Using a nanoscience context to develop student explanations of observable phenomena

Clara Cahill & Joseph S. Krajcik

University of Michigan

Abstract:

The particulate nature of matter is a consistently difficult conception for students. 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 a new potential method to help students understand the particle model of matter. 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 conception of dissolution as an interaction between solute and solvent, and who consistently thought about the accessibility of the solute demonstrated integrated understanding of dissolving and rates of dissolving at the observation-based principle level of reasoning and at the mechanistic level of reasoning.
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 discipline of chemistry is built around creating mechanistic models to explain material behaviors and observations, and principles of particle theory enable the development of a basic understanding of the underlying causes of phenomena (Erduran, 2001; Wu, 2003, p. 869). Scientists developed and refined the particle theory to elegantly and consistently explain the causal mechanisms of numerous diverse observable phenomena including dissolution, rates of dissolution, conservation of matter, evaporation, chemical reactions and reactivity, air pressure, and other essential chemical concepts (Snir, Smith, & Raz, 2003, p. 797).

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). Thus, a normative scientific understanding of the particle theory entails understanding how aspects of the particle theory can be used to explain phenomena. Hence, the construction of student understanding of the particle theory necessarily involves the use of the particle theory in mechanistic explanations about the behavior of materials (Russ, Scherr, Hammer, & Mikeska, 2008).

Using the particle theory to create normative, causal mechanistic explanations requires integrating two aspects of understanding: observationally-founded (macroscopic) descriptive and predictive conceptions of materials and phenomena and theory-based models characterizing the underlying behavior and characteristics of particles (Crespo & Pozo, 2004; Gabel, Samuel, & Hunn, 1987; Metz, 1991; Russ et al., 2008; Smith, Wiser, Anderson, & Krajcik, 2006). Complicating matters, 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 (Harrison & Treagust, 2002).

Before they can craft normative, mechanistic explanations, students must have a clear conception of the defining characteristics of the phenomena they are attempting to explain. Thus, they must be able to consistently recognize, describe, and predict what is happening from the observable, macroscopic perspective. Novice learners, including middle-school students, often lack consistent, coherent macroscale-based ways of 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 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 conceptions and models of macroscalar behavior as well as an understanding of particle theory to ensure that they are able to construct normative causal mechanistic explanations of phenomena. This does not imply that the macroscale conceptions and particle theory must be developed independently; rather, they are both essential components of students’ developing scientific literacy (American Association for the Advancement of Science, 2009).

In addition to, and perhaps partially because of, the difficulties that some students have in forming reliable predictive macroscalar conceptions of materials and phenomena, many aspects of the particulate nature of matter have proven to be difficult for most middle and many high school students (Driver, Squires, Rushworth, & Wood-Robinson, 1994; Harrison & Treagust,
Cahill — NARST

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 & Tregust, 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). Some 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).

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 (Prieto, 1989). Next, 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). 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 (Wu, 2003).

Another explanation of the difficulties that students experience involves the conceptual density and complexity of the particle theory of matter (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.

Further, some studies suggest that many of these non-normative ideas can be partially context- and situation-dependent. By situation-dependent cognition, we refer to the theory that
cognition is domain-specific, and 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 context-dependent ideas, we refer to the related theory that student ideas and representations of identical materials may depend on the phenomena they are attempting to explain. 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 be experienced enough to recognize the features of related phenomena or models that experts identify readily (Chi, Feltovich, & Glaser, 1981). For example, Teichert, Tein, Anthony, and Ricky (2008) found that, prior to interviewer prompting, some postsecondary students initially drew NaCl(aq) as dissociated Na and Cl ions in a context of conductivity, while drawing it as joined NaCl molecules shortly after, in the context of boiling point elevation.

The idea that some non-normative ideas are context-dependent is controversial, and
identifying context-bound ideas may be considered to be confounded when students use different types of reasoning to explain phenomena (Gomez, Benarroch, & Marin, 2006). As we subscribe to the perspective that knowledge is situated, and therefore exists only in use, we posit that both the type of reasoning that students use to express their ideas and the content represented in the ideas of the ideas constitute student cognition.

Several different forms of reasoning and explaining have been identified for explaining scientific phenomena. In this paper, we 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 way a student interpreted the question or prompt generating their response. Further characterizing the type of reasoning students use in any causal explanations a student uses provides clues as to how a student thinks about and characterizes different aspects of a phenomenon, and how he or she understands the nature of the connections among the different elements, properties, behaviors, and behavioral and characteristic rules that make up that phenomenon (J. K. Gilbert, C. Boulter, & M. Rutherford, 1998; Lombrozo & Carey, 2006; Metz, 1991; Russ et al., 2008). We describe the typological framework we use to characterize explanations and reasoning more fully in the methodological section of this paper (See Figure 1 for a summary of this framework).

