Using a nanoscience context to develop student explanations of observable phenomena

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Abstract:

The particle nature of matter is a consistently difficult theory for students to use in explanations. The nanoscience-based concept of surface-dependent properties provides a context through which to closely link observable behaviors and characteristics of materials to underlying causal mechanisms, including interactions between solute and solvent and the exposure of particles of solute. Thus, the concept of surface-dependent properties provides rich context to help students develop the ability to use particle-based mechanistic reasoning in their explanations of phenomena. This study evaluates the conceptual understanding of 32 diverse middle-school students participating in an intensive instructional intervention utilizing the aforementioned principles. Student use of particle-based mechanistic reasoning increased during the instructional intervention. Students who adopted a particle-based mechanistic conception of dissolution as an interaction between a vulnerable solute and solvent were likely to make connections between rates of dissolving, rates of concentration increase, and the process of dissolving, while students who did not adopt such a conception were less likely to develop consistent ideas. This correlation suggests that helping students develop mechanistic reasoning focused on a specific process can help foster the development of a usable particle model, and can help students integrate explanations across related phenomena.

The particle theory of matter has been identified as one of the most fundamental theories in science (Adbo & Taber, 2008; Feynman, Leighton, & Sands, 1963). The particle theory has
been developed and refined to elegantly and consistently explain the causal mechanisms of numerous diverse observations, including dissolution, rates of dissolution, conservation of matter, evaporation, chemical reactions and reactivity, air pressure, and other material behaviors and characteristics (Snir, Smith, & Raz, 2003, p. 797). The discipline of chemistry is built around creating and refining causal mechanisms to explain the underlying parts and patterns of interactions of the complex system responsible for the observations that can be made about materials (Glennan, 2002, p. S344). Although many material behaviors and characteristics may seem dissimilar and unrelated when only the directly observed effect is considered, the underlying structures and mechanisms causing behaviors may be similar. Thinking about phenomena from a mechanistic perspective can help highlight these similarities, and can contribute to deep, unified understanding of the way things behave and operate (Glennan, 2002; Salmon, 1984). Thus, the refinement, articulation, and utility of scientific theories, such as the collective group of models and principles that constitute the particle theory of matter, relates to their explanatory and predictive power (Kuhn, 1962; Lakatos, 1970).

Although particle theory is an essential aspect of an expert scientist’s understanding of the material world, novice learners often have trouble understanding how their macroscopic observations of material behaviors relate to submicroscopic particle-based causes. Much science education research has focused on student misconceptions and alternate conceptions related to the particle model. In this manuscript, we investigate how student explanations of the process of dissolving and rates of dissolving change as a result of an instructional intervention guided by the findings of these studies. In particular, we evaluate whether the qualities and features of student explanations change to involve more particle-based causal-mechanistic reasoning, and we elaborate notions and concepts that seem to enable students to reliably apply particle theory to explain multiple related phenomena. Through this investigation, we gain insight into how to
help students construct causal understandings of phenomena that integrate submicroscopic (particle theory-based) and macroscopic (observable) conceptions.

**Developing Causal-Mechanistic Explanations of Material Behavior**

*Developing and Integrating Submicroscopic and Macroscopic Understanding*

In order to create normative causal-mechanistic explanations using particle theory, three aspects of understanding about materials must be integrated. The explainer must have both an accurate understanding of the behavior to be explained (macroscopic understanding), and an accurate and sufficient particle model (submicroscopic understanding) (Crespo & Pozo, 2004; Gabel, Samuel, & Hunn, 1987; Johnstone, 1993; Metz, 1991; Russ, Scherr, Hammer, & Mikeska, 2008; Smith, Wiser, Anderson, & Krajcik, 2006). These two aspects must be able to be communicated through symbolic representations (Johnstone, 1993; Treagust, Chittleborough, & Mamiala, 2003; Wu, Krajcik, & Soloway, 2001). The macroscopic level of understanding involves developing conceptual understanding of the observations that characterize the behavior to be explained. This generally involves developing a set of observation-based principles to distinguish the phenomena or object. For dissolving, principles may include that solids seem to shrink in size as they dissolve, that materials with higher surface-area-to-volume ratio dissolve more quickly than materials with low surface-area-to-volume ratio, or that not all materials are able to dissolve. These principles define and constrain the features that the rules of interaction and elements of the causal mechanism must be able to explain. This means that the elements and rules of interaction used to explain any single observation-based principle must also be able to account other principles related to the same materials.

Each of these aspects—the observation-based principles at the macroscopic level of understanding, and particle theory at the submicroscopic - can be developed and assessed
individually, in conjunction with a learners’ understanding of symbolic representations, but neither alone represents deep understanding of phenomena (Harrison & Treagust, 2002).

Although observation-based principles can help students make general explanations and predictions about specific behaviors or observations, observations may not enable students to develop an integrated understanding of phenomena due to the fact that they are specific to a set of conditions and observations. In order to develop, reorganize, and structure a cohesive view of the world, students must be able to envision the connected nature of these observations, and must be able to see how they fit with prior experiences (Linn, 2006). Conversely, while students can learn to use symbolic representations to make models of materials using particle theory, these models are abstract and devoid of meaning unless they are tied to observable behaviors and observation-based principles. As students are guided to bridge their observational knowledge and experiences to the particle model, they can link the submicroscopic causal explanations to the resultant macroscopic observations. The development of unifying causal-mechanistic explanations for phenomena can help students structure their web of knowledge about the world. Thus, a normative particle model can explain a multitude of macroscopic principles, serving as a unifying causal mechanism experts and experienced students can rely upon to make predictions and explanations across multiple observations of material behavior. Thus, it is essential that students develop the ability to use the particle model to explain the mechanisms governing material behavior.

The current manifestation of particle theory can be considered to be the consistent complex system elements and rules of interaction\(^1\) that emerged as scientists developed general

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\(^1\) I use the term “rules of interaction” to refer to Glennan’s term of “change-related generalizations”. Glennan defines this term as the direct and indirect consistent rules that govern the interactions and spatial associations of parts within the complex system of a mechanism. “Rules of interaction” is used because, to me, it more directly specifies this meaning. In
causal-mechanistic explanations to explain their observations of the behavior and character of matter. As students learn and develop conceptual understanding of the mechanisms explaining their observations, they may be able to integrate these understandings via particle theory, in much the same way as particle theory emerged historically (Erduran, 2001; Wu, 2003, p. 869). Accordingly, helping students build and develop causal-mechanistic explanations of related behaviors or similar materials could contribute ultimately to a unified understanding of the world, and could help them refine their understanding of particle theory in a bottom-up manner. Alternately, helping students understand the particle theory from the top down could enable them to craft causal-mechanistic explanations of a variety of phenomena (Russ et al., 2008). We will discuss these alternative perspectives on the construction of a unified, mechanistically valuable particle theory in the section of this manuscript entitled Framing an Instructional Approach.

Developing and unifying causal-mechanistic explanations of material behavior is complicated by the fact that novice learners have only a fraction of the prior experience, observational familiarity, and usable knowledge that experts rely upon to recognize when and how it might be appropriate to apply the particle model to explain phenomena. Experts can hone a unified set of elements and rules of interaction to populate causal-mechanistic explanations expressly because they have a broad and well-defined knowledge of what characterizes material behavior in different situations. Experts recognize the utility of relying on the particle model to explain a number of observations in an integrated manner, and are able to recognize when a proposed submicroscopic behavior or structure might be contraindicated by an observationally-based principle.

Novice students do not have the cohesive and comprehensive macroscopic understanding addition, I use the term “causal-mechanistic explanations” to refer to Glennan’s idea of “mechanical models”.

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of materials and behaviors possessed by experts, and, therefore, may not recognize when a mechanistic explanation of one observation contradicts another observable behavior (Harrison & Treagust, 2002). Further, students may over generalize or misinterpret specific experiences with material behaviors, adopting alternative or incorrect principles that support a non-normative mechanistic explanation. Novice learners, including middle-school students, often lack consistent, coherent macroscale-based principles to describing and predicting the behavior and characteristics of materials (Berkheimer, 1990). For example, several studies have identified the alternative conception that a dissolved solute sinks to the bottom of a solution, rather than distributing throughout the solution (Blanco, 1997; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993; Prieto, 1989; Valanides, 2000). This conception may arise from experiences that seem to support this conclusion, such as the common experience of tasting or seeing concentrated solute that has not had a chance to diffuse at the bottom of a cup of cocoa, tea, or Kool-Aid. A novice’s lack of experiences and poorly-defined conception of dissolving may lead them to assume that this experience characterizes all instances of dissolving. This alternative conception may impede a student from connecting their observations of dissolution to one of the fundamental principles of the particle theory: the kinetics of particles in fluids. To develop a normative mechanistic understanding of dissolution, a student would need to refine his or her understanding of what it means for a material to dissolve. Thus, students must construct well-defined, reliable, predictive principles to describe macroscale observations and behavior in order to be able to understand and use particle-based causal-mechanistic explanations to help integrate their understanding of these phenomena with . to construct normative causal-mechanistic explanations of phenomena (American Association for the Advancement of Science, 2009).

In addition to, and partially because of, the difficulties that some students have in forming reliable predictive macroscale conceptions of materials and phenomena, many aspects of the
submicroscopic mechanistic elements and rules of interactions known as particle theory have proven to be difficult for most middle and many high school students (Driver, Squires, Rushworth, & Wood-Robinson, 1994; Harrison & Treagust, 2002; Lee et al., 1993; Novick & Nussbaum, 1978, 1981; Renström, 1988; Renström, Andersson, & Marton, 1990). For example, some students seem to have a conception that matter is continuous and homogenous (Harrison & Treagust, 2002; Nakhleh, 1992; Renström et al., 1990). Some students believe that particles are embedded in solid materials, and floating in liquid substances or gaseous substances (Johnson, 1998; Lee et al., 1993; Novick & Nussbaum, 1981). Students may believe that the behavior of particles mimics the behavior or the macroscopic material, such that gas particles expand when they are heated, or solid particles melt during a phase change (Ben-Zvi, Eylon, & Silberstein, 1986). Other students believe the properties of materials in different phases are caused by changes in the composition of the material and the identity and nature of molecules (Gabel et al., 1987). Many students have non-normative ideas about the sizes of molecules and atoms, conceptualizing them as visible under a light microscope (Margel, Eylon, & Scherz, 2004; Nakhleh, Samarapungavan, & Saglam, 2005). Students may believe that particles of solids are motionless, or particles of liquids do not move unless provoked (Lee et al., 1993; Novick & Nussbaum, 1981).

Barriers to Developing Causal-Mechanistic Explanations of Phenomena

Lack of scaffolding, support, and explicit guidance in instructional materials. The difficulties students encounter in conceptualizing the particle theory of matter can be accounted for in several ways. First, as mentioned earlier, students may simply generalize their macroscopic observations to the underlying particles (Harrison & Treagust, 2002; Prieto, 1989). In addition, representations of the particle nature of matter often emphasize specific, salient
aspects of the particle theory and de-emphasize others, in an effort to clearly demonstrate an idea within particle theory. Such representations may unintentionally cause misconceptions. For example, instructional diagrams of liquids often depict liquids as having much more space between molecules than solid materials in order to emphasize the lack of organization in liquids (Adbo & Taber, 2008; Andersson, 1990). Inaccuracies, such as a line intended to depict the surface of a liquid, may reinforce the idea that liquids are continuous materials studded with particles (Harrison & Treagust, 2001). Since students often value accuracy and realism in models initially, they may evaluate such depictions at face value, and adopt some of the embedded non-normative ideas in their understandings (J. K. Gilbert, C. Boulter, & F. J. Rutherford, 1998; Gilbert, Jong, Justi, Treagust, & Driel, 2002; Lehrer & Schauble, 2006; Snir et al., 2003). Instructors and curriculum designers often fail to distinguish and draw explicit connections between an observation-based phenomenon and the particle-theory-based mechanism or model that explains the behavior, and may fail to explain the purpose and usefulness of particle theory for explaining observations (Gabel et al., 1987; Harrison & Treagust, 2002; Snir et al., 2003; Wu et al., 2001). When instructors do not explicitly describe and explain scientific norms and representational conventions or assumptions to students, students may become confused about which ideas they should attend to, and may not make connections across multiple representations of the same ideas (Snir et al., 2003; Wu, 2003).

Complexity of particle theory and submicroscopic causal mechanisms. The very conceptual density and complexity that makes the particle theory of matter valuable for scientists and helpful for unifying conceptions of behavior may increase its difficulty for novices and students (Sheppard, 2006). Different aspects of the particle theory may be called upon to explain different observable phenomena. The multifaceted nature of the particle theory creates a myriad of opportunities for students to develop non-normative conceptions. For example, an expert’s
particle theory may include the kinetic nature of particles in solids, liquids, and gases; the characteristics and structure of molecules, the nature and strength of bonds between atoms and molecules, the behavior of atoms and molecules in different situations, the arrangement of atoms within molecules and molecules within materials, and the types of forces and interactions that may take place within and among molecules (Harrison & Treagust, 2002; Stevens, Delgado, & Krajcik, in press). Explanatory mechanisms of conservation of matter will use some different aspects of the particle model than explanatory mechanisms of phase changes. Even within phenomena, different aspects of the particle theory may be used to explain different predictable observations.

