical to develop understanding of concepts within multiple strands. The black arrows depict how knowledge from a 'critical point' may influence progress along several individual strands.



The study-

Learning progressions describe what it means to move towards more expert understanding in an area and gauges students' increased competence related to a core concept or a scientific practice (Smith, Wiser, Anderson, & Krajcik, 2006). They consist of a sequence of successively more complex ways of thinking about an idea that might reasonably follow one another in the process of students developing understanding about that idea. It is typical to think of this progression of understanding as being relatively linear. As science progresses, it becomes ever more apparent that the scientific disciplines cannot advance in isolation. Likewise, as we begin to address interdisciplinary subject matter in the classroom, such as emerging science, or the big ideas of science in general, we can no longer maintain the status quo. Rather, we define learning progressions as strategic sequencing that promotes both branching out and forming connections between ideas related to a core scientific concept.

This study describes work towards developing and validating the sequence and assumptions behind a learning progression for students' understanding of the nature of matter as it relates to nanoscale science. The work informs both the curricular organization and instruction by providing insight into how students connect ideas from other science disciplines with a core scientific concept. Thus, this approach might provide a method for identifying the connections that are required to obtain a deep conceptual understanding of an interdisciplinary field such as nanoscience.

Study Design and Methods

The process of developing a learning progression-

The framework that we chose to build our learning progression is based largely upon the evidence-centered design framework (Mislevy, & Riconscente, 2005; Mislevy, Steinberg, Almond, Haertel, & Penuel, 2003). This approach centers around answering three questions: (1) What should be assessed?, (2) What type of learning performances will best illustrate students' knowledge?, and (3) What tasks, questions or situations will bring about the appropriate type of response?

In order to determine what to assess, the first step is to create a model that describes what the learner should know. In our case, we developed a model that represents the set of ideas that defines expert understanding for the "Nature of Matter" as it relates to nanoscience. We divided the conceptual space up into four "conceptual dimensions" (Savinainen & Scott, 2002; Hestenes, Wells &

Swackhamer, 1992). Each of these dimensions is related to one of the 'big ideas' of nanoscience: (1) Structure of Matter, (2) Size-Dependent Properties, (3) Forces and Interactions, and (4) Quantum Effects. Ideas that describe concepts related to, or necessary for understanding nanoscale phenomena were collected and categorized within these four conceptual dimensions. Because of the interdisciplinary nature of the field, many ideas fall into multiple dimensions. (See Appendix A for our expert model).

Each of the ideas within the expert model is then evaluated to determine what would be acceptable evidence that students possess adequate knowledge about it. Since the ultimate method of assessment for each of the ideas might vary, we relied on broad categories based on Bloom's Taxonomy to characterize our evidence (Table 1) ((Krathwohl, 2002). In addition, we included communicating a model, or modeling as a potential source of evidence.

Table 1: Summary of Student-based Evidence

Describe	*A statement of fact, description of an object or phenomenon; answers what*
Explain	*A statement using evidence and/or reasoning; answers why, or how*
Evaluate or analyze	*Compare one phenomenon or model to another*
Apply	*Transfer knowledge to new problem; relate ideas to each other*
Model	*Build, create, generate, express model*

Finally, the type of tasks or questions that would allow the desired evidence of student understanding to be obtained was determined, and then the appropriate assessment items developed. While developing the questions and tasks to assess student understanding related to the nature of matter, we also incorporated knowledge of potential student misconceptions. This information was used to strategically choose tasks that would elicit students' misconceptions if present.

The Nature of Matter-

Nanoscience and nanotechnology are based largely in exploring, explaining and applying the novel, often unexpected properties of matter at the nanoscale. While atoms are the building blocks for molecules, the building blocks for nanoscale structures and assemblies are atoms, molecules and other nanoscale structures and assemblies. The physical laws that describe the behavior of these building blocks are the same. Therefore, an important aspect of nanoscience literacy must include a robust model of not only the structure of matter, but also its properties and what determines those properties, as well as how matter behaves and interacts under a variety of conditions.

In order to build a deep understanding of the nature of matter, students must be able to connect many related ideas. For example, in order to explain the difference between the formation of a salt (NaCl) and a diatomic gas (Cl_2), they must understand many ideas related to atoms and their structure and how they interact. In particular, students must know that atoms are the fundamental building blocks of matter. In addition, they must know the composition of atoms, and that the configuration of electrons, especially the outermost electrons, influences the manner in which atoms can interact. They must know that the arrangement of atoms is an important determinant of the properties of the substance and that electric forces hold atoms and molecules together and how that affects bond energy. They also must connect those concepts to knowledge of how the electrons behave. In particular, they must understand that the likelihood that an atom accepts or donates an extra electron is predicted by the Periodic Table. The difference in the tendency to accept or donate electrons plays a role in the type of electric forces that govern the interactions between atoms. Thus, students must be able to integrate ideas from several different topics in order to explain the formation of these two substances. These ideas cannot be developed at once but must be built up over time in conjunction with rich experiences. Most importantly, these ideas will only develop if students have developed other important build blocks of understanding.

