Using Learning Progressions to Inform Curriculum, Instruction and Assessment Design

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Introduction

Nanoscience research is rapidly developing strategies for creating new products and technologies by controlling matter at the nanoscale. New information and technologies from nanoscience research is and will continue to have broad societal implications that will be realized in many fields, including health care, agriculture, food, water, energy, and the environment. Moreover, nanoscience promises to have significantly greater impact on society than previous leaps in scientific knowledge because it represents a convergence of science disciplines on the nanoscale. (Stevens, Sutherland, Schank, & Krajcik, 2006). To understand the new discoveries and technologies of nanoscience research requires a population with a high degree of science literacy. It is the responsibility of our national, state and local education leadership to prepare our students such that they are scientifically literate, and can play a key role in securing the nation's economic prosperity, and participate in a global, technologically advanced society.

Nanoscience and nanotechnology incorporate aspects of chemistry, physics, biology and engineering to create highly interdisciplinary fields (Roco, 2001). One of the major challenges for bringing nanoscience and nanotechnology, as well as most emerging science, into the classroom is their interdisciplinary nature, requires students as well as science teachers to be able to integrate ideas from several topic areas in order to explain many nanoscale phenomena. Science is traditionally presented in a discipline-defined rather than cross-disciplinary manner. Thus, introducing nanoscience to the classroom requires changes in instruction, assessment and curriculum development. 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. In addition, we need to determine how to embed new ideas from nanoscience that are not traditionally covered in the current science curriculum.

Learning progressions, which describe how students build their knowledge over a period of time (NRC, 2007) can help address this challenge. To this end, we are working towards developing a learning progression that can be used to determine (1) how do concepts logically and successively build upon other concepts?, (2) What grade level is appropriate to introduce particular concepts?, and (3) What are the critical connections between ideas that students need to make in order to understand the nature of matter as it pertains to nanoscience?

Theoretical Background

What is a learning progression?

Learning progressions describe how students gain more expertise within a discipline over a period of time. They represent not only how knowledge and understanding develops, but also predict how the knowledge builds over time. Thus, the focus is not limited on the end-product knowledge as characterized by summative assessment, but on how students' ideas build upon other ideas (Duschl, et al., 2007). The period of time that a learning progression describes can vary. Wilson and coworkers use embedded assessment in order to track the growth of students' knowledge and understanding with in a single unit within a science curriculum (2006). However, learning progressions can describe student learning over a much longer period of time. For example Smith and colleagues described a learning progression as how students are 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, et al., 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 of other factors that promote learning can support students learning and engaging in difficult tasks at ages much earlier than previously suspected (Duschl, et al., 2007).

Why do we need learning progressions?

Learning progressions can inform strategies for instruction and assessment by providing a systematic measure of what can be regarded as "level appropriate". Most decisions about instruction and curriculum sequences in science have their foundation in standards. However, 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 research-based knowledge of what is level appropriate for learners, much of it was created based on how experts structure knowledge within the discipline. Therefore, learning progressions informed by a long-term understanding of learning and development that is grounded in the findings of contemporary cognitive, developmental, education, and learning science research can have a great impact on the success of instruction and assessment strategies.

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 et al., 2004). 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. However, 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 do so. Rather, we define learning progressions as strategic sequencing that promotes both branching out and forming connections between ideas related to a core scientific concept, or big idea.

In this case, a learning progression would describe a progression of *sets* of ideas instead of isolated strands of knowledge. Thus it identifies and characterizes 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 concepts between the related topics. Characterizing the development of understanding in this way can inform assessment strategies by highlighting which of the connections between key concepts within the big idea should be measured.