*Situated nature of understanding.* In addition, some studies suggest that many of these non-normative ideas can be partially phenomenon- and situation-dependent. Situation-dependent cognition refers to the theory that the multiple experiences and situations in which students encounter a phenomenon can influence what interpretive frames they use to classify, think about, and interpret the phenomena, and thereby how they explain the phenomena (Brown, Collins, & Duguid, 1989; Reif & Larkin, 1991). The situativity of cognition has been used to explain why students have difficulty transferring knowledge from one setting to another (e.g. (Nunes, Schliemann, & Carraher, 1993)) and can help explain why certain non-normative conceptions about phenomena are resistant to change (Cobern, 1995). For example, the conception that some first year graduate students express about rusting iron losing mass may be tied to the experiences they have had with rusting iron objects eroding away. Although secondary-level chemistry classes discuss the concept of combination reactions and conservation of mass, the experiential situations in which students have encountered rusting objects leads them to use this real-world experiential frame rather than their chemical understanding to make a non-normative scientific explanation of rusting (Bodner, 1991).
By phenomenon-dependent ideas, I refer to the idea that the elements and rules of behavior represented in novices’ causal-mechanistic explanations may be inconsistent or not integrated across phenomena. Thus, students may not use consistent ways of representing the underlying structure and function of materials across observations even when the materials involved in the observations to be explained are identical. These types of discrepancies may be accounted for by the differences in knowledge integration and recognition of related features between novice and expert thinking: students may not have experienced enough instantiations of phenomenon to have developed an accurate, normative conception of what the phenomenon entails (Chi, Feltovich, & Glaser, 1981); and students may not have constructed connected understandings of materials that enable consistent use of related features of underlying mechanisms (Linn, 2006). Further, as novices develop causal-mechanistic explanations for specific phenomena, this understanding does not necessarily transfer to causal-mechanistic explanations of other phenomena. For example, Teichert, Tein, Anthony, and Ricky (2008) found that, prior to interviewer prompting, some postsecondary students initially drew NaCl(aq) as dissociated sodium and chloride ions when explaining the phenomenon of conductivity, while drawing it as joined NaCl molecules shortly after, when explaining the mechanism of boiling point elevation. This suggests that the students did not have a fully unified and integrated understanding of materials, as their understanding and representation of the underlying nature of identical materials was dependent on the phenomenon they were explaining.

The idea that some non-normative ideas are phenomenon-dependent is controversial, and can be confounded when students use different types of reasoning to explain different observations (Gomez, Benaroch, & Marin, 2006). As I subscribe to the perspective that knowledge is situated, and therefore exists only in use, I posit that both the type of reasoning that students use to express their ideas and the content represented in the ideas constitute student
Characteristics of explanations and reasoning in science.

Several different forms of reasoning and explaining have been identified for explaining scientific phenomena. In this paper, I adopt and minimally adapt the typologies characterized in Gilbert, Boulter, and Rutherford (1998a), who identify several forms of scientific explanations, and Metz (1991), who identifies several forms of reasoning students use in causal and causal predictive explanations in science. Identifying the types of explanation used by a student helps to establish the situativity of the students’ response, by providing evidence for the framework the student used to interpret the question or prompt generating their response. Further characterizing the type of reasoning students use in making causal explanations provides clues as to how a student characterizes the phenomenon to be explained, and how and if he or she understands the complex system of elements, properties, behaviors, and rules governing behaviors that can explain the observed behavior (J. K. Gilbert, C. Boulter, & M. Rutherford, 1998; Lombrozo & Carey, 2006; Metz, 1991; Russ et al., 2008). I describe the typological framework I use to characterize explanations and reasoning fully in the next section.

Investigating the Use and Emergence of Particle-based Causal-Mechanistic Explanations about Dissolving

In this manuscript, I focus on how middle-school students’ causal-mechanistic explanations of different phenomena related to dissolving change through a 2-week instructional intervention focused on highlighting the connections between macroscopic observations and mechanistic explanations. Specifically, I address the following questions:

- In what ways do which students’ explanations and reasoning about dissolution and rates
of dissolution change as a result of contextualized instruction?

- What concepts and notions facilitate the development of a particle model that students can apply in an integrated manner (across multiple related phenomena)?

The instructional focus was created by using the nanoscale science big idea of surface-dependent properties to emphasize the importance of the spatial location of particles in determining the observable properties (Stevens, Sutherland, Schank, & Krajcik, in progress).

Developing an Instructional Context to Promote Conceptual Development and Foster the Development of Mechanistic Explanations

Connecting Student Understanding of Dissolution and Solution Chemistry

Several studies have emphasized the importance of connecting submicroscopic and macroscopic conceptions of matter towards the development of mechanistic reasoning in explanations of dissolution. Some researchers have focused on student conceptions of the dissolution of ionic or polar covalent materials, emphasizing the dissociation of solute particles and devaluing the interactions between the solute and the solvent (Teichert, Tien, Anthony, & Rickey, 2008; Tien, Teichert, & Rickey, 2007). Other researchers have focused on the distribution of solute particles throughout the liquid as a dynamic process, and on the dissolved solute’s occupation of spaces between solvent particles, deemphasizing the ionic or covalent nature of the solute and the interactions between the solute and the solvent in solution (She, 2004). Our research focuses on the development of mechanistic models of a solid solute dissolving in water, and of the corresponding relationship between shape, size, and rates of dissolution. Due to time constraints and the prior knowledge of the students, we did not relate
this process to the kinetic energy of the solute and solvent. The instructional materials were aimed at helping students construct the following related models of dissolving and of the relationship among shape, size and rates of dissolving:

Normative causal-mechanistic explanation of dissolving targeted by instructional intervention: When a solid material dissolves in water it appears to get smaller and smaller until it disappears, creating a uniform solution. Upon closer examination, one can observe that dissolving seems to occur at any interface between water and the solute. This happens because moving water particles help to pull or break off solute particles from the overall solid material, beginning with the most available solid particles on the exterior edges, corners, and surfaces of the material. As the solid dissolves, water particles surround the solid particles and move them away from the overall solid structure, distributing the solute throughout the solution.

Normative causal-mechanistic explanation of the relationships among shape, size, and the rate of dissolving targeted by the instructional intervention: If two samples of material have the same mass, are made of the same substance, and are dissolved under the same conditions, the rate of dissolving will depend on the size and shape of the pieces in the sample. Specifically, the sample with the highest the surface area will dissolve fastest. This is because different shapes and sizes of pieces of a soluble material have different proportions of surface, edge, and corner particles. Corner and edge particles, followed by surface particles, are the easiest particles in a material for the solvent to break or carry off because
they are the least strongly held to the remainder of the solid material, and because they are accessible to the water particles. Thus, the smaller the size of grains of solute, the more overall surface particles it contains. Shapes of materials that maximize the proportion of surface, edge, and corner particles dissolve faster than shapes that minimize these dimensions (National Center for Learning and Teaching in Nanoscale Science and Engineering, 2008a; Stevens et al., in progress).

These causal-mechanistic explanations are referred to as “normative” models for the purposes of this paper and our curriculum. They reflect related National Standards and Benchmarks for middle school students, as well as ideas important to developing an understanding of nanoscale science and engineering appropriate for middle school students (American Association for the Advancement of Science, 2009; National Research Council, 1996; Stevens et al., in progress), but are not intended to present an exhaustive expert model of either concept. See Appendix I for a summary of the curriculum and the construct maps the causal-mechanistic explanations serves as upper anchors for (Stevens et al., in press; Wilson, 2005).

**Framing an Instructional Approach**

From the previous discussion, there are clearly many obstacles impeding instructors’ ability to help students develop a normative, particle-based causal-mechanistic explanations of phenomena. In order to study how students develop the ability to use mechanistic models in explanations of phenomena, we needed to construct an instructional intervention that would evoke the kinds of changes we hoped to see. Possible instructional approaches to facilitate this development include a top-down preemptive introduction of the particle model, or a bottom-up
approach of guiding student development of a particle model to explain macroscopic phenomena. We evaluated the evidence for these different strategies, considering both how they fit into a social-constructivist theory of learning as well as how the types of learning gains and learning performances they enabled, in order to choose a strategy most likely to help students learn to use mechanistic reasoning in general, and the particle model to explain their observations and make predictions specifically.

The top-down approach to teaching mechanisms assumes that presenting students up front with an explanatory model can help them understand the macroscopic behaviors and characteristics of materials. This approach involves introducing the particle model to the student, and subsequently ratifying it by demonstrating to students how it can explain behaviors and characteristics of macroscopic materials. This is the approach of many traditional textbooks (Snir et al., 2003). Introducing the particle model to students who lack a normative predictive, descriptive macroscale concept of matter seems to promote the development of compartmentalized understandings of materials in many students. Some studies have shown that this didactic, top-down approach creates an inert particulate model: students can recite the model in a factual way, but are unable to apply it to explain phenomena (Lee et al., 1993). In addition, this instructional strategy seems unlikely to facilitate the students’ to construction of their own knowledge of materials, as it does not initially connect to students’ prior knowledge, and presumes to construct the knowledge for students by presenting them initially with the desired outcome. Thus, we chose not to adopt this instructional strategy.

The bottom-up approach assumes that student understanding of the particle model will be more robust and complex if they actively develop it through scaffolded instruction. One version of this approach takes a “knowledge-as-theory” perspective, that students develop naïve theories to explain their observations. From this perspective, the development of conceptual
understanding is coherent and holistic, and changes in explanatory theories for one phenomenon mean changes in theories about related phenomena (Vosniadou, 2007). This perspective assumes that student ideas progress in a wholesale manner, so that, although conceptual change towards a complete particle model may take place in a gradual manner, each time a student’s particle model changes, their explanations across related contexts and phenomena change and adjust accordingly (diSessa, 2006). Instruction following this method could involve using a variety of different observable phenomena to highlight different aspects of the particle model, with the expectation that students would build a cohesive explanatory particle theory that could explain across phenomena in the same way that experts created and refined the particle theory historically.

This strategy is problematic, in that it presumes that knowledge and cognition are not phenomenon-dependent, while some research (described previously) suggests that the elements and behavioral rules used in students’ causal-mechanistic explanations do indeed depend on the specific phenomenon being explained (Teichert et al., 2008). Correspondingly, some studies suggest that this method seems to have relatively low levels of success in helping students develop normative, particle-based explanatory models. Franco and Taber (2008) conducted a study of the explanations of 7th – 11th graders from English schools using a curriculum requiring students to learn the particle model to be able to explain in an integrated way a variety of macroscopic phenomena using the particle theory. For example, seventh and eighth grade students learned how the particle theory of matter can be used to explain properties of solids, liquids, and gases, diffusion, changes of state, pressure, the nature of elements, chemical change, and heat transfer. They found that only 17% of the 7th – 11th graders’ explanations were “scientifically acceptable particulate responses” according to their coding scheme. Within the context of dissolution specifically, only 63% of 7th – 11th graders’ explanations involve particles
in either normative or non-normative ways, and a total of approximately 8% of total explanations of dissolving were deemed “scientifically acceptable particulate responses, despite the focus of the curriculum. These findings support the theory that knowledge and cognition are phenomenon-dependent, and suggests that students may be most successful at developing causal-mechanistic explanations of phenomena if they concentrate on one phenomenon or group of phenomena to build deep explanatory understanding.

This leads us to a second version of the bottom-up approach to helping students develop normative particle-based causal-mechanistic explanations of behavior. This version assumes that student knowledge is partially fragmented and situated, and that the development of understanding involves helping students integrate their understanding within contexts, and to build understanding that bridges prior situated ideas within a normative scientific framework. From this perspective, conceptual change and idea development is context-dependent, and learners develop understanding in a gradual evolutionary manner (Harrison & Treagust, 2002). Thus, this approach focuses on integrating student conceptual understanding of separate macroscale behaviors and characteristics with the development of particle models to help explain the causal mechanisms driving these macroscale observations. Instruction guides students to build understanding of individual macroscopic behaviors and characteristics, and coordinates guided development of causal mechanisms incrementally, within each observational context. The particle model develops and is refined concurrently with student understanding of the macroscale characteristics and behavior, and provides a way to help students integrate and coordinate their conceptual understanding of materials and material behavior (She, 2004).

Several studies suggest that students can develop an particle-based causal-mechanistic explanation of various phenomena through this type of evolutionary conceptual change; that is, student conceptions change in a gradual and context-dependent way as their experience with
phenomena and instructional support increases (Merritt, Shwartz, & Krajcik, 2007; She, 2004). For example, the Dual Situated Learning Model of instruction, involves confronting the students with evidence to change thinking from a less desirable mental set\(^2\) to a more normative mental set by building normative situated understanding and creating dissonance with non-normative prior knowledge and ideas. Using this model of instruction, students in Taiwanese schools developed more normative, particle-based causal-mechanistic explanations of both dissolution and diffusion, with 90% of the students ultimately using particle theory (in a normative way within the framework of the study), to explain aspects of dissolution (She, 2004). She’s study suggests that addressing students’ prior knowledge and reasoning strategies about a specific phenomena directly, confronting students with disconfirming evidence to highlight the inadequacies of their initial model, and providing multiple opportunities for students to investigate phenomena and revise their ideas while helping them construct alternative ways of explaining their observations, can help students build mechanistic understanding.

In our study, we applied this bottom-up, constructivist theoretical and instructional framework to design our instruction. We felt that the literature provides evidence to support the idea that novices’ understanding of these concepts develops in phenomenon-bound ways. Thus, although at the highest levels scientific understanding of an expert is highly integrated across observations and phenomena, novice understanding must build first towards integrating the macroscopic and submicroscopic perspectives within a single phenomenon (Ausubel, 1968; Bodner, 1992).

In addition, we believed that scaffolding students to develop normative macroscopic observation-based principles about phenomena and to craft corresponding mechanistic models to

\(^2\) She defines a mental set as “a certain way of seeing a task or situation that may carry over to other tasks or situations, whether or not it is appropriate.” This encompasses the explanatory and reasoning frameworks as well as any mechanistic model applied to explain a phenomenon.
account for the principles entailed: building upon prior knowledge; investigating the characteristics and nature of the phenomena in detail; constructing mechanistic explanations that predict and explain all observations without contraindication; and, once mechanistic models were constructed, attempting to draw connections across mechanisms to help unify students’ understanding. In addition to the evidence for student learning provided by prior studies, this perspective is aligned with a social-constructivist perspective on learning, which we adopted to complete the development of our instructional intervention. We strongly felt that this approach to instruction would be more successful for improving student understanding than the top-down perspective of imposing an expert’s streamlined cross-context, integrated knowledge structures on the student or than the bottom-up, theory-theory perspective assuming that students develop cohesive theories of materials that they could apply in explanations across phenomena.

*Using a Situated Social Constructivist Perspective and a Problem-Based Nanoscale Science Context to Elaborate our Instructional Approach*

In addition, we subscribe to a situated, social constructivist approach to instruction, centered on building mechanistic explanations that integrate student ideas within a context, and build students’ normative usable ideas and reasoning strategies from the foundation of their initial conceptual frameworks. This perspective posits that knowledge is actively and collaboratively constructed, structured, restructured, organized, and reorganized through socially situated interactions. Thus, from this perspective, the knowledge of any individual reflects his or her unique set of contextualized sociocultural experiences and interactions both in its structure and content (M. Suzanne Donovan & John D. Bransford, 2005; Palincsar, 1998, p. 348; Palincsar & Scott, in press; Singer, Marx, Krajcik, & Chambers, 2000; Vygotsky, 1978). We situated the learning within a meaningful context that enabled students to develop mechanistic reasoning for
explaining phenomena in a school-science domain and in the domain of interpreting
advertisements and making health-related decisions, in an effort to broaden students’
understanding of the value of mechanistic models outside of the school-science domain.