We conducted interviews with middle school and high school chemistry and pre-chemistry students and undergraduate students to measure their conceptual understanding of the structure, properties and behavior of matter, in order to test aspects of this hypothetical progression. To complete the progression, we will interview undergraduate science and non-science majors and experts. However, here we report only on middle school and high school and a partial set of undergraduate students' conceptual understanding of the nature of matter.

Participants-

The participants belonged to three distinct populations. The middle and high school students were all from public school districts that were located in either a diverse, urban community where approximately half of the students were of low SES (N=36) or in suburban and rural, predominantly white middle-class communities (N=14). In addition, we interviewed undergraduates from a large Midwestern research university, both science and non-science majors (N=6).

The majority of middle school students were in seventh grade. The high school students were divided up into two groups, those who were in, or had taken chemistry, and those who had not. The middle and high school students were selected to fill out a 3-D matrix of educational level (middle school-high school), academic ability and gender. The academic ability was determined by their teacher and was not necessarily linked to their academic performance. The undergraduates were from a select university and had all completed at least one year of high school chemistry. Those who are science majors (N=2) had completed some undergraduate-level chemistry courses.

Instrument-

In order to test the validity of this progression of ideas, a 20-30 minute semi-structured interview was developed to probe students' understanding of concepts within the nature of matter. The topics included, the structure of matter, its properties and their source, conservation of matter, atomic models, and the forces and interactions that occur between atoms and molecules. Interviews were conducted with individual students ranging from middle school level to undergraduates. Table 2 presents a summary of the tasks/questions asked during the interview. Table 3 provides an example of how we collected evidence for student understanding.

Table 2: Summary of the tasks/questions-

Topic	**Task/Question**
Structure of Matter	*Draw and describe the structure of a sheet of metal; Draw and describe the process of melting*
Properties of Matter	*Compare powdered and granulated sugar; explain whether the arrangement of particles important* ***Model of Atoms-*** *Explain the importance of atoms; draw an atom and explain it; State how many particles thick a 0.5 mm metal is*
Electric forces; Forces & Interactions	*Explain what is keeping the particles of the solid (or liquid) together; explain why powdered sugar sticks to a surface more than granulated sugar does; explain ionic and covalent bonding*
Quantum Effects	*Explain your model of an atom*

See Appendix B for full interview protocol.

Table 3. Representative assessment item-

Sample assessment item	
Idea from claim space	Matter is made up of particles
Evidence	Explain; draw
Task	Please draw what you think this sheet of metal is made of. If student drew particles, they must explain their reasons for the arrangement and the characteristics of the particles.

Data analysis-

The data was analyzed using a set of codes designed to track progress in student knowledge of a given concept. Tables 4 and 5 give general formats of the coding schemes followed. The full coding scheme contains 26 different codes that largely follow one of these formats . The first author coded 100% of the data. A second independent rater coded a subset of the data that was selected at random. Approximately 80% agreement was achieved independently and 98% agreement was reached after discussion. We are continuing to work towards a better inter-rater reliability.

Table 4: Atomic model-

Code	Description	Examples
0	Does not know	
1	Student believes electrons are stationary	
2	Student adheres to a solar system model for electron orbitals.; (Bohr model)	“the electrons kind make a field around the nucleus, the nucleus is a tightly compact center where the protons and neutrons are and they just kind of form this circular middle where the electrons kind of go around in their orbits around the nucleus”(BC)
3	Student understands that solar system model is wrong; uses some kind of “cloud” explanation	“There is a like a nucleus kind of thing in the center of it. I know that much, And then there’s like all these crazy, like they draw them generally with like the nice little lines—like this is an atom. But truthfully, everything’s like cchzzzch…. (scratching around to show that the electron is moving fast) like it’s going crazy because it moves so fast…” 0086
4	Student discusses electron clouds and relates to probability.	

Table 5: Characterisitics of particles on the surface vs. bulk particles

Code	Description	Examples
0	Does not know	
1	Student believes that atoms on the edge of metal are different than those in the bulk.	Draws circles. Not sphere-like, but flat to make edge smooth; Draws an oval. All atoms are ovals because even the top is smooth. (7a) half circles instead now (on the edge) to make sure that they’re straight. (BG)
2	Student believes that the edge is smooth because the particles are too small to feel.	“I’d keep the same picture (ordered circles), well I’d draw a straighter line around them.” (RW) “I mean they’re small enough we can’t even tell if there are dips.” (VB)

Each of the codes was deconstructed and separated into single ideas (See Table 6) (Minstrell, 1982). This list could contain ideas from every level of the hierarchical scheme. This provided a finer measure for tracking how students build upon their ideas.

Table 6.