Following student learning-

Recently, educators have begun to focus on the potential for using learning progressions for the improvement of student learning of complex scientific knowledge and improving assessment practices. Smith and colleagues (2006) proposed a research-based learning progression as a useful tool for capturing conceptual change across grade levels. In their assessment approach, central concepts and principles of a discipline (big ideas) are essential for the development of a learning progression. They identified a coherent set of big ideas from research on student thinking and learning. Next, they elaborated the concepts within the big idea and organized them around the big ideas and scientific practices. The current national standards provided a guide for developing a learning progression based on grade range. In addition, they incorporated the results of an extensive set of research studies that focused on students' understanding of concepts related to the particle model of matter. From these efforts, they produced a version of the big ideas for each grade range that is suitable for the experiences, knowledge and cognitive ability of students at that level. Finally, the concepts from each grade range were used to generate learning performances and assessment items.

The authors of this study proposed that a research-based learning progression could be used to improve large-scale and classroom assessment by focusing on conceptual understanding instead of low level tasks such as description and recall. In addition, learning progressions can be used to organize themes and relationships within the science curriculum.

In an alternative approach to following student understanding, Hestense and colleagues (1992) developed the "Force concept inventory". The instrument was used to assess high school and undergraduate students' knowledge of Newtonian force concepts. They chose Newtonian force concepts as their big idea, then divided the conceptual space into six conceptual dimensions (or sub-big ideas). They then elaborated the dimensions to include the scientific concepts that describe expert understanding. This instrument was not designed to follow a progression of student learning, but as a diagnostic tool to inform instruction by assessing the level of student understanding of the concepts within the big idea. Therefore, their strategy employed typical misconceptions as distracters. Knowledge of student misconceptions can be used to inform curriculum and instruction.

The researchers suggest that misconceptions may be indicators of progress toward scientific understanding than obstacle to learning. The main idea of this approach is to assess conceptual growth across grade levels in a science topic independent of a specific curriculum. They argue that this approach generates diagnostic information about student understanding that can inform developers and practitioners of the correspondence between instruction and student grade levels (Hestense, Wells, & Swackhamer, 1992; Sadler, 1997). In addition, Briggs and colleagues (2006) proposed the use of such diagonistic information in tracking conceptual growth across grade levels by connecting student misconceptions to the developmental progression of student understanding.

Wilson and colleagues expanded on these ideas and applied them to assessing student learning progressions within an instructional unit (Roberts, Wilson & Dranney 1997; Willson & Sloane 2000; Wilson 2005). When developing a learning progression, they first define the progress variables, which are representations of the knowledge, skills, and other competencies that could be improved through the learning activities associated with a curriculum. Assessment activities based on the progress variables are developed in various formats and embedded throughout the course as an integral part of instruction in order to track student progress toward the curricular goals and monitor student performance with in a single unit within a science curriculum and build a learning progression (Briggs, Alonzo, Schwab & Wilson, 2006). This assessment system, (BEAR), provides processes for developing assessment and scoring schemes based on the learning progressions to track student progress toward learning goals. This approach shows how learning goals, instruction, and assessment activities can be aligned through the use of learning progressions. Their results suggest that assessment based on learning progressions can be used to measure student progress over time (Kennedy, Brown, Draney, & Wilson, 2006).

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, R. J., & Riconscente, M., 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 the target for what the learner should know. In our study, we developed a model that represents a set of ideas that defines expert understanding for the "Nature of Matter" as it relates to nanoscience. 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. Developing a learning progression for the 'Nature of Matter' will provide insight into the appropriate points to introduce nanoscience into the curriculum.

We divided the conceptual space for the Nature of Matter 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 (Stevens, Sutherland, Schank, & Krajcik, 2007): 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 (Krathwohl, 2002). In addition, we included communicating a model or modeling as a potential source of evidence (Table 1).

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	*Create, build, communicate 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.

We report our preliminary work towards developing a learning progression that describes how students build their understanding of the nature of matter. In particular, we focus on how and when they develop connections between ideas. We discuss how this work informs curriculum, instruction and assessment.

Methods

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-expert), 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 had completed some undergraduate-level chemistry courses. Ultimately we will fill out a matrix of both science majors and non-majors, but here just report on a small sample of undergraduates from a select university.