To help students build a mechanistic explanatory framework from the foundation of their
prior knowledge, we focused our instruction around meaningful questions promoted student
engagement, motivation and the creation of a “need-to-know” to propel student learning
(Cordova & Lepper, 1996; Krajcik & Czerniak, 2007). This approach provides a direct link
between the meaningful context and understanding of both the observable behaviors and the
particulate causal mechanism. This imbues the particle model with meaning despite its abstract
nature.

Our instructional framework includes several of the aspects of She’s instructional model,
described previously, in order to promote the use of particle-based mechanistic explanations of
dissolution and rates of dissolution, and to create a meaningful context that would encourage
students to use mechanistic particle-based reasoning to make predictions and explain
observations. Specifically, we attend to prior knowledge, and provide multiple opportunities and
multiple modalities for students to repeatedly make predictions, observe phenomena, and revise
their conflicting ideas in a scientific context.

Our instructional intervention was developed to help students explore and explain
macroscale and nanoscale behavior and characteristics of solid materials in terms of the
normative explanations of dissolving and of the relationships among shape, size, and the rate of
dissolution. We chose to use a nanoscale science focus to contextualize learning about the
particulate explanations of the dissolving and of the relationships among shape, size, and the rate
of dissolving. We chose to use a nanoscale/surface-dependent properties of dissolution and rates of
dissolution for three reasons. First, surface-dependent properties are directly related to the
percentage of exterior particles in a material. As any dimension of a material approaches the nanoscale, this percentage increases dramatically, influencing the behavior and properties of the material (Stevens et al., in progress). In addition, in nanoscale materials, there may be a relatively high percentage of particles on edges and corners of objects, leading to unexpected changes the behavior of materials and new functionalities (Gemming & Seifert, 2007). Thus, a nanoscale context enabled us to model and emphasize some of the mechanistic aspects of dissolution in multiple ways, increasing students’ experiences with the idea that particles of water pull apart particles of solute during the process of dissolution (Stevens et al., in progress).

Second, nanoscale powdered materials have far fewer total particles than larger scale materials. Thus, it was possible for students to count and compare the total number of external particles to the internal particles in our simplified representations and models of nanoscale materials during modeling and design activities, a simpler task than comparing the more abstracted characteristic of surface-area-to-volume ratios of materials.

Finally, real-world, problem-based explorations of nanoscale materials represent a novel and exciting setting within which to engage students in exploring the familiar but oft-misunderstood concepts of dissolution (Krajcik & Blumenfeld, 2006; Schank, Krajcik, & Yunker, in press). Thus, although students were learning about familiar concepts they had much prior experience with in the real-world domain, the nanoscale setting of the curriculum enabled us to build student experience and knowledge about dissolution toward the scientific domain. In other words, by situating our instruction in the experientially novel framework of nanoscale science, we enabled students to explore dissolution from a new, scientifically-situated lens. Our instructional intervention capitalized on the experientially rich prior-knowledge framework of real-world notions of dissolving students possessed, and the novel approach of nanoscale science to construct and organize new normative understandings in the scientific domain.
We contextualized our instruction within the framework of one of two questions: “How can nanotechnology help treat asthma?” or “How can nanotechnology help treat lung cancer?” During the 15-hour instructional intervention, students evaluated and critiqued claims that nanoparticulate formulations of dry-powder asthma medications or lung cancer treatments worked faster and more effectively than microparticulate formulations, and made recommendations to their friends and loved ones about whether or not to use these types of medications.

The construction of our learning environment enabled us to evaluate the content and use of student ideas at several different time points within the curriculum. We evaluated student artifacts to investigate two research questions:

1. How do students explain and reason about dissolution during an instructional intervention focused on surface-dependent properties?

2. What kinds of concepts and notions help students develop particle-based mechanistic reasoning to explain macroscale observations?

Methodology

Participants and Context

To investigate our research questions, we implemented an instructional intervention during a free, two-week Summer Nanoscience Academy. The overall Academy curriculum was focused on introducing middle-school students to concepts fundamental to the understanding of nanoscale science and engineering, and to engage students in nanoscale science contexts. To achieve this aim, students in the Academy participated in two complementary, problem-based, 15-hour instructional strands, each consisting of six 2.5 hour lessons. In addition to the instructional strand on which this research is based (described previously), the second
instructional strand engaged students in investigations of size and scale. The overall Academy curriculum was developed using the Construct-Centered Design process to coordinate learning goals, curriculum, and assessment in a principled manner (National Center for Learning and Teaching in Nanoscale Science and Engineering, 2008b). For each phenomenon, we define successively more sophisticated levels of mechanistic reasoning. The progression of levels was established by developing a construct map, with the lowest level of mechanistic reasoning as the lower anchor and the desired normative scientific reasoning at the upper anchor (Smith et al., 2006; Stevens et al., in press; Wilson, 2005). The construct map described general increasingly sophisticated levels of explanation, between a basic description of what is observed when something dissolves to a complex explanation of the elements, spatial organization, and rules of behavior responsible for causing the observed behaviors. See Appendix I for a summary of the content and activities involved in the instructional intervention.

Learning goals were assessed at multiple points through the curriculum, through written formative assessments, pre- and post- written assessments, and summative performance assessments designed to scaffold understanding and promote sense-making, while probing for student explanatory levels of understanding (Rivard & Straw, 2000; Ruiz-Primo, Li, Ayala, & Shavelson, 2004). In addition, a comparative assessment of explanation-embedded content was conducted 6 months after the completion of the Summer Science Academy. This comparative assessment, which will be described in the next section, was used in combination with the pre- and post- Academy internal assessments to evaluate the effectiveness of the instructional intervention for helping students develop normative, mechanistic causal explanations of dissolving and the relationship between size, shape, and rates of dissolution. In addition, the comparative assessment enabled us to evaluate the robustness of any changes in student explanations over time. The comparative retention assessment, in contrast to the pre- post-
instruction assessment, mainly a multiple-choice assessment, with three short-answer questions and 14 multiple-choice question. The multiple-choice questions had multiple correct responses, which corresponded to different levels of the construct-maps of dissolution and the relationship between size, shape, and rates of dissolution. As a result, the retention assessment enables us to gauge students’ ability to choose between different types of explanations. Because of the different natures of the cognitive processes of choosing a best response, as in a multiple-choice test, or crafting a complete response, as in an open-ended question, we do not consider these assessments to be comparable. Rather, we use both assessments to look for changes and differences in student thinking.

We chose to follow the development of student ideas by collecting written artifacts throughout the curriculum, including group and individual written explanations, observations, and models. Written artifacts provide comprehensive evidence for evaluating student understanding and illustrating cognitive development in terms of conceptual and organizational changes and development (Fellows, 1996; Ruiz-Primo et al., 2004). Additionally, writing promotes sense-making and conceptual development, and thus formed an integral part of our instructional intervention (Rivard & Straw, 2000).

The Academy enrolled 32 middle-school students from a diverse midwestern school district, in which 56% of the students qualify for free or reduced-price lunch. Students were divided into sections based on grade level and ability. Each section had similar instructional activities and assessments, contextualized with different driving questions. Student demographics for the overall Academy are detailed in Table 1.

This 6-month post-Academy analysis enabled a comparison between students who applied and attended the summer science academy (n=19, 62.5% of attendees), and students who applied but chose not to attend the summer science camp (n=18, 62.1% of non-attendees). We posit that
these groups are similar on the basis of age, race, gender, school, and quality of application essay. As the comparison non-attendees applied to a summer science academy focused on nanotechnology, we assume that they had the same level of interest in science as the attending group. Students provided a variety of reasons for not attending the academy after voluntarily applying, including that they had attended before, had other conflicting summer activities, unexpected personal conflicts, or problems getting transportation to and from the school pick-up site. However, there was a variety of reasons that students chose to attend the academy as well, including interest, parent insistence, and to have something to do during the summer. Thus, we suggest that the groups represent a relatively fair comparison through which to evaluate the effectiveness of our instructional intervention. In addition, conducting a comparative analysis rather than re-administering the pre-post assessment to attendees to determine retention enabled us to eliminate the possibility of a testing effect. Demographics of the attendees, comparison subsample of attendees, and non-attendees are detailed in Table 1.
### Table 1

**Student Demographics**

<table>
<thead>
<tr>
<th></th>
<th>Total Attendees</th>
<th>Comparison Attendees (Subsample, 6-month retention)</th>
<th>Comparison Non-Attendees for 6-month retention study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>16</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Male</td>
<td>16</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td><strong>Last Grade completed</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6th</td>
<td>16</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>7th</td>
<td>12</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>8th</td>
<td>4</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Race</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Caucasian (African American, Hispanic, biracial, or multiracial)</td>
<td>21</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Caucasian</td>
<td>9</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>No response</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td><strong>Overall</strong></td>
<td>32</td>
<td>19</td>
<td>18</td>
</tr>
</tbody>
</table>

*Assessment Instruments and Analytical Framework*
To investigate our research questions, we characterized and interpreted student understanding by investigating artifacts produced prior to the instructional intervention, during the instruction, at the end of instruction, and six months after the culmination of instruction. Each artifact was evaluated in several ways. We first identified student responses that represented incorrect theories or principles about dissolution as non-normative. We define these non-normative ideas as ideas not supported by scientific evidence or ideas that contradict the concepts embedded in the construct map guiding the instructional intervention. This allowed us to evaluate for persistence of non-normative ideas within students’ conceptions, and enabled us to characterize changes in student explanations and reasoning within the confines of normative understanding. A list of non-normative ideas observed in student responses can be found in Appendix II.

Using the typology of student explanations and causal reasoning adapted from Gilbert et al. (1998), Metz (1991), and Russ et al. (2008), we created a coding scheme to enable the evaluation of student conceptual understanding of these three phenomena in use. Gilbert et al. (1998) suggests that the multiple meanings of “explain” in a scientific context can lead to confusion in students, and cause them to interpret questions in different ways that are intended. We first coded the data using the typology of explanations suggested in Gilbert et al. (1998), to categorize the ways that students were interpreting our requests to “explain your reasoning.” This enabled us to compare students’ causal reasoning through instruction without confounding reasoning strategies with explanatory frames. We categorizing any causal reasoning students used as teleological reasoning, observational principle-based implicit reasoning, observational principle-based explicit reasoning, and mechanistic reasoning. Any mechanistic reasoning students used was further characterized to elucidate the types of features important to our target
understanding students used in their reasoning strategies. This coding scheme is further categorized below. See Figure 1 for a schematic of the coding scheme.

Figure 1

*Schematic of Coding Scheme to Characterize Student Responses*

We coded explanations as *intentional or belief-based* when students used beliefs, intent, goals or non-evidence-based justifications in their explanations, as though they were answering the question “Explain why you believe or do not believe that this phenomenon is good/real/practical?” *Descriptive explanations* were characterized as when students provide a non-interpretive, description of a phenomenon, as if they were answering the question, “Explain how this phenomena behaves?” In these explanations, students provide a descriptive account of what they observe on the macroscopic level, without applying further interpretation. We coded *typifying explanations* instances in which students’ explanations focused on the components of a
phenomenon. In these types of explanations, students seemed to be interpreting the request to explain their reasoning as “Explain what characterizes or typifies this phenomenon?” This category is similar to a descriptive explanation, but abstracted in the sense that it defines the scope of concepts and general commonalities between phenomena. A causal explanation or causal predictive explanation provides any type of justification for the observed phenomenon or expected observation. These types of explanations are further categorized as using teleological, surface-level, and mechanistic reasoning. See Table 2 for a summary of the explanation categories and examples of student responses in each category.
### Table 2

**Summary of types of explanations, and examples of their use by students**

<table>
<thead>
<tr>
<th>Type of explanation</th>
<th>Description of Use in Science</th>
<th>Examples of different explanatory frameworks used by students to answer the question:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intentional</strong></td>
<td>Explain why an investigation is being carried out in terms of justifications, and intent.</td>
<td>“I think the advertisement is accurate, because I think Nano technology can do all these things for the [solute] to help them dissolve faster.”</td>
</tr>
<tr>
<td><strong>Descriptive</strong></td>
<td>Describes how a phenomenon behaves</td>
<td>“…they improved their [product] and now it desolve (sic) faster…”</td>
</tr>
<tr>
<td><strong>Typifying</strong></td>
<td>Explains what a phenomenon consists of</td>
<td>“Its going to depend on how much water and how much they use and the temperature.”</td>
</tr>
<tr>
<td><strong>Causal / Predictive</strong></td>
<td>Explains why a phenomenon behaves as it does, or what will happen in novel circumstances</td>
<td>“yes beacuse (sic) since it is a finer powder, it will take less time to dissolve”</td>
</tr>
</tbody>
</table>

Although the use of different types of explanations is common throughout scientific and everyday domains, our goals in the instructional intervention was to help students develop
causal-mechanistic reasoning strategies using the particle model. Thus, we further characterized students’ causal reasoning to determine whether they were using teleological reasoning, implicitly or explicitly using principle-based reasoning, or mechanistic reasoning.