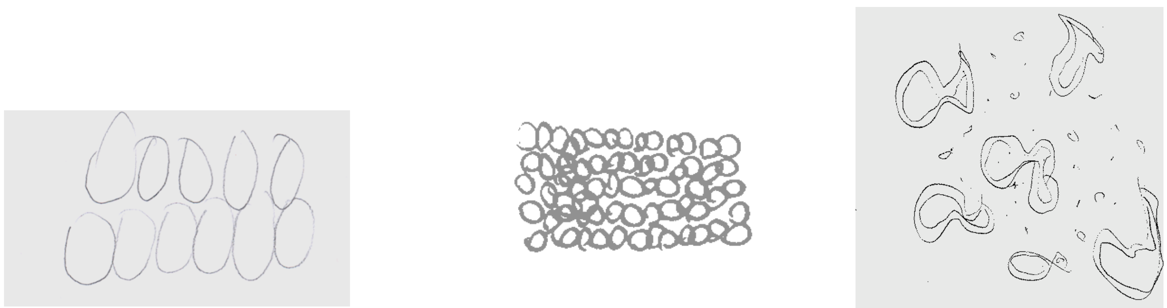
Atomic model-
All matter is made up of atoms
Atoms are made up of protons, neutrons and electrons
The nucleus is in the center of the atom and consists of protons and neutrons; the electrons lie on the outside
The mass of neutrons and protons is about equal and much greater than that of electrons
The nucleus takes up only a small percentage of the atom's volume
The number of protons defines the type of atom
Changing the number of neutrons while the protons remain constant creates a different isotope of the same element
The relative number of protons and electrons is important. If the number is not equal, an ion is formed and has a non-neutral charge
The electrons are in motion around the nucleus
The electrons do not move in planetary-like orbits, but electron clouds
Probability model for electron behavior. Heisenberg Uncertainty Principle

Table 6. The table describes the different ideas students may have as they build up an expert model of the structure of an atom. These ideas do not necessarily represent any purposeful progression.

Different types of progressions were created using this data. Summarizing the hierarchical codes and graphing them versus the point that the students fell in the curriculum provided insight into how their ideas about each separate concept were developing over time with respect to science instruction. The hierarchical codes tended to represent multi-faceted models. The codes were deconstructed and divided into single ideas in order to determine how students build their models. The data was analyzed as a binary variable in which the students understood it or not. The percentage of students who held the idea within the model was tabulated and ordered to form a preliminary progression that describes how students add ideas to build more sophisticated knowledge.

RESULTS AND DISCUSSION-

The interview data were coded using a hierarchical coding scheme to rate student understanding of ideas related to the nature of matter. Figure 4 depicts three student drawings of the structure of a solid sheet of metal with accompanying descriptions.



A. Code- 4
"Evenly spaced rows of atoms"
"In solids they are (packed together) …all closer together"
3002

B. Code- 3
"Made outta atoms"
"more bunched up than that"
0061
(missing ordered)

C. Code- 2
"Little dots and stuff would be the molecules… (blotches) would be like the molecules when they come together and get stuck into each other…to harden they have to like all come together"
0049
(seems to oscillate between particle and continuous model; no mention of order)

Figure 4. Examples of student generated drawings of their beliefs of what a sheet of aluminum is made with excerpts from their explanations of their drawings.

We conducted statistical analysis using the one-way ANOVA with three groups of students (middle school = 17 students, pre-chemistry = 16 students, and chemistry = 18 students). We did not use the data from college students in the analysis because of its small sample size (N = 6). Although we excluded the college students from the data analysis, the sample size in each group was still not be enough to conduct statistical analysis in some of the 26 categories because of missing data. However when possible, we ran analyses for investigating statistical differences among three groups on their scores to support qualitative data results. The statistical results were interpreted only if the data met a basic assumption for the use of ANOVA, which the variances of three groups are similar (homogeneity of variance). As shown in Figure 5, the quantitative data results indicate there are statistically significant differences among three groups (middle school, pre-chemistry, and chemistry student) on their performances in the particle model of matter, $F(2, 44) = 3.39$, $p < 0.43$. The chemistry group ($N = 17$, Mean = 3.26, $SD = 0.94$) outperformed the middle school ($N = 16$, Mean = 2.63, $SD = 0.89$) and the pre-chemistry ($N = 14$, Mean = 2.57, $SD = 0.65$) groups. However, there is not a significant difference between the middle school and the pre-chemistry students on their scores for the particle model of matter.

The data indicate that as students progress through the science curriculum, their knowledge builds toward a more sophisticated model for the particle model of matter. In this case, the middle school and high school students that had not yet studied chemistry possessed a similar understanding of the structure of solids. Chemistry instruction appears to shift their understanding to a more complete model. A portion of the undergraduates had completed more than one year of chemistry (AP- Chemistry or college-level. However, the increase in understanding may also be due to the fact that they attend a competitive university. Once we collect a full sample of undergraduate students, both science majors and non-majors, we should be able to make more definitive conclusions. A qualitatively similar type of progression of understanding was observed in most of the 26 categories for which we coded.

While this type of growth was observed for most of the ideas related to the nature of matter, there were a few ideas where students' conceptions did not predictably advance. In particular, no significant progress was observed in the students' ability to provide properties to unambiguously identify a substance (Figure 6). The pre-chemistry (N = 12, Mean = 1.67, SD = 0.49) and chemistry groups (N = 13, Mean = 1.62, SD = 0.51) had slightly higher scores than middle school group (N = 15, Mean = 1.33, SD = 0.72). However, the differences among three groups are not statistically significant. Moreover, the overall performances on the properties of substance were relatively poor, 1.53 (31%) out of 5 points in a maximum score.