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 the source of those properties; 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 brief summary of the tasks/questions asked during the interview (see Appendix B for the interview protocol). 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* ***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*
Properties of Matter	*Compare powdered and granulated sugar; explain whether the arrangement of particles important*
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 protocol

Table 3. Representative assessment item-

Sample assessment item	
Idea from claim space	Matter is made up of particles
Evidence	Explain; Model
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 (Calik & Ayas, 2005; Renstrom, Andersson, & Marton, 1990). 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.	

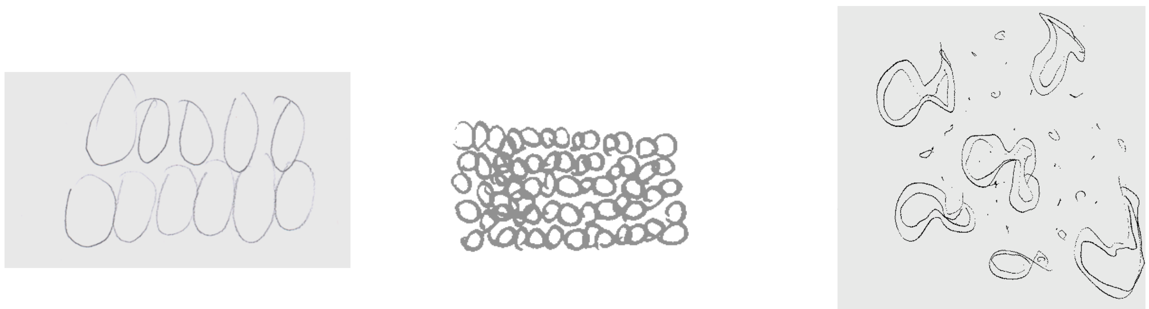
Table 5: Characterisitics of particles on the surface vs. bulk particles

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)

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 instruction.

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 1 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 1. 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 2, 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. Although several of the undergraduates had completed more than one year of chemistry (AP-Chemistry or college-level), the increase in understanding may also be due to the fact that they attend a competitive university. Once we complete a sample of undergraduate students, we will 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.

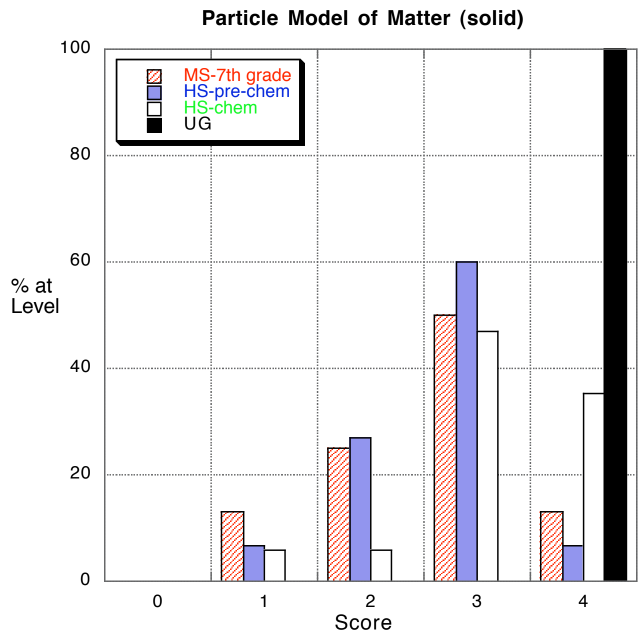


Figure 2. Representative graph depicting how students' particle models develop as they move through the science curriculum.

0 Does not know
1 Continuous model of matter
2 Particle model with misconceptions
3 Particle model, incomplete
4 Solids are made of particles that are

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 3). 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.