*Teleological reasoning* is the least sophisticated level of reasoning used in causal explanations, and involves simply attributing a phenomenon or behavior to the identity or purpose of a material (Carey, 1995; Russ et al., 2008). *Observational principle-based reasoning* is divided into implicit and explicit types, and refers to a principle abstracted from observations. Principle-based reasoning attributes cause to a general observable interaction, relationship, behavior, or correlation. We classified student responses as *implicit* if the principle had to be inferred from their statement, and seemed to be used by the student in their reasoning, and as *explicit* if the abstracted principle was directly stated in the students’ reasoning. *Mechanistic reasoning* was our target level of causal reasoning. Mechanistic reasoning attributes behavior to an underlying cause, describing the root interactions or structures responsible for the observation. See Table 3 for a summary and examples of our coding for causal reasoning.
### Table 3

Causal Reasoning Types: Summary and Coding

<table>
<thead>
<tr>
<th>Type of reasoning</th>
<th>Description</th>
<th>Example:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Teleological</strong></td>
<td>Proposes that observed behavior is attributable to the purpose or identity of a material (Carey, 1995; Russ et al., 2008)</td>
<td>[Crushed solute dissolves faster because] “Powder-like things such as salt and sugar always dissolve in liquids”</td>
</tr>
<tr>
<td><strong>Observational principle-based</strong></td>
<td>Refers to a principle abstracted from observations</td>
<td>“Since the crushed salt was smaller, it should desolved (sic) faster.”</td>
</tr>
<tr>
<td><strong>Implicit</strong></td>
<td>Principle implied in reasoning</td>
<td>“My reasoning is that smaller things dissolve more faster, and if it is crushed it will dissolve faster…”</td>
</tr>
<tr>
<td><strong>Explicit</strong></td>
<td>Abstract, general principle directly stated</td>
<td>“More surfaces of the Nanopran touches the mucus so it breaks it down faster into particles [than Micropran]”</td>
</tr>
<tr>
<td><strong>Mechanistic</strong></td>
<td>Provides an underlying cause for behavior or characteristics related to the root interactions or structures responsible (Russ et al., 2008)</td>
<td>“More surfaces of the Nanopran touches the mucus so it breaks it down faster into particles [than Micropran]”</td>
</tr>
</tbody>
</table>

Although principle-based reasoning is a legitimate reasoning strategy used commonly in everyday decision-making and scientific explanations, we position mechanistic reasoning at the highest level of causal reasoning strategies. This characterization is based on three principles:
the idea that mechanistic reasoning about phenomena are most highly valued in science (Metz, 1991; Reif & Larkin, 1991; Russ et al., 2008); the understanding that mechanistic explanations of the phenomena requires students to understand phenomena from both a observational and theory-based perspective (Cakmakci, Donnelly, & Leach, 2005; Lombrozo & Carey, 2006); and higher usability of mechanistic reasoning in making complex inferences when compared to other methods of causal reasoning (John K. Gilbert et al., 1998; Metz, 1991; Reif & Larkin, 1991).

Our final level of coding focused on the content of students’ mechanistic reasoning relative to our target mechanistic model. We identified five essential aspects of a mechanistic explanation of dissolution relevant to our target learning goals: a **connection** to observationally-base principles, the importance of **spatial association** between the solute and the solvent, the **agency** or action of the solvent in the process of dissolution, a statement explaining the mechanical **process** occurring during dissolution, and the description of **particles** of solute, solvent, or both (See Table 4 for a summary and examples of these aspects of mechanistic reasoning from student work).
Table 4

*Features of Mechanistic Reasoning and Examples from Student work*

<table>
<thead>
<tr>
<th>Feature</th>
<th>Example from Student Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial association of solute and solvent</td>
<td>“All of the particals (sic) are showing, <strong>so the water can reach</strong> them…”</td>
</tr>
<tr>
<td>Agency of solvent</td>
<td>“<strong>H₂O is coming and taking particles away</strong>… [from the solute]”</td>
</tr>
<tr>
<td>Process of Dissolution</td>
<td>“The water molecules have <strong>broken many too small to see pieces off</strong> [of the solute]…”</td>
</tr>
<tr>
<td>Use of particles in describing solute, solvent, or both</td>
<td>“<strong>The water molecules</strong> are attacking the <strong>Ibuprofen molecules</strong>…”</td>
</tr>
<tr>
<td>Connection to Observation-based Principles</td>
<td>I need to know how much <strong>surface area each crystal has</strong> because the <strong>surface gets hit by the water first so the water molecules can pull the sugar molecules away.</strong></td>
</tr>
</tbody>
</table>

To evaluate changes in conceptual understanding and the use of conceptual understanding in explanations and predictions, we applied this overall coding scheme to all student artifacts, focusing on student responses to prompts that asked specifically for explanations. This enabled us to interpret the aspects of students’ reasoning most impacted by the instructional intervention, as well as to identify students whose reasoning changed dramatically and students whose reasoning remained stable through instruction. Interrater reliability of 91% was established by a colleague coding 20% of the students’ responses. After discussion, 100% agreement was reached. By comparing evidence of change in understanding
from artifacts among students with high gains in different aspects of reasoning and students with low gains, we are able to get a sense of how student reasoning changed through instruction, and what conceptual understandings and connections between ideas were essential to helping students increase their ability to reason about dissolution in a normative manner.

Analyses and Findings

Did students’ explanations, reasoning, and content understanding change during the instructional intervention, and, if so, in what ways?

Content understanding: In addition to the types of reasoning that students used, we evaluated the content of students’ ideas using the retention comparative analysis. The content analysis subsumes the reasoning that students use (See Appendix II for a table demonstrating how the content analysis maps onto the explanations and reasoning analysis), and enables us to compare in a unified manner changes in normative ideas, explanation and reasoning types, and the content of the processes and principles. Content of students’ ideas was evaluated using rubrics generated from the construct maps of dissolving and rates of dissolution that guided the development of the Academy (See Appendix I). We conducted content analyses using the open-ended pre- and post instruction assessments, as well as in the multiple-choice comparative analysis (See Appendix IV and V for the pre-post and comparative assessments). For the understanding of sugar dissolving in water, our pre-post linear regression analysis indicated that the Academy had an effect size of 1.23 (p<0.001), while for the understanding of the relationship between size and shape and the rate of dissolution of materials, when all other conditions were kept constant, the Academy had an effect size of 1.63 (p<0.001). Race, gender, and grade had no significant impact on student scores. The retention analysis suggests that the effect size of the Academy on understanding of the process of dissolution was 1.77 (p<0.001), and for the
relationship between size and shape and the rate of dissolution of materials, when all other conditions were kept constant, was 1.94 (p<0.001). This increase in effect size may be explained in several ways. First, students may have gained content understanding in school that they were able to apply to the context of dissolution, increasing their understanding of dissolving and the influence of size and shape on dissolution rates. Another explanation may be that the open-ended pre-post analysis required the cognitive ability to generate explanations, while the multiple choice assessment just required the recognition of appropriate explanations. Finally, the discrepancy may be explained by small differences causing non-equivalency in the comparison groups, despite their demographic and science-interest similarities.

Students’ non-normative ideas about dissolution decreased significantly through the Academy. Prior to instruction, an average of 23% of students’ responses involved non-normative ideas. These non-normative ideas included the idea that dissolution is intentional on the part of the solute, that some solutes do not dissolve because they are too hard to dissolve, and that particles get broken up into smaller pieces during dissolution (See Appendix II for a full list). After instruction, non-normative ideas constituted an average of 1% of responses (p<0.001), indicating that students harbored fewer non-normative ideas after instruction than before instruction. In the comparison study, non-normative ideas constituted approximately 11% of responses, suggesting that some of the non-normative ideas harbored by students may not have been changed in lasting ways. Some of these non-normative ideas included that objects of identical mass and material composition would dissolve at the same rate regardless of shape or surface area, and that once a solute was dissolved into water, it was impossible to retrieve it into any pure, solid form. However, non-normative ideas constituted 29% of the responses chosen by

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3 All further significance tests reported were calculated with non-parametric correlation analyses using Spearman’s Rho, unless otherwise noted.
the comparison group of students, indicating that, for some of the Academy students, changes in non-normative ideas may have been persistent (ES=1.13, p<0.01).

*Explanations and Reasoning.*

Overall, the pre-post analysis indicated that student-generated responses tended to become more causal-mechanistic as a result of instruction (ES 1.05, p<0.001). Students use descriptive responses more frequently prior to instruction, not-surprisingly indicating a reliance on observation rather than theory or mechanism in their interpretations of phenomena. For example, one 6th-grade female student responded to a request to explain what really happens to that causes things to dissolve by stating solutes “get smaller”, depicting bubbles emanating from the solute as it dissolved. In contrast, after instruction, the same student represented water molecules “carrying away” particles of solute as the solute dissolved. Another 6th grade female student responded to the same question by describing how “bubbles are rising and popping …the water is getting mistey with the [solute],” a macroscopic description of dissolution. In contrast, after instruction, the same student described and drew how “H\textsubscript{2}O is taking particles [of solid] away, increasing the concentration…”

Students rarely responded to the pre- and post-assessment items using intentional or typifying reasoning, and never used causal-teleological reasoning in response to these specific comparison items. There was no significant difference in student use of implicit principles in causal reasoning, but students seemed to use causal-explicit principles more frequently prior to instruction than they did after instruction. This can be explained in two ways. First, students may have felt the need to explicitly state the principle they were using to describe behavior in their responses initially in the pre-instruction phase. However, during instruction, student explored the phenomena and focal principles in a number of activities, and had numerous
opportunities to explain their reasoning. Thus, they may have felt that, by the post-instructional time point, they no longer needed to explicitly state the principle. Second, principle-based reasoning constitutes a higher percentage of students’ responses in the pre-instruction time period in general, and this may be responsible for the higher percentage of explicit principles used in the pre-instruction time period. See Table 5 for a summary of the proportion of responses using each type of reasoning, and Figure 2 for a graphical representation of the changes in students’ explanations and reasoning.

The percentage of students using each of the aspects of mechanistic reasoning increased significantly after the instructional intervention. In particular, use of either solute or solvent particles in mechanistic reasoning increased from 12.5% of students to 84.3% of students (p<0.001), while use of the feature of agency of solvent increased from 3.1% of students pre-instruction to 65.6% of students post-instruction. See Figure 3 for a graph of changes in students’ use of aspects of mechanistic reasoning.
Table 5

Proportion of responses using each type of reasoning

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Instruction</td>
<td>0.02</td>
<td>0.24***</td>
<td>0.023</td>
<td>0.21</td>
<td>0.38*</td>
<td>0.11***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(SD=0.15)</td>
<td>(SD=0.43)</td>
<td>(SD=0.15)</td>
<td>(SD=0.41)</td>
<td>(SD=0.49)</td>
<td>(SD=0.32)</td>
<td></td>
</tr>
<tr>
<td>Post-Instruction</td>
<td>0</td>
<td>0.06***</td>
<td>0</td>
<td>0.16</td>
<td>0.23*</td>
<td>0.55***</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>(SD=0.24)</td>
<td>0</td>
<td>0 (SD=0.37)</td>
<td>(SD=0.43)</td>
<td>(SD=0.50)</td>
<td></td>
</tr>
</tbody>
</table>

( *p<0.05, **=p<0.01, ***=p<0.001)
Figure 2

Average Responses Pre- and Post-Instruction

(*=p<0.05, **=p<0.01, ***=p<0.001)
Figure 3:

*Students’ use of aspects of mechanistic reasoning, pre and post instruction*

Aspects of Mechanistic Reasoning

\[ (*=p<0.05, \quad **=p<0.01, \quad ***=p<0.001) \]
The retention study multiple-choice analysis suggested that there was no significant difference between the types of *normative* explanations chosen by attendees and the comparison group. In other words, any observed differences in responses among these groups can be explained by the content of their responses rather than the type of reasoning they felt was appropriate to answering the question. We emphasize that choosing a response from a set of multiple choice possibilities requires a lower level of engagement and understanding than selecting crafting a original response, and do not intend to make comparisons to the pre-post assessment as we consider this second analysis.

There were two significant differences in the ways that students responded to the multiple choice assessments. First, Academy attendees, tended to choose responses that involve more connections between principles and the mechanism in their reasoning and explanations than non-Attendees (p<0.05). For example, in response to the question “You need to *quickly* dissolve a big crystal of salt in water. Your friend Ella suggests that you crush up the salt into tiny pieces to help it dissolve more quickly. Do you think this is a good idea or a bad idea? Pick the best explanation to support your response,” Academy attendees were more likely than non-attendees to chose a mechanistic response that expressed: “**Good idea** – Crushing the salt will make it more exposed to the water, which will help break it down faster”, while non-Attendees a were more likely to choose the correct, but non-mechanistic response that “**Good idea** - You have noticed that crushing things gets them to mix in the water faster, so her idea might work!” to respond to the question. This suggests that Academy attendees may have recognized the value and explanatory power of mechanistic models in ways not fully recognized by non-Attendees.

Second, Attendees were more likely to choose responses that featured both solute and solvent particles, suggesting that they may have more complete and complex understandings of the use of particle models of matter than the non-Attendees (p<0.05). For example, in response to the
question “Your 15-year-old neighbor, Hagar, doesn’t understand what happens to Kool-Aid powder when it dissolves. How would you best explain dissolving to him?”, students could choose from the following responses:

a. “When the Kool-Aid dissolves, the pieces of the powder look like they become part of the water.”

b. “When the Kool-Aid dissolves, the pieces of powder get smaller and smaller until they mix together evenly with the water.”

c. “The water surrounds the Kool-Aid and pulls it apart from the outside, until water surrounds each particle of Kool-Aid material.”

d. “The water molecules pull apart the Kool-Aid molecules.”

e. “The Kool-Aid breaks apart into smaller pieces when it dissolves.”

Although each response is technically correct, over one third of Academy participants chose either response “c” or “d”, indicating that they felt that the best responses involved particles of solute and solvent, while only 11% of non-Attendees chose either of these options. Further, half of non-attendees chose descriptive response (“a”) while only one attendee (5%) thought this was the most appropriate response to the question. This indicates that attendees use a different explanatory and reasoning framework for explaining dissolution than non-attendees. See Table 6 and Figure 4 for details of the differences in features of normative mechanistic reasoning chosen by each group in the comparison sample.
Table 6

*Features of mechanistic models: Percent of students who selected responses with each feature*

<table>
<thead>
<tr>
<th>Spatial</th>
<th>Connections *</th>
<th>Association</th>
<th>Agency</th>
<th>Process</th>
<th>Either solute or solvent</th>
<th>Both solute particles</th>
<th>Both solute particles *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attendees</td>
<td>89.5%</td>
<td>94.7%</td>
<td>100%</td>
<td>100%</td>
<td>73.7%</td>
<td>36.8%</td>
<td></td>
</tr>
<tr>
<td>Non-Attendees</td>
<td>55.6%</td>
<td>83%</td>
<td>100%</td>
<td>100%</td>
<td>66.7%</td>
<td>11.1%</td>
<td></td>
</tr>
</tbody>
</table>

(*=p<0.05)

Figure 4

*Percent of students choosing responses with each feature of mechanistic reasoning important to dissolution*
In summary, from these analyses, we suggest that students’ explanations and reasoning about dissolution changed in significant ways through instruction, and that some of these changes were retained six months after instruction. We suggest that student generated instances of causal-mechanistic reasoning about dissolution using particles increased, suggesting an improvement in student understanding of the utility and content of the particle model. In the next section, we further explore how students’ understanding changed through instruction, focusing on comparing artifacts from 4 students who experienced a dramatic change in reasoning with artifacts from 3 students who experienced the least dramatic increase in reasoning ability as a result of the summer science academy.