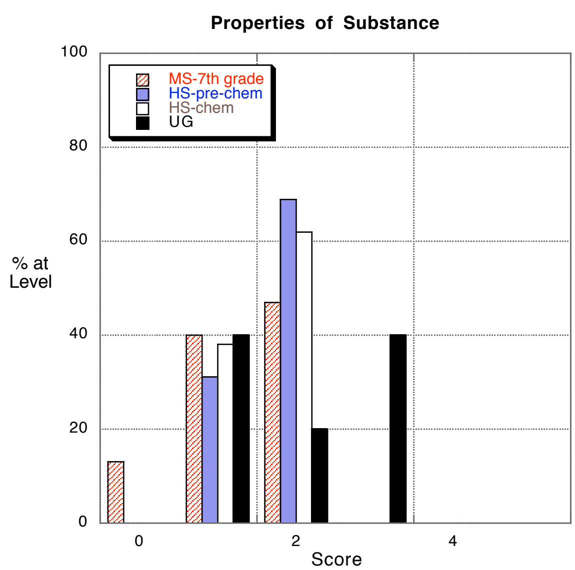


Figure 6. Representation of the properties students would use to characterize a substance.

Coding scheme for properties of a substance
0 Does not know
1 Relies only on extensive properties
2 Extensive + intensive properties, but does not specify any meaning to the difference
3 Extensive + intensive properties; understands the value of intensive properties
4 Separates the bulk properties (intensive + extensive) from the atomic/molecular properties
5 Intensive properties likely change at the nanoscale.

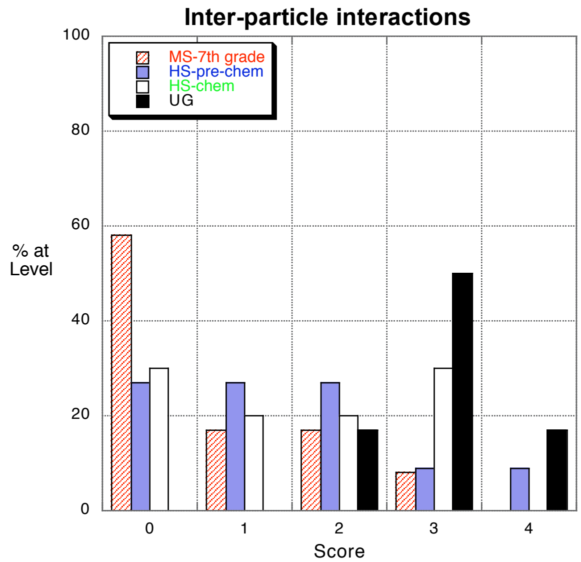


Figure 7. Representative graph depicting students' ideas about inter-particle forces within a solid as they move through the curriculum.

0 Does not know
1 Student believes something other than a force keeps the particles together.
2 Student believes gravity keeps the particles together.
3 Student provides a scientifically accurate, but incomplete answer. May mention a force, but not sure what it is.
4 Student believes interactions between electrons keep the particles together

In addition, students appeared to make little progress in regards to developing an understanding of the electric forces that govern interactions on any scale. Figure 4 depicts the slow advancement of students' knowledge about intermolecular forces. The results of the data analysis for inter-particle interactions indicates that the scores increased from the middle school (N = 13, Mean = 0.69, SD = 1.03), pre-chemistry (N = 10, Mean = 1.20, SD = 0.10), to chemistry (N = 10, Mean = 1.50, SD = 1.27) groups. However, the increased scores are not statistically significant among three groups. The student performances in three groups were lower than 40% out of the maximum score (Mean = 1,09 out of 4 points). A similar trend was seen in their responses to questions regarding similar phenomena related to electric forces.

We probed students' ideas about electric forces multiple times and in multiple contexts throughout the interview. However, these probes require students to apply their knowledge in a way that may not be typical of their experience. We assessed student knowledge of dipole-dipole and van der Waals forces by asking them to explain the phenomenon of powdered sugar sticking to a plastic surface. This task may be difficult for students for several reasons. First, students often believe that bonding can only be intramolecular (Taber & Coll, 2002). Therefore, they may not make the connection between the electrical forces that govern inter-atomic interactions in relation to macroscopic phenomena. In addition, students traditionally have more difficulty understanding intermediate bonds (e.g. hydrogen bonding and van der Waals forces) (Taber & Coll, 2002; Peterson & Treagust, 1989; Nahum, Mamlok-Naaman, Hofstein & Krajcik, *in press*). Often, they rely only the octet model to explain inter-atomic interactions, which makes it difficult for them to explain the other types of interactions that form the continuum of electric forces at the nano- and atomic scales. In our next phase of data collection, we will work to assess student knowledge of forces in both familiar and applied contexts.