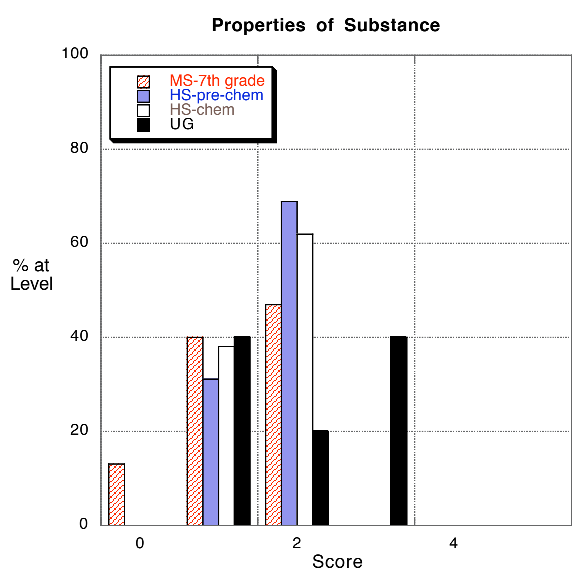


Figure 3. Representation of the properties students would use to characterize a substance.

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

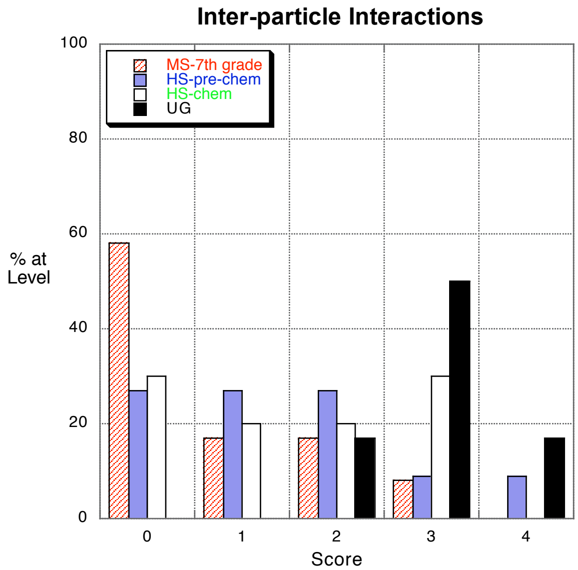


Figure 4. Representative graph depicting students' ideas about inter-particle forces within a solid as they move through the curriculum.

Coding scheme for inter-particle interactions within a solid.

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.

Gaps in students' knowledge regarding the structure of matter-

From a graph depicting the percent of students that gave responses that were coded at the highest level for several concepts related to the structure of matter, it is clear how much student understanding of certain concepts lags behind the others (Figure 5). In particular, students cannot explain the forces that keep the atoms together in a solid (inter-particle forces). Nor do they volunteer that the arrangement of atoms gives a substance its properties, for if they are arranged differently, then it is a different substance.