What types of concepts and notions help students develop particle-based mechanistic reasoning to explain macroscale observations?

Evaluating changes in reasoning. While some students improved dramatically in both reasoning and content understanding during the course of our instructional intervention, some students did not experience changes in their reasoning through instruction. Our final analysis compared four students who had high gains in aspects of mechanistic reasoning (students HG1, HG2, HG3, and HG4) with three students who had low gains in aspects of mechanistic reasoning (students LG1, LG2, and LG3) to determine what factors and conceptual understandings were important in the development of our target understanding (particle-based causal-mechanistic reasoning about dissolution). We evaluated students who had started with the same general model of dissolution, in order to evaluate relatively equivalent groups of students. Combining the reasoning coding with a grounded-theory analysis, we evaluated student responses for changes in the use and content of principles and reasoning in response to instruction. Appendix
III is a summary table of this analysis, consolidating the responses of each of the student who moved from descriptive, macroscopic explanations to particle-based causal-mechanistic explanations by initial, formative, and post-instruction time points. Each time point is divided into a how students responded to particular items or explained specific concepts during that timepoint. The high-gain students are compared to the low-gain students to elucidate any patterns of differences in the reasoning strategies, conceptions, and general ideas between the two groups of students.

In our cross-student analysis, we found two important changes in reasoning strategies essential to the emergence of our target reasoning about dissolution. 1. Successful students adopted a notion of solutes as “vulnerable” or “reachable” to water particles during instruction. In other words, successful students changed from thinking about dissolving in terms of solute only, to thinking of dissolving as a relationship between solutes and solvents; and 2. Successful students constructed an integrated and hierarchical understanding of the observation-based principles of dissolving, as evidenced by their use of the concepts of increased surface area and the particle nature of matter to explain why small grain-sized materials dissolve faster than large grain-size materials, and to explain why solution concentration increases quickly when a small grain-sized material is dissolving. These changes in reasoning strategies essential to an improved understanding of the process of dissolution and differences in rates of dissolution are detailed below.

1. Successful students adopted a notion of solutes as “vulnerable” or “reachable” to water particles during instruction. Successful students changed from thinking about dissolving in terms of solute only, to thinking of dissolving as a relationship between solutes and solvents.
In each of the successful students, a conception of solutes as vulnerable or susceptible to being dissolved emerged and seemed to subsume principle-based reasoning. Student HG2 referred to the vulnerability of the surface of the solute to attack in four of her responses after the idea emerged during a scaffolded activity geared towards helping students develop this conception of dissolution. Students HG1 and HG3 also adopted the concept of the “vulnerability” of the solute to being broken up or pulled apart by the water molecules to explain the relationship between size and surface area and rate of dissolution. Student HG4 used the concept of the water molecules needing to “reach” the particles of solute in order to dissolve them. Once HG4 completed the instructional activities focused on this concept, he began using it to explain the relationship between size and rate of dissolution as well as the relationship between the amount of solute and the final concentration of a material.

In comparison, although students LG1 and LG2 identified that the amount of “outside surface” was important in rates of dissolving in highly scaffolded activities, they did not retain the principle when the scaffolding was removed. When asking to explain the process of dissolution after these structured activities, these students relied on descriptive reasoning, indicating that they had not adopted a model of dissolution in which the outside surface held importance. LG3 developed an understanding of the importance of “outside surface” during the scaffolded activities, and continued to use this idea in reasoning once the scaffolds were removed. However, LG3 only used the principle to predict differences in rates of dissolution between two objects of identical mass and different shapes, and not to describe the process of dissolving or to predict differences in rates of dissolution in different grain sizes of materials. This suggests that LG3’s conception of the importance of the amount of outside surface was fragmented and specific to the situation in which it was learned.
2. Successful students constructed hierarchical integrated understandings of the observation-based principles of dissolving

Two of the observation-based principles that we explored in the Academy were hierarchically related: The relationship between size and rate of dissolution is due to the increased surface area of smaller grain-sized solutes. The principle relating final concentration to overall amount of solute is related non-hierarchically to both of these principles. Students who were able to connect principles generally did so by relating the principles to the particle model. For example, student HG2 used particles and the process of dissolution to describe the principles that surface area is important in rates of dissolution, and that as a substance dissolves, the solution increases in concentration in her explanation of the process of dissolution. Each time the student referenced the process of dissolution, she described “H₂O coming to attack the surface [of the solute] to take particles away,” indicating an integrated understanding of dissolution in each case. This reasoning strategy was fruitful and enabled her to predict and explain mechanistically dissolution in different contexts.

In contrast, LG3 attempted to use size to explain differences in rates of dissolution among different shapes of the same mass of material, predicting that thinner materials will break into pieces that will dissolve faster than thicker materials. However, this integration strategy did not give her insight into the process of dissolution, and therefore did not help her improve her reasoning. Thus, integration of concepts in a hierarchical manner seems to be important in the development of our target mechanistic reasoning about dissolution.

In addition to these differences in the development of reasoning strategies, we found that students who came in with a particle model of solids or liquids often did not initially use these models to explain dissolution, even when prompted to “Zoom in all the way, as far as you can go, so that you can show what is really happening.” Among the 16 students who provided a
model of solids or liquids involving particles initially, outside of the context of dissolution, only four used their particle models to explain the process of dissolution, and only two identified particles or molecules as something similar between their diagrams of solids and liquids. There was no significant relationship between an initial particle model of solids and liquids and a final particle model of dissolution, suggesting that top-down introduction of the particle model would not improve student reasoning about dissolving. However, since the sample size of this study is small, it is not possible to verify that an initial particle model had no influence on students’ final reasoning about dissolution.

Discussion and Implications

Our aim in this analysis was to investigate what types of concepts and notions help middle schools students develop particle-based mechanistic reasoning about dissolving. To this end, we developed an instructional intervention focused on surface-dependent properties, seeking to help students understand the usefulness and reliability of the particle model in predicting macroscale observations.

Our analysis suggests that middle school students’ explanations and reasoning about dissolution became more causal-mechanistic and less descriptive during the course of our instructional intervention. Specifically, students improved their ability to connect the mechanistic process of dissolution to observable phenomena, and to use both particles of solute and solvent in their explanations. Although over half of the Academy attendees had a particle-based model of either solids or liquids prior to instruction, only 12.5% of these students used this model to explain what happened in dissolution, supporting the idea that students have context-dependent, fragmented understanding of materials, as suggested by Harrison & Treagust (2002) and Teichert et al. (2008). In contrast, by the end of instruction, 84.4% of students used either
particles of solute or solvent in their explanations of dissolution (p<0.001). This provides evidence that our bottom-up instructional approach of focusing on developing particle-based causal-mechanistic explanations within a specific behavior, can help students develop causal-mechanistic explanations for material behavior (diSessa, 2006). The instructional intervention helped to integrate and improve students’ understandings of materials and dissolving, and helped some students develop a usable particle theory relative to dissolution. The comparison analysis suggests that changes in students’ reasoning and conceptual understanding were retained over a six-month time period, indicating lasting changes. Further research must be conducted to investigate how these causal-mechanistic explanations can be synthesized across phenomena as students move towards more expert understandings of materials.

Students who successfully transitioned from descriptive explanations and implicit observation-based causal reasoning to more particle-based causal-mechanistic reasoning adopted a notion or “internal representation” of solutes as materials whose surfaces are vulnerable to interactions with solvents (Gilbert, 2008). This notion seemed to provide a relatable way for students reliably interpret differences in rates of dissolution and sizes or shapes of materials, as well as a way for students to describe the process of dissolution (Rapp & Kurby, 2008). Not surprisingly, this simple notion as an internal representation or notion, it embodies most of the essential features of the causal-mechanistic explanation we targeted specifically: Vulnerability suggests the agency of another entity (solvent), association between two entities, and the imminent threat of a process of dissolving. We suggest that identifying richly evocative notions that can be adopted by learners as internal representations could promote the use of causal-mechanistic explanations. This builds on the findings discussed in Zhang and Norman (1994) that providing external representations that “anchor and structure” cognition, and build understanding of essential relationships spatially can facilitate problem solving. This type of
external representation, in the form of a related concept or visual image, transitions easily into an internal cognitive tool that summarizes the features of the causal-mechanistic explanation in a meaningful way (Zhang & Norman, 1994). Generally speaking, similarly structured external representations, that concisely and eloquently suggest the spatial, structural, or behavioral aspects of the desired mechanism can serve as potent conceptual scaffolds for the novice learner.

In addition, we posit that studying surface-dependent properties specifically highlights this interaction between the solute and solvent, and provides a need-to-know about particles (Bulte, Westbroek, Jong, & Pilot, 2006; M. Suzanne Donovan & J.D. Bransford, 2005). In general, the idea of need-to-know is based on generally motivating students by connecting science learning to everyday experiences. In this case, by encouraging students to create a causal-mechanistic explanation of why a nanoscale asthma medicine might work better than a microscale formulation, we created a need-to-know that was both content-specific and generally motivating. By connecting surface-dependent properties to a medical decision-making context, we personalize and connect the content in general to everyday experience. In addition, the heightened importance of locations of specific particles in determining rates of dissolution creates a need to understand the particle nature of matter. The nanoscale context illuminates the importance of the position of particles on surfaces, edges, and corners of materials, since, as any dimension of a material approaches the nanoscale, the proportion of particles on the surface increases exponentially, causing unexpected changes in the properties of the material.

We also observed that students who developed particle-based mechanistic reasoning during the instructional intervention additionally constructed hierarchical integrated understandings of the observable principles of dissolving. Our instructional intervention implicitly connected the principles that smaller materials dissolve faster and that dissolution rate is related to surface area. We found evidence of this hierarchical integration exclusively among
students who successfully developed the target particle-based causal-mechanistic explanation. This suggests that building causal-mechanistic explanations has a unifying effect on students’ understanding of materials. This finding is interesting from the perspective that experts develop causal-mechanistic explanations with the purpose of developing a unified understanding of phenomena, thus suggesting that developing a causal-mechanistic explanation within a context could support the transferability of students’ understanding to novel problems (Beach, 2003; Glennan, 2002; Salmon, 1984). Although situated problem-based and project-based learning environments have been criticized for not enabling transfer of knowledge to novel problems and context, this finding suggests that transferability can be enhanced in these rich learning environments through by helping students develop causal-mechanistic explanations of phenomena (Lave, 1988; Lobato, 2006; National Research Council, 1999).

Further research is needed to test the assertions that a conception of solutes as exposed or vulnerable helps students adopt causal-mechanistic reasoning strategies about dissolution. In addition, our analysis made it difficult to determine how particle notions of dissolution initially emerged among students. This type of analysis would help instructional designers and teachers develop strategies for helping struggling students develop target particle-based mechanistic reasoning. In addition, further research is needed to determine how mechanistic reasoning can be integrated between different phenomena.
References


**Appendix I: Instructional Design**

**Construct map:**

*Student explanations of the relationship between surface area and the rate of dissolution*

*Direction of increasing understanding of the relationship between a material’s surface and the rate of dissolution*

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**Student with a causal-mechanistic explanation of the relationship between surface area and rate of dissolution, including spatial association, agency of solvent, and particles of solute and solvent.**

*In addition to level 4:* Students are able to use the idea that certain particles on the surface of materials, such as edge and corner particles, are more vulnerable to dissolution because they are less strongly connected to the solid solute, and easier for water particles to pull or break off.

---

**Students with a causal-mechanistic explanation of the relationship between rates of dissolution and surface area that involves spatial association of solute and solvent, and possibly agency of solvent.**

*In addition to level 3:* Students are able to use the idea that, the more surface area a material has, the more exposure it has to water, to explain why materials with different surface areas dissolve at different rates.

---

**Students with an explicit observational-principle-based explanation of dissolution focused on surface area.**

*In addition to level 2:* Students are able to explain that some things dissolve more quickly than others because they have more surface area. Students are consistently able to use this principle to predict whether objects of different shapes and sizes will dissolve at different rates.

---

**Student with an explicit observational-principle-based explanation of dissolution, focused on mass, volume, or general size.**

*In addition to level 1:* Students are able to predict that a crushed material will dissolve faster than an intact material, because the material is smaller or has less mass per piece. Students may or may not be able to predict that shape can influence rates of dissolution.

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**Students with a descriptive, typifying, or teleological explanation of differences in rates of dissolution.**

Student responses indicate that some things dissolve faster than others, or that dissolving takes time, but does not provide evidence for a cause of differences in rates or processes accounting for rates.

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*Direction of decreasing understanding of the relationship between a material’s surface and the rate of dissolution*
Construct map:
Student explanations of a solid solute dissolving into water

Direction of increasing understanding of the mechanism of dissolution

Building on level 4, the student describes the association of solvent and solute particles in solution, and the student is able to apply the particulate explanatory model to reliably compare the dissolution of different shapes and sizes of solutes. Student explanations include both a macroscopic and particulate description of dissolution. Student describes explicitly how water “particles” pull apart solid “particles”, beginning with the most available solid particles on the exterior edges, corners, and surfaces of the material. The water “particles” surround the solid “particles” and move them away from the overall solid structure.

Building on level 3, the student is able to explain that the water molecules (particles) pull apart the solid pieces (particles), and can explain that both liquids and solids are made up of particles. Student gives an explanation that involves the water particles pulling apart the solid into particles. Student explanations indicate that the water is particulate. The resulting solution consists of particles of the original solid and liquid.

Building on level 2, the student is able to explain that the solute breaks down during dissolution, and that the resultant solution contains non-visible pieces (particles) of the solid. Student gives a macroscopic explanation in which the solute breaks down into smaller and smaller pieces. The resultant solution contains either water or solute particles.