Building progressions for the four dimensions of the nature of matter-

In Figure 8, we have summarized the data relating to students knowledge of the structure of solids. The graph depicts the number of students that achieved the top level in the coding scheme. In general, the students exhibit a progression towards understanding the individual ideas. However, it is clear that they do not progress very far towards building an understanding of the importance of the arrangement of particles and the forces that govern the interactions between them.

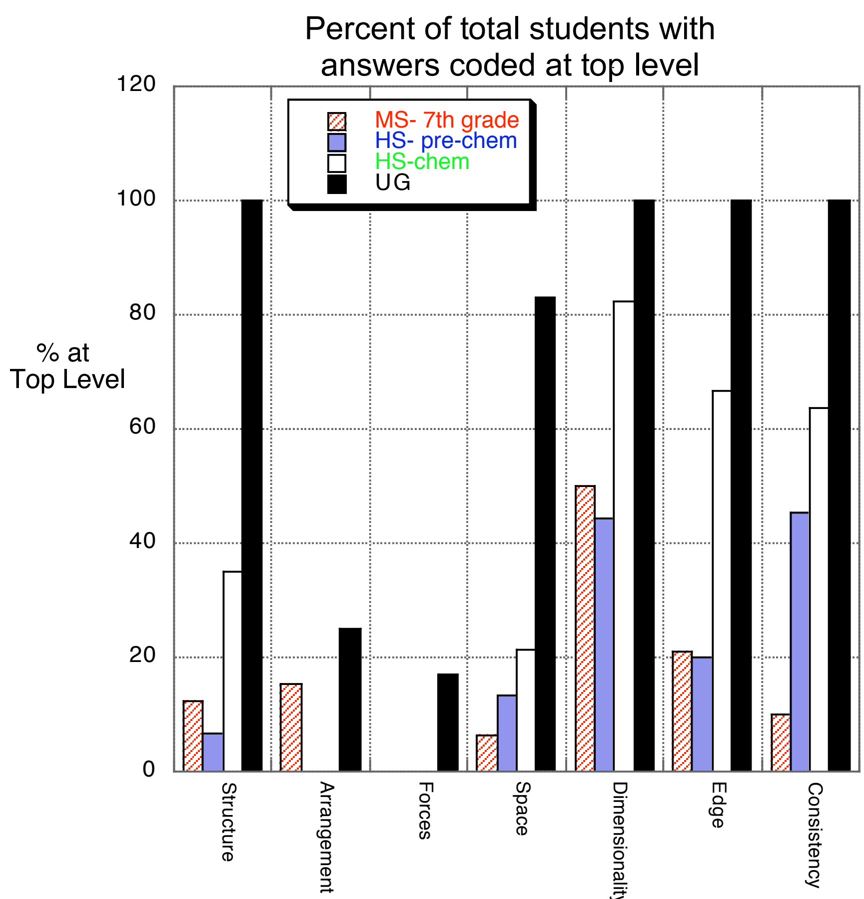


Figure 8. Graph depicting the percent of students that achieve the top level of the code as they advance through the science curriculum. Structure is structure of matter as depicted in Fig. 6. Arrangement refers to the effects that the arrangement of atoms has on matter. Forces refer to the inter-particle interactions within a solid. Space refers to what is in the space between atoms. Dimensionality refers to whether atoms are 2-D or 3D. Edge indicates students' responses when asked to reconcile why the edge of a sheet of metal feels smooth when their drawing of rows of circles looks like it would be bumpy. Consistency refers to students' beliefs about the consistency of size and shape of atoms.

Structure of Matter (solid)

We then began to build a preliminary progression that describes how students develop their models of the structure of matter. We grouped several related individual ideas to build up an expert model for the particle model of matter (Table 7). The ideas were sorted by the percentage of total students that held these ideas. The majority of students believed that solids are made of particles (83%). Fewer (approximately half) were able to express both verbally and through drawings that the particles were arranged in an ordered, compact manner in a solid. Likewise, about half of the total students made the connection that the particles are atoms. With our current data set, we cannot tell which idea students tend to hold first. The understanding that the atoms are in constant motion and the importance of their arrangement comes much later in the students' model development. 31 of 35 students fit this tentative progression: P1- solids are made up of particles; P2/P3/P4 (in an as-yet-to-be-determined order), particles in a solid are arranged in a compact ordered manner, the particles are atoms; P5/P6/P7 (also in an as-yet-to-be-determined order). Two students who did not fit the progression stated the importance of arrangement of particles before they made the connection to atoms. Another believed that the particles are in constant motion even though they could not name the particles to be atoms. As this progression becomes more robust, we will compare it to the progressions proposed by the national standards (AAAS, 2001).

Table 7.

Particle model of matter (solid)		
Individual Idea		**% of total students**
P1	Solids are made up of particles	83%
P2	Particles are arranged in a compact way	50%
P3	Particles are arranged in an ordered way	44%
P4	The particles are atoms	42%
P5	The particles/atoms are in constant motion	12%
P6	The arrangement of atoms determines the properties	7%
P7	The arrangement of atoms determines the substance	6%

Table 7. Description of the individual ideas that fall within the particle model of matter and the percentage of total students that hold them.