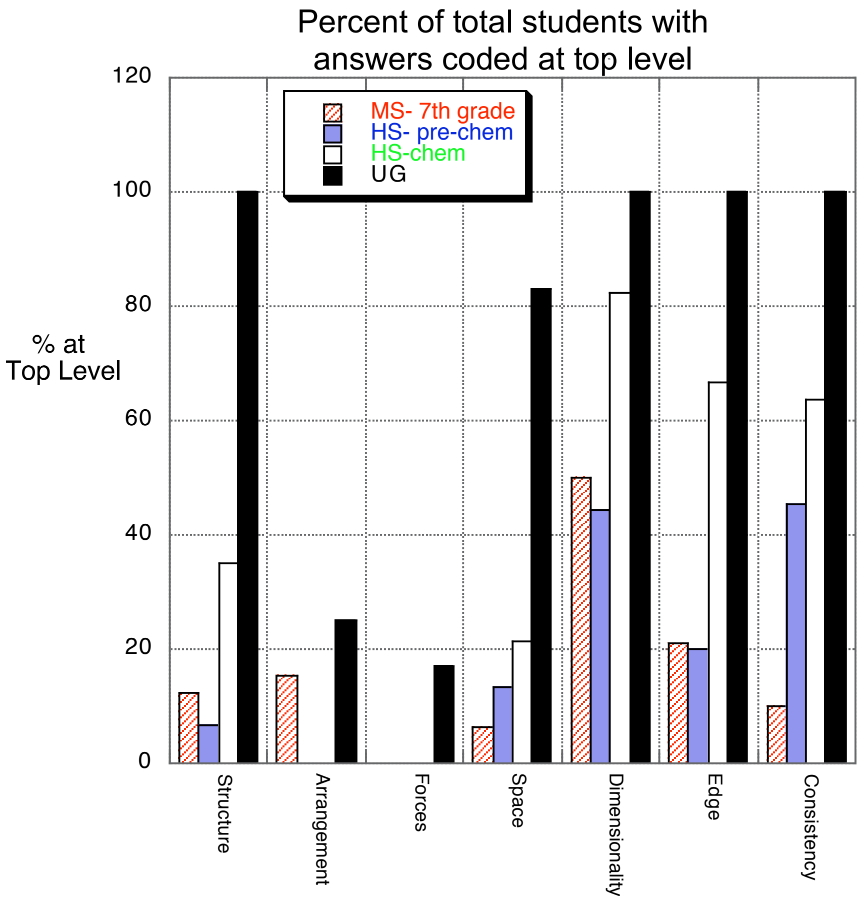


Figure 5. Graph depicting the percent of students that achieve the top level of the code as they advance through the science curriculum. Structure is structure of matter as depicted in Fig. 5. Arrangement refers to the effects that the arrangement of atoms has on matter. Forces refer to the inter-particle interactions within a solid. Space refers to what is in the space between atoms. Dimensionality refers to whether atoms are 2-D or 3-D. 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.

There could be several reasons for the slow development of understanding of these topics. They may be more difficult than other concepts that we assessed, so the lag observed may just be a function of the progression towards building understanding. In addition, we may have assessed their knowledge in a way that was unfamiliar to them. When we match up the tasks created to obtain the evidence needed to confirm student understanding, we found that we assessed students' knowledge of properties somewhat indirectly. The students were asked about the properties of the powdered and granulated sugar that were the same, and which ones were different. Rarely did students rely on intensive properties except taste. Only when we questioned them about the behavior of the two substances did they tend to discuss properties like solubility. Other more traditionally characteristic properties such as density and melting point were not volunteered. Perhaps more direct and multiple assessments would provide a different result.

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.

An alternative reason for the lack of growth could be due to instruction. Too often, it is first as a dichotomy of ionic or covalent bonding that can be explained using the 'octet model' (Coll & Taber, 2002; Nahum, Mamlok-Naaman, Hofstein & Krajcik, *in press*). In addition, chemical bonding is not usually addressed in terms of forces. Instead, students learn to apply the octet model and begin to define bonding in terms of atoms *needing* or *wanting to give away* electrons (Coll & Taber, 2002). In addition, using the 'bonding' terminology instead of forces may make it difficult for students to understand intermolecular and intramolecular interactions. Together, these factors make it difficult for students to extend their understanding to other interactions that are governed by electrical forces. (Coll & Taber, 2002; Nahum, Mamlok-Naaman, Hofstein & Krajcik, *in press*)

We surveyed the 2000 and 2005 National Assessment of Educational Progress (NAEP) for items related to these concepts. In the both the 8^{th} grade and 9^{th}-12^{th} grade released tests, the items pertaining to forces assessed only Newtonian force concepts. Only two items were even somewhat related to the forces that occur on the atomic or nanoscale on the 9^{th}-12^{th} grade test. The first item primarily assessed knowledge of the properties of ionic solids.

30. Which of the following observations about a certain pure solid would indicate most strongly that the solid is ionic?

A) Its water solution is a good conductor of electricity.
B) It is composed of small white crystals.
C) It has a density grater than 1.0 grams/cm^3
D) It has a high melting point.