Building on level 1, the student is able to explain dissolving behavior from a macroscopic perspective, and can describe that the resultant solution still somehow contains the solid. Student gives a macroscopic description and provides a macroscopic explanation focused on what happens to the solid. The student indicates that the solid does not just disappear, and continues to remain after it is no longer visible. Student description may indicate that the resultant solution is homogenous (uniform) or may contain visible suspended pieces of solid.

Student gives only a macroscopic description of what they observe when solids dissolve in liquids. Student description focuses only on what they have observed happening to solids.

Direction of decreasing understanding of the mechanism of dissolution

Students with a detailed particulate explanatory model of dissolution.

Students with a basic particulate explanatory model of dissolution.

Students with a semi-particulate model of dissolution.

Students with a solid-based macroscopic explanatory understanding of the process of dissolution. Students with a solid-focused semi-particulate explanatory model of dissolution.

Students with a descriptive macroscopic model of the process of dissolution, focused on the solid.
Appendix I, Table 1: Correspondence between the construct map “student explanations of the relationship between surface area and the rate of dissolution” and explanations and reasoning framework.

<table>
<thead>
<tr>
<th>Level &amp; Name</th>
<th>Principles</th>
<th>Particles</th>
<th>Agency of solvent</th>
<th>Specific spatial Association</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 – causal-mechanistic explanation of the relationship between surface area and rate of dissolution, including spatial association, agency of solvent, and particles of solute and solvent.</td>
<td>Relationship between surface area and dissolving and possible relationship between mass, volume, shape, or general size and rate of dissolving</td>
<td>Particles of Solute and/or Solvent</td>
<td>Mentioned in response</td>
<td>Dissolution happens at the surface of materials. Corner and edge particles are the easiest to remove from the overall solute because they are least attracted / connected to other particles</td>
<td>Liquid particles pull or break solid materials apart into particles</td>
</tr>
<tr>
<td>4 – Students with a causal-mechanistic explanation of the relationship between rates of dissolution and surface area that involves spatial association of solute and solvent, and possibly agency of solvent.</td>
<td>Relationship between surface area and dissolving and possible relationship between mass, volume, shape, or general size and rate of dissolving</td>
<td>Not used</td>
<td>Possibly mentioned in response</td>
<td>Dissolution happens at the surface of materials</td>
<td>N/A</td>
</tr>
<tr>
<td>3 – Students with an explicit observational-principle-based explanation of dissolution focused on surface area.</td>
<td>Relationship between surface area and dissolving and possible relationship between mass, volume, or general size and rate of dissolving</td>
<td>Not used</td>
<td>Not used</td>
<td>Not used</td>
<td>N/A</td>
</tr>
<tr>
<td>2 – Student with an explicit observational-principle-based explanation of dissolution, focused on mass, volume, or general size</td>
<td>Relationship between mass, volume, or general size and rate of dissolving</td>
<td>Not used</td>
<td>Not used</td>
<td>Not used</td>
<td>N/A</td>
</tr>
<tr>
<td>1 – Students with a descriptive, typifying, or teleological explanation of differences in rates of dissolution.</td>
<td>None</td>
<td>Not used</td>
<td>Not used</td>
<td>Not used</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Appendix I, Table 2: Correspondence between construct map of “*student explanations of a solid solute dissolving into water*” and explanations and reasoning framework

<table>
<thead>
<tr>
<th>Level &amp; Name</th>
<th>Particles</th>
<th>Agency of solvent</th>
<th>Specific spatial Association</th>
<th>Process</th>
<th>Homogeneity of solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 – Complex particle-based, mechanistic relationship</td>
<td>Particles of Solute and Solvent</td>
<td>Mentioned in response</td>
<td>Dissolution happens at the surface of materials. Corner and edge particles are the easiest to remove from the overall solute because they are least attracted / connected to other particles</td>
<td>Liquid particles pull or break solid materials apart into particles, then surround them</td>
<td>Solute particles surrounded by solute particles and spread throughout solution</td>
</tr>
<tr>
<td>4 – Simple particle-based mechanistic relationship</td>
<td>Particles of Solute, Solvent, or both mentioned, but no evidence of continuous liquid or solid</td>
<td>Mentioned in response</td>
<td>Dissolution happens at the surface of materials</td>
<td>Liquid particles pull or break apart solid materials</td>
<td>Solute particles spread throughout solution</td>
</tr>
<tr>
<td>3 – Solute-focused, mechanistic</td>
<td>Particles of solute, solvent, or both may be mentioned, but one or both may be continuous</td>
<td>Not used</td>
<td>Not used</td>
<td>Solute focused: solute breaks down into smaller pieces</td>
<td>Solute spread throughout solvent</td>
</tr>
<tr>
<td>2 – Descriptive, outcome-focused</td>
<td>Not used</td>
<td>Not used</td>
<td>Not used</td>
<td>Macroscopic and descriptive</td>
<td>General evidence of homogeneity (solute and solvent are mixed together, or that pieces of the solute are dispersed throughout the solution)</td>
</tr>
<tr>
<td>1 – Descriptive, macroscopic</td>
<td>Not used</td>
<td>Not used</td>
<td>Not used</td>
<td>Macroscopic and descriptive</td>
<td>Not described</td>
</tr>
</tbody>
</table>
Size-dependent Properties: Fighting Asthma with Nanotechnology

How can nanotechnology improve asthma treatment?

<table>
<thead>
<tr>
<th>Author: Clara Cahill</th>
<th>Content Areas: chemistry, engineering, science, technology and society, some biology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Draft Date: 7/14/2008</td>
<td>Grade level: 6-8</td>
</tr>
</tbody>
</table>

STRAND OVERVIEW:

Estimated time of overall strand: 15 hours

Strand Descriptions:

Students investigate the how asthma medication can be made more effective by nanosizing the pieces of medicine in dry inhaler spray, focusing on the question about whether reducing the size of solid pieces could actually improve their rate of dissolution. This series of lessons connects primarily to chemistry topics, in particular connecting surface and size to overall rates of dissolution. This five-lesson sequence is designed to help students understand the particulate nature of matter in solids and liquids, and the connection of the particulate nature of matter to the properties and behavior of materials. There are 5 2-hour lessons in this sequence:

- **Lesson 1**: Students are introduced to a claim made by fictional drug manufacturers that their nano-sized dry-powder asthma medication works faster and more effectively than other methods. They conduct an initial experiment to determine whether or not breaking things up into smaller pieces makes it dissolve faster.

- **Lesson 2**: Students further investigate the claims of the manufacturer about the effectiveness of the drug, using probeware to compare the increase in the concentration of a “drug” when it’s in large pieces vs. when it is in small pieces.

- **Lesson 3**: To better understand why things broken up into smaller pieces dissolve faster, students investigate the particulate nature of solids by trying to create the smallest possible piece of a material, by observing a model of a Scanning Probe Microscope, and by looking for patterns in SPM images of identical and different materials.

- **Lesson 4**: Students next look at the particulate nature of liquid, comparing the characteristics of solids and liquids, making observations about dye dispersion, making models of liquid using ping-pong balls, and investigating the movement of liquid particles through the microscope.

- **Lesson 5**: Students combine their observations of liquids and solids to begin to develop a model for what happens when a solid dissolves into a liquid. They observe salt crystals formed through evaporation, manipulate models of solids and liquids to understand the functioning of dissolution, and observe the process of dissolution through the microscope.

- **Lesson 6**: Students connect what they have learned about dissolution to volume and surface area, through observing how vinegar visibly diffuses into agar imbued with acid/base indicator, and connecting these observations directly to models of solids and liquids. Finally, students use what they have learned in an engineering task.

Learning Performances / Learning Goals:

1. **Students apply and explain how changing the size of materials impacts macroscopic rates.**

   - **Critical Concepts:**
     - Under identical conditions, (when temperature, liquid and solid volume, and agitation are controlled), solids broken up into smaller pieces dissolve faster than solids in larger pieces. [or - The more a soluble material is subdivided, the smaller the individual pieces of the material are, and the faster the material dissolves.]
     - When the rate of dissolution increases, the concentration of the solution created increases more quickly. Solids broken up into smaller pieces increase the concentration of a solution more quickly than solids in larger pieces.
1. **Student** will model and explain what happens when a solid dissolves in a liquid, emphasizing that dissolution occurs at the surface.

   - **Critical Concepts - In addition to the critical concepts above:**
     - All matter is made up of particles. A solid material is made of a regular arrangement of particles stuck together.
     - In liquid materials, particles are fairly close together, but they are not bound in a fixed position to their neighbor particles and they move relative to one another.
     - When a solid dissolves in a liquid, the particles of solid are detached from the overall solid structure and surrounded by liquid particles.

2. **Students exemplify and explain the importance of object surface as the interface between two materials.**

   - **Critical Concepts - In addition to the critical concepts above:**
     - Only particles that are accessible on (on the surface of) solid materials are available to interact with liquid particles.
     - The greater the percentage of exposed particles on a solid object, the faster the object can dissolve, react, catalyze, etc.

3. **Students are able to explain and apply how changing the size of materials impacts the percentage of material exposed in an object.**

   - **Critical Concepts - In addition to the critical concepts above:**
     - The more an object is divided or broken up into smaller pieces, the more exposed particles it has. In other words, the size of pieces of a material impacts the percentage of overall particles in a substance that are exposed or available.

4. **Students compare the factors affecting properties in nanoscale and bulk materials.**

   - **Critical Concepts - In addition to the critical concepts above:**
     - Changing an object’s size has a very small effect on the percentage of particles on the surface at the macroscopic and a big effect at the nanoscale. Due to this, the size-dependency of a property can be very sensitive for a nanoscale object.
     - Surface-related properties, like reactivity and solubility, may differ between the nano and bulk forms due to nanoscale materials’ high percentage of exposed particles.

**Big Ideas in Nanoscience:**

- **Size-Dependent Properties:** “The properties of matter can change with scale. In particular, as the size of a material approaches the nanoscale, it often exhibits unexpected properties that lead to new functionality.” (Stevens, Sutherland, Schank, & Krajcik, in progress)

  - These lessons focus on surface-dependent properties, formalizing prior experience with the relationship between material size and rate, and providing a framework for understanding the importance of surface in determining properties. Since the concept (that rates of dissolution increase as size decreases) is in effect in bulk and nano materials, it enables students to observe the effects of size directly and connect these effects to unobservable, microscale characteristics of materials. The importance of the percentage of surface particles in a material is then connected to the relationship between surface-dependent properties and size in nanoscale materials.

**National standards:**

1. **Standards we address directly in our curriculum**
   1. All matter is made up of atoms, which are far too small to see directly through a microscope. 4D/M1a (6-8) Benchmarks
   2. Properties of systems that depend on volume, such as capacity and weight, change out of proportion to properties that depend on area, such as strength or surface processes. Benchmarks 11D/2 6-8
   3. When the linear size of a shape changes by some factor, its area and volume change disproportionately ... Properties of an object that depend on its area or volume also change disproportionately. Benchmarks 9C/2 9-12
II. Standards we address indirectly in our curriculum

1. Equal volumes of different materials usually have different masses. 4D/M2* (6-8) Benchmarks
2. Atoms and molecules are perpetually in motion. Increased temperature means greater average energy of motion, so most substances expand when heated. 4D/M3ab (6-8) Benchmarks
3. The idea of atoms explains the conservation of matter: If the number of atoms stays the same no matter how the same atoms are rearranged, then their total mass stays the same. 4D/M7b Benchmarks
4. The physical properties of compounds reflect the nature of the interactions among its molecules. These interactions are determined by the structure of the molecule, including the constituent atoms and the distances and angles between them. NSES 9-12
5. In solids, the atoms or molecules are closely locked in position and can only vibrate. In liquids, they have higher energy, are more loosely connected, and can slide past one another; some molecules may get enough energy to escape into a gas. In gases, the atoms or molecules have still more energy and are free of one another except during occasional collisions. 4D/M3cd Benchmarks
6. A substance has characteristic properties such as density, a boiling point, and solubility, all of which are independent of the amount of the substance and can be used to identify it. 4D/M10** (NSES) Benchmarks
7. A substance has characteristic properties, such as density, a boiling point, and solubility, all of which are independent of the amount of the sample...NSES 5-8
   o However, this statement is only true on the macroscale—the scale that is directly experienced. Many “intensive properties” do change as the size of the sample gets smaller. It is unclear how relevant properties like boiling point and melting point are at the nanoscale. Therefore, this concept should be clarified in order to be scientifically accurate.”

LESSON STRAND PREPARATION

Teacher Background Content Knowledge:

- Particulate nature of matter:
  - In these lessons, a “particle” refers to the unit (atoms or molecules) that make up a material.
  - Solids are highly-compact, regular arrangements of particles. The particles individually have vibrational motion, but do not generally switch positions relative to one another.
  - Liquids are nearly as compact as solids, but the particles can flow around one another. In other words, a liquid material is made of small particles that are not regularly arranged, but can flow freely around one another.

- Size-Dependent Properties:
  - Size can impact the properties of a material, particularly at the nanoscale.
  - Properties can be dependent directly on the overall size of materials (true “size-dependent properties”), or on the surface area of materials (“surface-dependent properties”).
  - SImply size-dependent properties include optical and magnetic properties. We are not investigating these properties in these lessons.
  - These lessons focus on the size-dependent properties related to size through surface area, “surface-dependent properties.” For surface-dependent properties, the arrangement and accessibility of the particles to the environment impacts the properties of matter and the rates at which certain chemical and physical changes can occur. These properties include reactivity, solubility, catalytic behavior, melting point, and rates of dissolution, reaction, catalysis, and melting (Stevens et al., in progress).
    - The size-dependent change in rates is apparent even at the mesoscale: When the surface-area-to-volume ratio of a material is increased, rates of reaction, dissolution, catalysis, melting, etc., increase.
    - The size-dependent changes in catalytic behavior, melting point, solubility, and reactivity happen only at the nanoscale. As any dimension of a material approaches the nanoscale, the surface-area-to-volume ratio increases dramatically.
• simplify the comparisons and calculations students will make using the models provided, 2. to emphasize the particulate nature of matter, and 3. To functionalize the difference between corner, edge, and face particles. Corner particles are the least connected to the rest of the solid material, and are thus the most physically accessible, and require the least amount of energy to interact with. Edge particles are less accessible and require slightly more energy, and face particles are the least accessible and require the most energy of all of the exterior particles. Although these lessons do not delve deeply into this functionality, the accessibility of particles can be extremely important in determining surface-dependent properties, and has been used in numerous technological applications. More advanced students may be able to understand and apply these concepts.