Characteristics of particles/atoms-

Since the majority of students held a particle model of matter, we evaluated how they characterized the particles themselves (Table 8). When students hold a particle model of matter, but have not made the connection that the particles are atoms, they have not developed a sophisticated model for the particles. In contrast, once they believe that the particles are atoms, they also seem to have a better conception of the characteristics of the particles.

Table 8.

CP Characteristics of particles-		
Individual Idea	**% students particle model**	**% students particles are atoms**
Dimension of particles (2D or 3D)	45%	100%
Particles on the surface vs. bulk particles	25%	86%
Consistency of size	33%	83%
Consistency of shape	29%	80%

Table 8. The table describes the percentage of students characterizing the particles/atoms and compares how student understanding differs in relation to whether they have made the connection that the particles are atoms.

Students' model of the atom-

We then sought to characterize how students progress towards building their models of atoms (Table 9). A majority of students possessed the declarative knowledge that "all matter is made up of atoms". However, only half of those students knew anything about the structure of the atoms. While the electron cloud model was relatively frequently part of their models of the atom, discussion of probability to explain electron behavior was rare. 29 of 33 students fit the progression represented in Table 9. 72 percent of the students believed that all matter is made up of atoms. This was likely just declarative knowledge for a significant portion of them because only half of those students had any degree of understanding about the composition or structure of atoms. Approximately half of the students that believed that atoms make up all of matter were able to discuss the composition and structure of atoms in an as-yet-to-be determined order: atoms are composed of protons, electrons and neutrons; protons and neutrons make up the nucleus, which is the most dense part of the atom; electrons are much less massive than protons and neutrons; electrons surround the nucleus in cloud-like orbitals; the number of protons defines what kind of element the atom is. Finally, only nine percent of students described electron behavior in terms of probability. Two of the nine students did not state that all matter is made up of atoms even though they used atoms as part of their model of a solid.

Table 9.

Atomic Structure		
Individual Idea		**% of total students**
A1	All matter is made up of atoms	72%
A2	Atoms are made of protons, electrons and neutrons	39%
A3	Protons and neutrons make up the nucleus which is surrounded by electrons	39%
A4	Protons and neutrons are approximately of the same mass, which is much greater than the mass of electrons	31%
A5	Electron cloud model	28%
A6	The relative number of protons, electrons and neutrons is important	23%
A7	Probability model for electron behavior; Heisenberg Uncertainty Principle	9%

Table 9. Description of the individual ideas that fall within Atomic Structure and the percentage of total students that hold them.

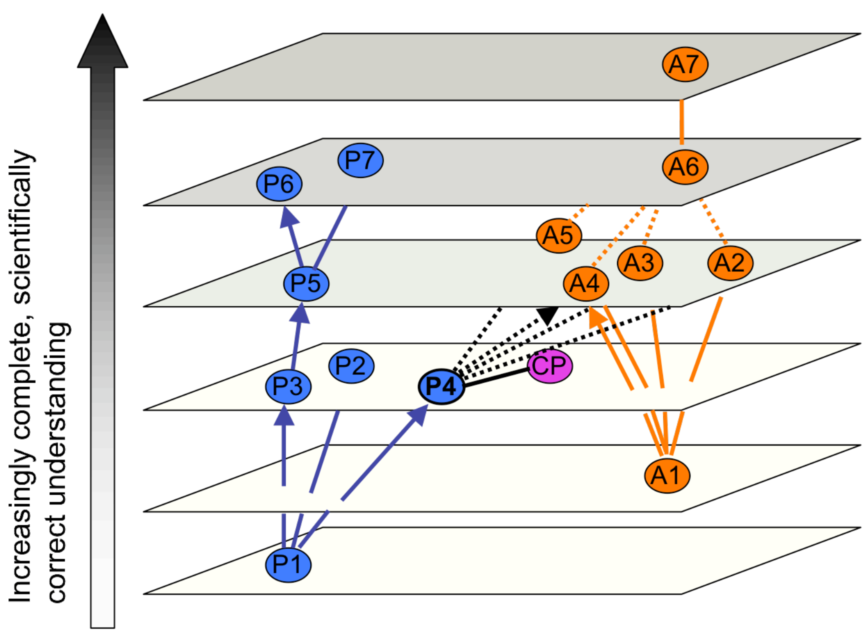


Figure 9. Part of a preliminary multi-dimensional progression of ideas for the Structure of Matter are depicted. Tentative connections are depicted with dashed lines. The connections are tentative because we cannot definitively define the progression between A2, A3, A4 and A5 with our current data set. Most of the students that understand that the particles are atoms are able to begin to understand parts of the structure of atoms. The solid black line depicts a connection within the same plane. See Tables 7, 8 & 9 for descriptions of the abbreviated codes and colors.