The other item asks student to apply a theory (Classical Mechanics) that fails on the atomic- and nanoscales to explain the behavior of the components of an atom.

56. A planetary model of a system, such as the models of the Solar System and the atom discussed here, is appropriate whenever the components of the system and the nature of the forces between them have certain properties. Which of the following might be some of these properties?

A One of the components is much more massive than the others and exerts an attractive force on each of the other components.
B) One of the components is much more massive than the others and exerts a force on each of the other components that is perpendicular to the line connecting their centers.
C) All the components are equally massive, are far apart, and attract each other.
D) All the components are equally massive, are close together, and repel each other.

Items related to properties are more plentiful. In addition to the items above, they assess the concept of density as well as the chemical and physical properties of elements and compounds (solubility, combustibility and state of matter at room temperature). In addition, there is an assessment of the relationship between the component atoms of a substance and the properties of the substance (a comparison of the properties of carbon and carbon dioxide). However, the importance of the arrangement of atoms in regards to properties was not assessed in the released items. Although not all aspects of properties of matter were represented in the NAEP items, there was a significant presence. If the curriculum truly aligns with the tests, then the students should be adequately prepared to discuss the characteristic properties of matter.

With a lack of emphasis on concepts related to forces on the atomic and nanoscales on this high-stakes test, we cannot expect the curriculum to emphasize them. Both the instruction and assessment will have to change if students are to gain an understanding of electrical forces, which is an important concept in nanoscience. From our assessment of students so far, the current science curriculum is not supporting students as they work to build a model of interactions at the nano- and atomic scales.

Discontinuities in students' models

As we begin to characterize the way that students build their ideas about the nature of matter, we also found that there were some discontinuities in the students' learning progressions. As observed in Figure 4, we found that as a whole, within the population of students, there were some concepts that were much less prevalent in the students' models of the structure of solids. When we examine the responses of individual students, we find some gaps in understanding.

For example, six high school students that had completed a year of chemistry provided relatively complete descriptions for both the particle model of matter (solid) and the process of melting (liquid). They described solids as an ordered array of atoms that are close together. Additionally, they believed that the atoms are in constant motion, even in a solid. When the solid melts, they indicated that the particles become more disordered due to increased motion from the increased heat. In addition, there is more space between the particles. However, four of the six believed that grinding the granulated sugar to make powdered sugar resulted in a change on the molecular level. These explanations were provided as they tried to explain why powdered sugar tends to stick to a plastic surface more than granulated sugar does.

"There's more air in the powdered sugar than there is in that because that one's more compact than this one is. So these (granulated sugar) atoms are probably closer together than these (in powdered sugar) atoms are, but it's still a solid." (high-performing female, HS chemistry student)

"I'd think the powdered, I think there'd be a lot more particles in the powder than there would be in the crystal of the sugar." (high-performing male, HS chemistry student)

"I like guess the, uh, make up is kinda' different, like on a molecular level…there's not as much space between them." (high-performing female HS physics student (1 year of HS chemistry)

"…the intermolecular structure isn't as strong …as crystallized sugar." (high-performing male HS chemistry student)

Johnson (2000) proposed a progression of concepts necessary for understanding chemical change. First a student must have a good understanding of exactly what a substance is. They must also know that it is make up of atoms. The arrangement of atoms determines what the substance is as well as its properties. Therefore, results of changing the arrangement of atoms, changes the identity of the substance and its properties.

These six students in this study believed that granulated and powdered sugar are the same substance. Some even went as far to say that the two sugars were composed of the same molecules. Thus, although they appear to have a good conception of a substance, they do not have a clear understanding of a chemical change and how it differs from a physical change. Because they are missing this connection, they equate breaking up a solid into smaller pieces to a chemical change, and thus believe that a change at the molecular level is the reason for the change in behavior. This confusion is not unusual as students often use the term chemical change in reference to physical changes (Calik & Ayas, 2005).