• Shape and size of a material impacts the arrangement and accessibility of particles. As mentioned earlier, since only particles that are exposed on the exterior surface of an object can interact with the environment, the higher the number of particles on the exterior surface of an object, the higher the number of simultaneous reactions that can occur. In other words, the higher the proportion of overall particles in a substance that are on the exterior face, the more quickly overall the chemical or physical changes can occur throughout the entire object.

• The dissolution of a solid in a liquid is an example of this principle. When a solid dissolves in a liquid, the liquid “pulls apart” the solid, particle by particle. The liquid particles surround the particles from the solid, enabling the particles from the solid to ‘flow’ with the liquid. Only particles that are accessible on (on the surface of) solid materials are able to dissolve into the liquid, so the higher the proportion of atoms on the surface of the solid object, the more quickly overall the solid can dissolve.

• Overall, in nanoscale materials, a higher percentage of the total particles are exposed on the surface than in non-nano materials, allowing nanoscale solids to dissolve and react extremely quickly compared to bulk materials.

• Scientific explanations include: Claims, Evidence, and Reasoning (McNeill, Lizotte, Krajcik, & Marx, 2006)
  • A “claim” is an assertion, proposition, or thesis - the point of the explanation.
  • Evidence refers to the data that supports the claim. Evidence, in scientific situations, should be empirical, and be derived from data
  • Reasoning is “the logic for why the evidence supports the claim” (McNeill et al., 2006, p. 156). The reasoning connects the evidence to the claim.

  For example:

  • Claim: Things dissolve faster when they have a higher surface-area-to-volume ratio.

  • Evidence: When two 5-g samples of salt crystals are measured out, and one is crushed into smaller pieces while the other sample is left intact, the one that is crushed dissolves more quickly in 100 mL of 10 ºC water than the one that is left intact.

  • Reasoning: Crushing the sample of salt increased the surface area of the salt while keeping the volume intact. Thus, the surface-area-to-volume ratio of the crushed salt was higher than that of the intact salt. Since all other factors were controlled, the faster dissolution time of the crushed salt supports the claim.

Student Prior Knowledge Expectations*

• Some solid substances can dissolve in liquid substances (SSI 2007 interview and video)
• Solids and liquids are different forms of matter

Potential Student Alternative Ideas*

• Students describe ‘outside’ vs. ‘inside’ in unified terms. (SSI 2007 interview and video)
• Things dissolve by crushing and mixing them in water. (SSI 2007 interview and video)
• Melting and dissolving are the same thing. Salt becomes liquid salt when it dissolves. Dissolving sugar becomes melted.
• When sugar is dissolved in water the water takes on properties of the sugar., or when sugar is dissolved in water the sugar takes on properties of the water.
• Matter is continuous, but contains particles.
• The space between molecules contains air.
• Matter is continuous, homogeneous and static.
• Grinding is how one makes “matter” from “objects”.
• Substances and atoms are different names for the same things.
• Copper atoms have the properties of bulk copper.
• Molecules are small particles formed by successive partitioning of matter and hence keep their macro properties such as hard, soft, etc.
• The properties of molecules depend on the phase of the material composed of them.
• Molecules of solids are hard; of gasses are soft.
• Water is something different from H₂O molecules

From Student Preconceptions and Misconceptions in Chemistry, Integrated Physics and Chemistry Modeling Workshop, Arizona State University, June 2001, Version 1.35, unless otherwise noted

References:


Appendix II
Non-Normative Ideas about Dissolving Observed During Instruction

Observed Non-Normative Ideas:
About dissolving:
• Dissolution is intentional on the part of the solute.
• Particles get broken up into smaller pieces during dissolution.
• The solute floats up [as it dissolves]
• Confusion between chemical reaction and dissolution
• Different sized things dissolve in different ways.
• Dissolution is related to the hardness of the material
• Less solid things dissolve better than more solid things
• Particles get smaller as they dissolve
• Solid things don't dissolve easily
• Smoothness increases the rate of dissolution
• Dissolution is dependent on the strength of the solvent,
• Dissolution requires acids.
• Solvent must be strong enough to break the outside of the solute.
• Solute shrinks to become part of water
• Solute turns into solvent
• The liquid absorbs solute.
• Solute melts as it dissolves.
• Dry things don’t dissolve,
• Solvent particles absorb solute particles in dissolution
• Solubility is related to the density of materials

About materials:
• Crushing things reduces the amount of material overall.
• Powder is not a solid material

About rates of dissolution and changes in concentration of solutions
• Dissolution rate is dependent only on the overall amount of solute
• Faster dissolution means higher final concentration
• Dissolution rate is dependent only on the number of particles
• Dissolution rate is dependent only on the number of particles and size
• Less crushed materials have higher final concentrations
• Rate of dissolution is only dependent on the environment in which the dissolution is happening
### Appendix III:
Comparison of Students with High and Low Gains in Particle-based Mechanistic Reasoning

<table>
<thead>
<tr>
<th>High Gain Students</th>
<th>Low Gain Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 (HG1)</td>
<td>17 (LG1)</td>
</tr>
<tr>
<td><strong>Initial explanations: Summary</strong></td>
<td><strong>Descriptive model of dissolving</strong></td>
</tr>
<tr>
<td>Student depicts particles in solids and liquids</td>
<td>No connection made between composition of solids and liquids</td>
</tr>
<tr>
<td>No connections made between particles in solids and liquids</td>
<td>No connection made between composition of solids and liquids</td>
</tr>
<tr>
<td>Teleological and descriptive models of dissolution</td>
<td>Continuous, macroscopic models of solids and liquids.</td>
</tr>
<tr>
<td>Implicit understanding of the principle that smaller things dissolve faster than bigger things</td>
<td>Implicit understanding of the principle that smaller things dissolve faster than bigger things</td>
</tr>
<tr>
<td>Student depicts particles in solids and liquids only</td>
<td>Implicit understanding of the principle that smaller things dissolve faster than bigger things</td>
</tr>
<tr>
<td><strong>Initial Explanations:</strong> why a material might not dissolve easily:</td>
<td><strong>Initial Explanations:</strong> why a material might not dissolve easily:</td>
</tr>
<tr>
<td>“Because it is resistant. Because the chemicals do not dissolve easily.” (Teleological reasoning)</td>
<td>“...because...[it is] very hard...and it must dissolve for the cells to spread throughout the body“ (Teleological reasoning and non-normative principle-based reasoning)</td>
</tr>
<tr>
<td>“[the solvent] might not know the [solute] is there...”</td>
<td>“because they’re using too much,” suggesting an observational understanding of saturation</td>
</tr>
<tr>
<td><strong>Initial Explanations:</strong> On what one could do to improve how fast a material dissolves:</td>
<td><strong>Initial Explanations:</strong> On what one could do to improve how fast a material dissolves:</td>
</tr>
<tr>
<td>“Make it smoother.” (Descriptive, lacking easoning): n/a</td>
<td>“Make [it] smaller...” “any powder dissolves more faster...”</td>
</tr>
<tr>
<td>Student suggests to use a smaller amount or reduce the size, indicating the implicit observational principle that size is related to rate of dissolution.</td>
<td>Suggests changing the chemical composition to a material that dissolves more easily.</td>
</tr>
<tr>
<td><strong>Initial Ideas:</strong> On what one could do to improve how fast a material dissolves:</td>
<td><strong>Initial Ideas:</strong> On what one could do to improve how fast a material dissolves:</td>
</tr>
<tr>
<td>Student represented</td>
<td>Student represented</td>
</tr>
<tr>
<td>Solids are depicted as</td>
<td>Solids and liquids are</td>
</tr>
<tr>
<td>Solids and liquids</td>
<td>Solids and liquids</td>
</tr>
<tr>
<td>solid and liquid materials:</td>
<td>particles in both the solid and the liquid, but did not make the connection that both solids and liquids were made of particles, suggesting a fragmented conception of materials.</td>
</tr>
<tr>
<td>Initial Explanations: On what happens when you “zoom in to see what liquids and solids are made of, so you can see what is really happening” when something dissolves:</td>
<td>Student drew a descriptive diagram of dissolution, showing a solute getting gradual smaller until it disappears. Student diagram depicted bubbles to indicate the process of dissolution.</td>
</tr>
<tr>
<td>Formative Explanations: Addressing the principle: Smaller grain-sizes of materials dissolve faster than larger grain sizes</td>
<td>Student initially implicitly states the principle smaller things dissolve faster at the beginning of the instructional sequence. However, non-normative ideas related to the principle emerge as the student equates a faster rate of dissolution to an increase in concentration of the solution, indicating possible non-normative ideas about the meaning of an increased rate of dissolution. Disconfirming</td>
</tr>
<tr>
<td>Activity</td>
<td>Description</td>
</tr>
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<td>-------------</td>
</tr>
<tr>
<td><strong>Formative Explanations:</strong></td>
<td>After several learning activities, a new implicit principle seems to emerge: the more exposed a material, the faster it dissolves. Later discusses the vulnerability of exposed materials to water. New descriptions of dissolving focus on how the “water molecules are taking away the [solute] molecules” from the surface of materials.</td>
</tr>
<tr>
<td>First focuses on the idea that some different shaped materials seem to be fragile and falling apart, thus will dissolve faster.</td>
<td>In initial scaffolded learning activities, student identified the relative ease of dissolution of edge and corner particles, and maintained this principle in use through less scaffolded activities, explaining that dissolution is faster when “more [particles] are on the outside…so that water can reach the particles.”</td>
</tr>
<tr>
<td>During the initial scaffolded learning activities, student identifies that certain particles (on the surface, corners, and edges) are less connected to the rest of the material, and therefore will dissolve before other particles. However, in several subsequent instructional activities, the student uses only the number of particles and the apparent size of a material, rather than surface area and features, to determine relative rates of dissolution, focusing on the features of the solute but not the accessibility of the solute to the solvent. By the final activity, the student is able to use surface area to predict relative rates of dissolution, citing the accessibility of solute particles to the solvent. This indicates a shift towards the principle that materials with higher surface area dissolve faster, as the student was not directly addressed in the curriculum, so the student was not prompted to correct this non-normative understanding.</td>
<td></td>
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<tr>
<td>During the initial scaffolded learning activities, the student identifies that particles that are first touched by water will dissolve first, but seems to assume that water will seep between spaces in the solute to dissolve the material, negating the importance of surface area in determining rates of dissolution. The student applies the non-normative principle that the only factor important in determining rates of dissolution is the total mass of the solute. This non-normative idea, and the disconfirming evidence provided by the different dissolution rates between materials of different sizes, were not directly addressed in the curriculum, so the student was not prompted to correct this non-normative understanding.</td>
<td></td>
</tr>
<tr>
<td>During the initial scaffolded learning activities about the relationship between surface area and rates of dissolution, student identifies that the external particles in a material will dissolve first “because they are on the outside.” The student uses this principle consistently to respond to subsequent prompts about the relationship between surface area and rate of dissolution with reduced levels of support. She continues to use this principle in her responses in the retention study as well. However, the student never connects this principle to the relationship between size and rates of dissolution, or to the relationship between particles of solute and solvent.</td>
<td></td>
</tr>
</tbody>
</table>
well as a shift towards the functional process of dissolution. The student reiterates this principle several times throughout the remainder of the instructional unit supporting it with the reasoning that the solvent particles needs to be able to access the solute for dissolution to occur.

size and shape and rates of dissolution. In subsequent highly structured activities, the student is able to recognize the importance of surface, but the student is unable to apply this principle when the scaffolding is removed situations. In the distal assessment, the student uses the principle that dissolution rate is only related to the number of particles in materials of the same sizes but different shapes, indicating that this non-normative idea was robust for this student.

**Formative Explanations:**

<table>
<thead>
<tr>
<th>Prior to instruction, student believed that crushed materials will have a lower final concentration than intact materials, suggesting one of three things. 1. That he has a disconnected understanding of the relationship between overall mass of solute and final concentration of solution; 2. That he believes that, because the crushed materials are in smaller pieces,</th>
<th></th>
<th>n/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior to instruction, the student believed that crushed materials will have a higher final concentration than intact materials. Faced with disconfirming evidence, the student artifacts indicate that she has revised this conception to relate final concentration of solution to the initial mass of the solute.</td>
<td></td>
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</tr>
<tr>
<td>The student equates a faster rate of dissolution to an increase in concentration of the solution, indicating possible non-normative ideas about the meaning of an increased rate of dissolution. Disconfirming evidence described, but no revision of principles expressed:</td>
<td>The student focuses on rate of dissolution rather than concentration during experiments, does not address final concentration initially. When discussing dose and concentration in later assessments, student refers back to the experiments, stating that two differently grain-sized materials have the same number of particles, but that a crushed</td>
<td>Focuses on both rate of dissolution and concentration, correctly identifying that “the [crushed material] will dissolve faster and have more color at first.” The idea that concentration is independent of rate of dissolution was implicitly referred to repeatedly, but never explicitly stated.</td>
</tr>
<tr>
<td>The student focuses on rate of dissolution rather than concentration during experiments, does not address final concentration initially. When discussing dose and concentration in later assessments, student refers back to the experiments, stating that two differently grain-sized materials have the same number of particles, but that a crushed</td>
<td>Focuses on both rate of dissolution and concentration, correctly identifying that “the [crushed material] will dissolve faster and have more color at first.” The idea that concentration is independent of rate of dissolution was implicitly referred to repeatedly, but never explicitly stated.</td>
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</tr>
<tr>
<td>n/a</td>
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</table>

**Formative Explanations:**

- Addressing the principle: Identical masses of solute result in identical concentrations of solutions under identical conditions.
- Disconfirming evidence described, but no revision of principles expressed:

The student focuses on rate of dissolution rather than concentration during experiments, does not address final concentration initially. When discussing dose and concentration in later assessments, student refers back to the experiments, stating that two differently grain-sized materials have the same number of particles, but that a crushed material will dissolve faster and have more color at first.” The idea that concentration is independent of rate of dissolution was implicitly referred to repeatedly, but never explicitly stated.
material “puts concentration in your body faster”

does not grasp the relationship between the mass of material and the overall amount of material present, independent of volume. After experiments indicating that the rate of concentration change was larger in crushed materials than in intact materials, but that the final concentration was the same, the student acknowledged that “[Crushed materials] will end up with the same concentration as [intact] materials, but they’ll just get there faster. There is a smaller total amount (mass) of them, or 3. That he does not have a cohesive understanding of the concept of concentration. The student does not correct this misconception, reiterating that the concentration of the solution made with crushed material is lower than the concentration or the solution made with intact material, even after being presented with disconfirming evidence three different times within the course of the instructional intervention.