A tentative multi-dimensional progression-

From this data, we can begin to construct a very tentative multi-dimensional learning progression for the Structure of Matter dimension of our model for the Nature of Matter as it relates to nanoscience. We found that students do not hold robust ideas about the characteristics of the particles that make up solids until they make the connection that the particles are atoms. Therefore, the 'characteristics of particles' is in the same set (or plane) as the idea that the particles that make up solids are atoms. Since students' knowledge about atoms comes in later, their model for atomic structure and composition must start at a higher level. We have placed it on the diagram just to illustrate the process. We are beginning to look for the connections which are represented by the black dotted lines as we work to connect the individual progressions. These progressions are all quite tentative. We will continue to collect and analyze data to build validity for the progression.

Future work-

We found that many of the ideas in the claim space were not fully understood by students earlier in the curriculum (i.e. pre-chemistry). Therefore, we will expand the claim space to better describe the more fundamental ideas that are prerequisite to those in the claim space. We will continue to build and revise the multi-dimensional progressions of ideas to better represent not only the final ideas that students must hold, but also ideas that lead to conceptual understanding. In addition, we will revise our interview protocol to better assess our claim space. Once we collect more data, we will be able to begin evaluating the ideas for covariance.

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Appendix A- Expert model.

What will we take as evidence of Nano-related Matter Knowledge?

How well do our tasks collect the desired evidence?

Nature of Matter (nano-related)

Structure of Matter

Kinetic theory-
1, 2 -particles are always in motion (except at 0° K) describe
2 -degree of motion dependent on temperature explain

States of matter-
1, 2 Motion of particles
solid < liquid < gas explain apply model
2 Different states have different degrees of order explain model
solid < liquid < gas
1, 2 There is empty space between particles
- the amount of space is related to the phase it's in explain model
solid < liquid < gas

Particle model
X -The stuff everything is made of is matter explain
1, 2 -Matter is made up of particles explain model
1 -Particles are too small to see describe
1 -Particles are too small to see with a light microscope describe
1 -The particles are actually atoms describe

Atoms
4 - Atoms make up all of matter describe
4 - fundamental building block of matter (smallest unit of an element) describe

Size of atoms
1,4 - atoms are too small to see describe
1,4 - atoms are too small to see with an optical microscope explain
1 - atoms of same type are same size explain
1 - all atoms are ~1-2Å in diameter describe

Elements-
- ~100 elements make up all matter describe
The Periodic Table:
5 - predicts many properties of elements explain apply
5 - predicts how a type of atom will interact with another explain apply evaluate
4 - indicates the number of protons in an atom describe
5 - indicates the number of electrons in the outer shell of a neutral atom describe apply

Properties of Matter

Properties-
3 - Extensive properties describe evaluate
- external appearance, size, mass, etc.
3 - Intensive properties do not change at the macroscale explain evaluate
3 - chemical, density, melting point. etc describe
3 - macroscale properties vs atoms and molecules explain
3 - Nanoscale properties vs macroscale explain

Composition of Atoms
4 - atoms are made of electrons, neutrons and protons describe model
4 - neutrons and protons are of similar mass, electron mass is much smaller describe model
4 - electrons are negatively charged, protons are positively charged and neutrons are neutral describe apply
4 - the number of protons determines the type of element describe
4, 5 - adding or subtracting electrons creates an ion explain model apply

Arrangement of particles
1,3, 5 - determines the substance explain
1, 3 - determines the properties explain
There is space between particles
1, 2 - there is empty space between the atoms explain model
1 - metals have delocalized electrons between atoms explain

Forces & Interactions

Quantum Effects

Forces
0 - gravity is always attractive explain
0 - gravity is dependent on mass explain apply
0 - electric forces depend on charge explain
5 - opposite charges attract; like charges repel explain apply

Inter-particle forces
1,2,3, 5 - there is an attraction between particles describe explain model
0 - a range of electric forces govern interactions between atoms, molecules and nanoscale objects explain
5 - electrostatic interactions (charge-charge, ionic) explain model apply
5 - covalent explain model apply
0 - hydrogen bonds explain model apply
0 - dipole-dipole explain model apply
1,2,3, 5 - induced-dipole--induced-dipole (London dispersion forces) explain model apply
0 - metallic bonds explain model apply
5 - the outer shell of electrons is involved in inter-atomic interactions

Structure of Atoms
4 - neutrons & protons make up nucleus of the atom, electrons on the outside describe model
4 - electrons are in constant motion describe
4, 5 - electrons exist in "orbitals" describe
5 - a certain number of electrons are allowed in each orbital describe
4 - the electron orbitals/shells take up the majority of the space explain
0 - the energy of the electrons within an atom is quantized explain
4 - electron motion is not like solar system model explain
0 - electrons exhibit particulate and wavelike behavior describe
4 - electron cloud model describes the probability of the electron location explain apply
0 - Heisenberg's uncertainty principle explain

OUR TASKS-
1- Draw what a sheet of metal is made of and explain your drawing
2- What happens if we heat the metal and melt it?
3- Difference in properties and behavior of granulated and powdered sugar
4- importance of atoms & structure
5- Ionic vs covalent interactions & substances
0- not probed
#- not probed directly