Integrating knowledge and making connections between ideas is key to conceptual understanding. The traditional science curriculum often compartmentalizes the various aspects of the study of matter (e.g. structure of matter, conservation of matter, chemical reactions, phase changes). Teachers are not encouraged to help students make those connections because the typical large-scale assessments focus on isolated topics that do not require students to connect currently taught concepts with concepts from other science areas that were previously learned (NRC, 2005; NRC, 2001). Not surprisingly, the ultimate result is compartmentalized knowledge of science concepts.

An example of a high school chemistry student (0089) with such compartmentalized knowledge is illustrated in Figure 6. This student had obtained the highest score on the test given just previous to our visit to his classroom. During the interview, he was able to describe the difference between the inter-atomic interactions that occur in sodium chloride and chlorine in a relatively accurate manner. He used the octet model to explain how chlorine has only seven electrons on the outer shell and shares one with another chlorine atom in order to complete the octet. When explaining the interactions within sodium chloride, he states that sodium transfers an electron to the chlorine so that each atom has a complete outer shell (Figure 6a,b). As described above, in order to truly understand the difference between the formation of these substances, a student must have an understanding of atoms and their composition, elements, the Periodic Table, electric forces, etc.

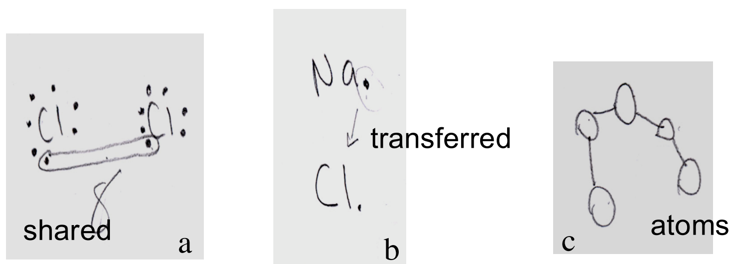


Figure 6. High performing HS chemistry student's models relating to questions regarding the structure of matter and forces and interactions. **a**. Drawing explaining that chlorine (atoms) each have seven electrons and they each share one to complete the octet. **b.** Drawing explaining that when sodium and chlorine interact, sodium transfers an electron to chlorine. **c**. Student's drawing of atoms. He could not provide information on the composition of atoms. He was not sure what the lines represented.

However, we found that although he could provide a relatively adequate answer to explain the ionic and covalent bonding, further probing revealed great gaps in his knowledge.

Although he used electrons to explain the interactions between the chloride and sodium atoms, student 0089 was unaware that atoms contain electrons. In his model, an atom is just a sphere (Figure 6c). His explanation relied just on what he saw in his textbook. He believed that the color of the spheres was important. When asked directly what the Na and Cl symbols meant he answered “elements”. In his model, elements make up molecules and atoms are a totally separate entity. In addition, he did not have a very accessible model of the atomic and kinetic theories. Thus, although he was a high achieving student, he had very little connected or transferable knowledge about the structure of matter.

The degree to which student 0089’s knowledge is disconnected is not typical of the students we interviewed, but provides an example of how instruction and assessment have failed to identify his conceptual difficulties. It illustrates how important it is to focus instructional and assessment practices on the connections between ideas that define conceptual understanding.

Conclusion-

We are working 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 nature of matter, but also how they connect ideas *between* the related topics. . Developing this sort of progression, may help characterize how students build their understanding and learn how to make these key connections and turn their “pieces” of knowledge into a coherent model. We are working to identify and characterize the connections that students are able to make easily as well as those that they find difficult. As we collect and analyze more data, we will begin the process creating a research-based multi-dimensional learning progression of the ideas within to the nature of matter as it relates to nanoscience. This information will provide information regarding the level appropriate introduction of nanoscience concepts into the curriculum.