<table>
<thead>
<tr>
<th>Final reasoning and explanations: summary</th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Connections among principles</strong></td>
<td><strong>Connections among principles</strong></td>
<td><strong>Uses particles of solvent and solute, agency, association between solute and solvent, and process to describe dissolution. In addition, discusses principle related to concentration in explanation of dissolution.</strong></td>
<td><strong>Uses particles of solvent and solute, agency, association between solute and solvent, and process to describe dissolution. In addition, discusses principle related to concentration in explanation of dissolution.</strong></td>
<td><strong>Student provides a descriptive, non-particle-based explanation of dissolving at the end of instruction, and does not provide evidence of a particle model of matter.</strong></td>
</tr>
<tr>
<td>that smaller things dissolve faster, the principle that smaller things are more exposed, and the process of dissolution are referenced by the student.</td>
<td>that smaller things dissolve faster, the principle that smaller things are more exposed, and the process of dissolution are referenced by the student.</td>
<td>Maintainence of a usable mechanistic, particle-based</td>
<td>Maintainence of a usable mechanistic, particle-based</td>
<td>Student maintains the implicit and explicit use of the principles that crushed materials dissolve faster than uncrushed materials, and that basic understanding of the concept of concentration. The student does not correct this misconception, reiterating that the concentration of the solution made with crushed material is lower than the concentration or the solution made with intact material, even after being presented with disconfirming evidence three different times within the course of the instructional intervention.</td>
</tr>
<tr>
<td><strong>Representation of particle-based mechanistic model detailing specific interactions between particles of solute and solvent</strong></td>
<td><strong>Uses particles of solvent and solute, agency, association between solute and solvent, and process to describe dissolution. In addition, discusses principle related to concentration in explanation of dissolution.</strong></td>
<td><strong>Uses particles of solvent and solute, agency, association between solute and solvent, and process to describe dissolution. In addition, discusses principle related to concentration in explanation of dissolution.</strong></td>
<td><strong>Student provides a descriptive, non-particle-based explanation of dissolving at the end of instruction, and does not provide evidence of a particle model of matter.</strong></td>
<td><strong>Student maintains the implicit and explicit use of the principles that crushed materials dissolve faster than uncrushed materials, and that</strong></td>
</tr>
<tr>
<td>solvent - approaching target normative understanding</td>
<td>describe dissolution.</td>
<td>understanding of dissolution and factors in determining the rate of dissolution.</td>
<td>understanding of dissolution and factors in determining the rate of dissolution.</td>
<td>final concentration is related to the initial mass of the solute rather than the rate of dissolution.</td>
</tr>
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<td>---</td>
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</tr>
<tr>
<td>• Evidence of maintenance of a usable mechanistic, particle-based understanding of the dissolution found in 6-months post-camp assessment: The student indicated that she believed a long, narrow object would dissolve faster than a cubic object “Because it has a larger flat surface and would be easier for the water molecules to attach and dissolve it faster.”</td>
<td></td>
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</tr>
</tbody>
</table>
Appendix IV: Pre/Post Assessments

What do you think is really going on when a solid dissolves in a liquid?

Draw a solid medicine!

In this box, draw a piece of solid medicine by itself, before it has been taken. Zoom in all the way, as far as you can go, so that you can show what it is really made of. Label the parts of your diagram.

In this box, draw the same piece of medicine 2 seconds later, still before it has been taken.

Has anything changed about the solid medicine in 2 seconds? If so, what? Explain your answer.

__________________________________________________________________________

__________________________________________________________________________

Draw liquid water!

In this box, draw liquid water, zoomed in all the way, as far as you can go, so that you can see what it is made of. Label the parts of your diagram.

In this box, draw the liquid water 2 seconds later.

Has anything changed about the liquid in 2 seconds? If so, what? Explain your answer.

__________________________________________________________________________

What are some similarities between the liquid and the solid in your diagrams? What are some differences?

__________________________________________________________________________
Dissolving! Make a short flipbook of what happens when the solid medicine dissolves into the liquid.

Be sure to show what is happening to both the liquid and to the solid in each box. Zoom in as far as you can go so that we can see what makes up both the solid and the liquid.

Time 1: The instant the medicine is put in the liquid.
Explain what is happening:

Time 2: The medicine is just starting to dissolve.
Explain what is happening:

Time 3: The solid medicine is about 1/3rd dissolved.
Explain what is happening:

Time 4: The solid medicine is ½ dissolved.
Explain what is happening:

Time 5: The solid medicine 2/3rd delicious.
Explain what is happening:

Time 6: The solid medicine is completely dissolved.
Explain what is happening:
Improving Vitamins: (A sample of Flintstones vitamins is presented with this problem).

Problem:
Imagine that you are a chemical engineer. A vitamin company recently hired you to help them improve their product. Their vitamins are in a pill form that people swallow whole, without chewing.
1. The vitamin must be able to dissolve after it is swallowed.
2. The vitamin must be sold in a dry form.

A recent newspaper article about vitamins just came out, claiming the following:

“When you take a pill vitamin, it takes hours to dissolve in your body. That means that it can take hours before you get the nutrition and energy you need. Worse, valuable nutrition is lost as most of the vitamins pass through your body before they have a chance to dissolve completely.”

What recommendations can you make to improve the vitamin?

After the vitamin company improved how their vitamins dissolved, they produced the following advertisement:

“\textbf{NANOVITAMINS}
Great Nutrition – Immediately!
Nano-sized pieces of vitamins dissolve instantly in your body, providing the nutrition boost you need right away!

You need complete nutrition now!
Our NanoVitamins contain the same amount of vitamins as your regular vitamin tablet – broken up into nano-sized pieces.
Because NanoVitamins are in nano-sized pieces, they dissolve faster and better than the same dose of regular-sized vitamins.
Taking NanoVitamins assures that you get all of the nutrients you need as soon as you take them.”

Do you think their advertisement is accurate? Why or why not? Explain your reasoning, and provide evidence for your explanation.
Make a scientific explanation of whether Nanopran™ is better than Micropran™ including:

- Your CLAIMS comparing effectiveness and describing the differences in how Nanodox™ and Microdox™ work

- EVIDENCE to support your claim of how Nanodox™ functions

- REASONING that connects your evidence to the claim, based on what you know about how things dissolve.
Appendix V:
Comparative Retention Assessment:

Name: ___________________________
Grade: _______ School: ___________

Thank you for taking this short test and helping us learn more about what students know about dissolving! We really appreciate your participation! Some questions may have several answers that seem correct, but choose the one that you think best answers the question. When you have finished the first part, let the test administrator know, and she will give you the second part. This whole test should take approximately 15-30 minutes to complete.

PART I:

1. Here is a glass of absolutely pure water:
Imagine that you have invented the most powerful microscope in the world, a microscope powerful enough to zoom in and show what the water is made of. Draw a picture of what you might see through this microscope. Be sure to label all of the parts of your drawing.

2. Here is a crystal of sugar, as you would see it under a normal (light) microscope.
Imagine that you used the powerful microscope you invented to zoom in as far as possible, and show what the sugar is made of. Draw what you would see below in the circle. Label all parts of your drawing.
3. If you put the sugar crystal in the water, and dissolved the sugar crystal in the water completely, what would you see using your extremely powerful microscope? Remember: you can zoom in so far that it can show what things are made of. Draw what you would see through the microscope in the view below. Be sure to label all parts of your diagram.
PART II: Remember: some questions may have several answers that seem correct, but choose the one that you think best answers the question.

4. What would you observe if you dropped a medium-sized crystal of sugar into a glass of room temperature water and watched it dissolve?
   a. The sugar crystal would gradually turn into water.
   b. The sugar crystal would crumble up into smaller and smaller pieces, and when they become too small to see, the crystal is dissolved.
   c. The sugar crystal would gradually disappear, and the water would gradually get misty with the sugar.
   d. The sugar crystal would get smaller and smaller, little by little, as the water worked to break it up.

5. You need to quickly dissolve a big crystal of salt in water. Your friend Ella suggests that you crush up the salt into tiny pieces to help it dissolve more quickly. Do you think this is a good idea or a bad idea? Pick the best explanation to support your response.
   a. Bad idea - Crushing up the salt would create more pieces of salt to dissolve, which would take longer than just dissolving one large piece.
   b. Bad idea – Crushing the salt would make no difference! The crushed salt will take the same amount of time to dissolve as the non-crushed salt, because it is still the same overall amount of salt
   c. Good idea - You have noticed that crushing things gets them to mix in the water faster, so her idea might work!
   d. Good idea – Crushing the salt will make it more exposed to the water, which will help break it down faster.
   e. Good idea – crushing the salt will help it fall apart more easily as it dissolves!
6. Your friend Terrence suggests that you heat water as the salt dissolves to help it dissolve faster. Pick the best explanation of why this does or does not work.

   a. Heating knocks the salt into little pieces, so it can dissolve faster.
   b. Heating helps moves the salt into the water
   c. Heating turns the salt into water.
   d. Heating gives the water more energy to pull the salt apart.
   e. Heating melts the salt so it dissolves faster.

7. Your 15-year-old neighbor, Hagar, doesn’t understand what happens to Kool-Aid powder when it dissolves. How would you best explain dissolving to him?

   a. “When the Kool-Aid dissolves, the pieces of the powder look like they become part of the water.”
   b. “When the Kool-Aid dissolves, the pieces of powder get smaller and smaller until they mix together evenly with the water.”
   c. “The water surrounds the Kool-Aid and pulls it apart from the outside, until water surrounds each particle of Kool-Aid material.”
   d. “The water molecules pull apart the Kool-Aid molecules.”
   e. “The Kool-Aid breaks apart into littler pieces when it dissolves.”

8. Hagar, your 15-year-old neighbor, now wants to know why Kool-Aid dissolves, but sand doesn’t dissolve. How could you best explain why Kool-Aid dissolves but sand doesn’t?

   a. “Sand doesn’t mix with water as easily as Kool-Aid. That’s what allows it to dissolve.”
   b. “Water can’t break into the middle of sand, but it can break into Kool-Aid. Things that can be broken up by water can be dissolved.”
   c. “Sand is harder than Kool-Aid, so it can’t dissolve. Only softer things, like Kool-Aid and salt, are able to dissolve!”
   d. “Water doesn’t have enough energy to pull particles off of a grain of sand. Water can pull off particles of Kool-Aid, and that’s how it dissolves.”
9. Which part of this sugar crystal, if any, would be the first and easiest part to dissolve, and why? Choose the best possible answer.

   a. Only particles of the crystal touching water would dissolve first, but the edges and the corners dissolve first because they are least connected to the rest of the sugar.
   b. Whatever part of the sugar touches the water will dissolve easily, so anything on the surface that water can get to will dissolve right away.
   c. All parts of the sugar crystal dissolve equally, so the sugar will just break up into smaller and smaller pieces until it is dissolved.
   d. The ends will dissolve first because they are thinner than the rest of the crystal, and the thicker parts will take the longest to dissolve.
   e. The narrowest part of the sugar will break up quickly, but will take longer for the sugar in the center to break up.

10. A scientist drew a model of pure water, shown below.

    ![Diagram of water model]

    She told you that this model shows what you would see if you could use a microscope to zoom in to see the smallest possible unit of liquid water, and that the scale of the picture is about 5 nanometers across. However, she forgot to label the dots in her picture. Please choose the best explanation of what you think the scientist is showing at in the model of water above:

   a. The scientist is showing atoms floating in the water.
   b. The scientist is showing particles of water.
   c. The scientist is showing minerals in the water.
   d. The scientist is showing bubbles in the water.
11. You dissolved some Kool-Aid in water, but decided that you don’t want it anymore. Is there any way to get the Kool-Aid back to its powder form? Explain.

   a. Yes, you could use a really small filter to get the tiny pieces of Kool-Aid out, and then dry it.
   b. Yes, you could wait for all of the Kool-Aid to settle to the bottom, and then pour off the water.
   c. Yes, you could boil away all of the water to get the Kool-Aid back.
   d. No, the Kool-Aid is part of the water now, and you can’t get it back.

12. Once you mix sugar and water together, the sugar dissolves. Which of the following best describes what has happened to the dissolved sugar.

   a. The sugar has become liquid and mixed with the water.
   b. The water particles and the sugar particles have mixed together.
   c. The sugar particles are floating in the water.
   d. The water particles have surrounded each sugar particle.
   e. The sugar has blended into the water.
Use the magnified images of salt #1 and salt #2 above to answer the following questions. **Both pieces of salt weigh exactly the same and are made of the same material.** The only difference between the pieces of salt is their shape.

13. Which do you think will dissolve more quickly? Choose the best answer and explanation.

   a. Salt #1 will dissolve more quickly because it has more easy-to-pull-off edge, corners, and surface particles than salt #2
   
   b. Salt #1 will dissolve more quickly because it is already more broken apart and crumbled up than salt #2, so it will come apart faster.
   
   c. Salt #2 will dissolve more quickly because it is simpler
   
   d. Salt #2 will dissolve more quickly because it has more surface than salt #1, so it will get smaller faster.
   
   e. Salt #1 and Salt #2 will dissolve in the same amount of time because they weigh the same, so it will take the same amount of time for them to break up.

14. Which salt has the most surface?

   a. Salt #1
   
   b. Salt #2
   
   c. They both have the same surface.

15. Which salt has the most atoms?

   a. Salt #1
   
   b. Salt #2
   
   c. They both have the same number of atoms
16. Above are two different crystals of salt. Each crystal of salt has exactly the same mass – the only difference between them is the shape of the crystals. You add both salt crystals to a glass of room-temperature water, and wait for them to dissolve. Which crystal of salt do you think will dissolve the fastest in water?
   a. Salt crystal A
   b. Salt crystal B
   c. They will dissolve in the same amount of time.
   d. I need more information.
      (Explain:________________________________________
      ______________________________________________________)

17. Explain all of your reasoning for choosing your answer in question 16. Make sure to include all of the factors you considered in making your decision!