DIMENSIONS-
Structure of matter
Properties of matter
Forces & Interactions
Quantum effects

EVIDENCE-

Describe-	statement, description, declarative
Explain-	describe + why it's that way/ a phenomenon
Evaluate-	compare + describe + why
Apply-	evaluate + describe + why/ a phenomenon
Model-	build, generate, express model

Appdenix B. Nature of matter interview protocol

Hi. Thanks for volunteering to talk with me. This is an interview so that we can find out what you think about some science topics. I'm going to ask you some questions about matter, you know, the stuff things are made of. This will not affect your course grade. We are not looking for right or wrong answers. We just want to know what you think. This will help us design better science materials. Also, this will be completely confidential. Your teacher Mr. Sowder will not hear anything that you say. Do you mind if I turn on the tape recorder? Thanks.

-What is your name?

-What grade are you in?

-What science class are you taking now?

Structure of matter

Verbally scaffold. DO NOT use the term atom or molecule.

I have this sheet of metal. *(Hand it to them so that they can touch it, etc.)*
Imagine that we have an instrument that lets us "zoom in" and see what it's made of –
What do you think the surface would look like?

Will you draw it for me?

Explain to me what I'm looking at. *(probe as necessary)*

If they don't get down to the atomic/molecular scale, then continue to find out their perception of fundamental structure. (If student doesn't understand, ask him/her to draw what a "speck" of metal looks like from very close, "blow it up big on this paper".)

-OK, now let's zoom in some more. Does the surface still look the same?
-What does it look like?
-Can you draw it for me?
-Describe your picture to me… *(probe as necessary)*

If they draw particles-

- What are those dots (or whatever) you have drawn?
- Tell me about them.
- What do they represent?
- How big are they?

(whatever's appropriate from the picture)
Those particles are in a very regular pattern.
-What makes them arrange like that?

-Do they have to be in that arrangement?
-What makes them stay that way?
-Why don't they fall apart?
-What's in the space between the particles?
-Are they 2D or 3D (like penny or marble)

-How many particles do you think are stacked up to make the metal this thick?

This edge looks looks like it would be lumpy. (point to edge the last row of circles)
-Why does it feel so smooth?

if say cut or polished, etc.--
Would you draw what you think the edge looks like?

Now let's heat the metal and melt it.
-What do you think melting means?
-What is happening when it melts?
-Is anything happening to the particles?

Would you draw a picture of what it looks like now?
-Explain what I'm looking at.

Probe as necessary-
You have drawn some difference between the pictures of the liquid and solid form of this substance.
-Is there anything different about the particles in this liquid versus the solid up here?
-Are they the same?
It looks like you drew more space between your particles here than in the solid.
-Why is that?
-What's in that space?

OR

You haven't drawn any particles in the liquid.
-What happened to them?

Change of properties with scale—change in dominant force

Now we're going to talk about a different substance. Here are 3 forms of sugar—a big crystal or rock candy, granulated sugar and powdered sugar.

-Would you still consider these to be the same substance?
If no, -why not?

-Which properties do you think are the same? Different?

-Do you think the sugar act the same way no matter what size it is?

Here is a little experiment using our sugar samples.
Pour the granulated sugar and powdered sugar off of the black contact paper. ***Do not tap on table.***

-Do you notice any differences in the behavior of the two samples?
-What differences do you see?
-What do you think causes those differences?

If necessary-

Part of the card is covered with a single layer of powdered sugar, and part has some clumps of sugar.
-What's keeping it from falling down?
-What's keeping the clumps together and stuck to the card?
-How come most of the powdered sugar did fall down?
-Why aren't there any clumps on the regular sugar card?

OK, now powdered sugar is made up of pretty small pieces but we can keep crushing it up even more. How long can I keep crushing it up? What is the smallest piece of sugar there can be?

If get molecules--

-Is there anything different about properties of sugar molecules than the sugar we see here?
-What makes the molecules come together and stay together to make the substance that we can see and use?
-Is this going to be the same for any substance?

If get "disappeared" or "it's gone", etc., probe further.

Nature of Atoms

Now I'd like to talk about atoms.

If they never mentioned atoms above,
-Do you know what an atom is?

Otherwise, keep going.
-Why are atoms important?
Think about what an atom looks like.

- Would you please draw a picture of an atom for me?

Describe what I'm looking at.

If they get to protons, neutrons and electrons-

Tell me about p, n and e.

- How do they **compare?**
  - -size (is your drawing to scale?)
  - -mass
  - -charge
  - -location (nucleus vs electrons)
  - -behavior (movement, etc.)
- Is the number of p, n, e important?
  - (Is there always the same number of each in each element?)

Electronic Nature of Chemical Reactions-

Atoms combine to make up all of the substances around us. Two examples are chlorine and sodium chloride.
(give them the periodic table and a paper with formulas written on them.)

-Can you explain why the atoms combine in these ways?

If necessary can reword as-

-What determines how atoms can combine?

Feel free to write on the paper if that's easier for you.

-What is different about how these two substances are formed?