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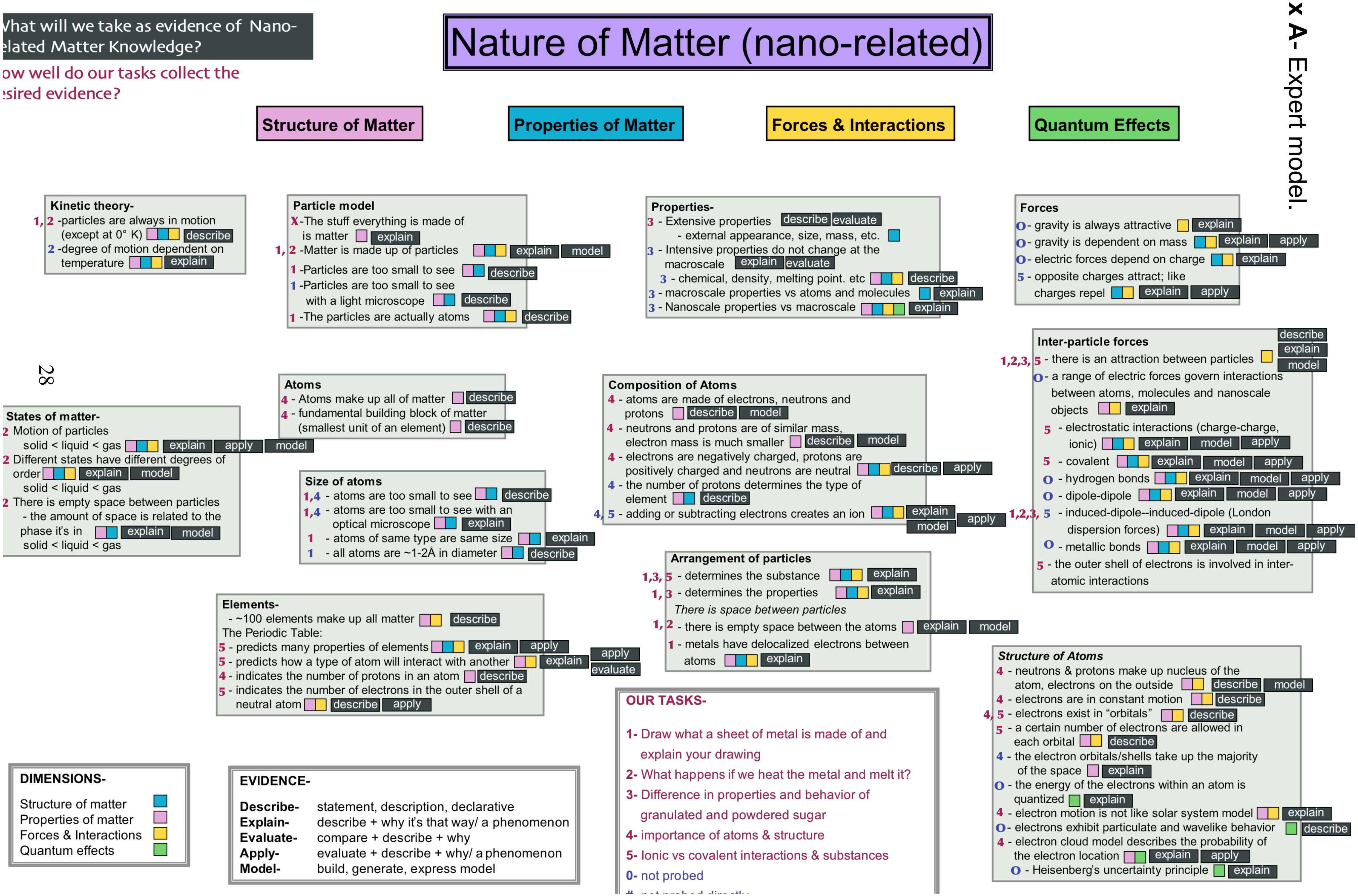
Appendix A- Expert model.



Appendix B- Interview protocol to probe student understanding of the nature of matter.

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?