In this paper, as we explore how students’ conceptual understanding of dissolution, liquid and solid forms of matter, and rates of dissolution change during a 2-week summer science camp focused on ideas important to nanoscale science and technology, we focus on both the content of students ideas and the types of explanations and reasoning they use to express those ideas in
order to gain an understanding of if and how macroscale, descriptive conceptions and particle theory are adapted and connected during our instructional intervention. Our aim is to characterize how a highly-contextualized, problem-based, nanoscale science context integrating real-world and scientific domains as well as particle theory and macroscale observations, influences how students predict and explain dissolution and the relationship among size, shape, and rates of dissolution, and how different questioning prompts and contexts influence the type of reasoning students use to make explanations about familiar concepts.

Figure 1

*Schematic of Coding Scheme to Characterize Student Responses*
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 molecular and macroscopic models 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 polar covalent solid material dissolving in water, and of the corresponding relationship between shape, size, and rates of dissolution. The instructional materials were aimed to help students construct the following related models of dissolving and of the relationship among shape, size and rates of dissolving:

Normative explanation of dissolving: When a solid material dissolves in water, the water particles help to pull or break off solute particles, 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. As the solid is completely dissolved, solute particles are distributed throughout the solution.
Normative explanation of the relationships among shape, size, and the rate of dissolving: 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. 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 dissolve. The smaller the size of pieces of the dissolving material, the more surface particles it has. Shapes of materials that maximize 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, Sutherland, Schank, & Krajcik, in progress).

These models 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 normative explanations are derived from.

Framing an Instructional Approach

From the previous discussion, there are clearly many obstacles impeding instructors’
ability to help students develop a normative, causal-mechanistic model of phenomena based on particles. We designed our instructional intervention to promote the integrated development of these two normative models. 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.

The top-down approach 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).

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 through revolutionary changes, so that, although conceptual change may take place in a gradual manner, changes in conceptual understanding will alter student
conceptions across related contexts and phenomena. Instruction following this method would involve using a variety of observable phenomena in conjunction with the particle model to help account for and explain various macroscopic observations. 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.

Another version of the bottom-up approach 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 explanatory particle model for 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, using the Dual Situated Learning Model of instruction, which involves confronting the students with evidence to change thinking from a less desirable mental set (domain and concepts) to a more normative mental set by building normative situated understanding and creating dissonance with non-normative prior knowledge and ideas, students in Taiwanese schools developed more normative, mechanistic explanatory models of both dissolution and diffusion, with 90% of the students using particle models (in a normative way within the framework of the study), to explain aspects of dissolution (She, 2004). She’s study suggests that attending to the situative prior knowledge aspects of cognition, confronting students with phenomena in a scientific context, and providing multiple opportunities for students to investigate phenomena and revise their ideas can help students build mechanistic understanding.

In our study, we approach student development of the particle model from this second theoretical and instructional framework. We feel that the literature provides evidence to support the idea that novices’ understanding of these concepts develops in situated and context-bound
ways, and we believe that scaffolding student learning in ways that build harmoniously with their prior knowledge structures is a more fruitful and successful approach to instruction than imposing an expert’s streamlined cross-context, integrated knowledge structures on the student (Ausubel, 1968; Bodner, 1992). Thus, although at the highest levels scientific understanding of an expert is highly integrated across topics, novice understanding must build first towards integration within a context. 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’ expand student’s normative usable ideas from situated 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; Palinscar, 1998, p. 348; Palinscar & Scott, in press; Singer, Marx, Krajcik, & Chambers, 2000; Vygotsky, 1978). This perspective is consistent with the research mentioned previously, which suggests that learners’ understandings of dissolution and the nature of matter can be highly domain-dependent (situated) and context-dependent.

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

To help students build a mechanistic explanatory framework from the foundation of their prior knowledge, we focusing 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 situated 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 dissolving. We chose to use a nanoscale science focus to contextualize learning about the particulate explanations of the 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 mechanical 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 directly the total number of external particles to the internal particles in our simplified models of nanoscale materials during modeling and design activities, instead of asking students to compare 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 dually 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 timepoints 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 and analyzed an instructional intervention during the 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). 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 chose 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 followed 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 comparative analysis 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</th>
<th>Comparison</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Attendees</td>
<td>Attendees</td>
<td>Non-Attendees</td>
</tr>
<tr>
<td></td>
<td>(Subsample, 6 month retention)</td>
<td>for 6-month retention study</td>
<td></td>
</tr>
<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,</td>
<td>21</td>
<td>13</td>
<td>13</td>
</tr>
</tbody>
</table>
Table 1: Student Responses to the Dissolution Question

<table>
<thead>
<tr>
<th>Ethnicity</th>
<th>Correct</th>
<th>Partial</th>
<th>Incorrect</th>
</tr>
</thead>
<tbody>
<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*

We adopt a naturalist paradigm in our interpretation, which assumes that meaning is negotiated between the model’s author and the interpreter (Moschkovich & Brenner, 2000). This perspective enables us to use both the written artifacts created by the student and a shared understanding of the classroom experiences influencing the development of the artifacts in our analysis of student work. For example, we use this shared meaning represented by cultural norms or shared experiences established in the classroom, such as representations of particles as circles, or shared ideas and terminology for describing phenomena, to interpret student understanding in the absence of explicit labels or other written explanations. This paradigm enriches our ability to create a picture of student thinking, and corresponds with the situated social constructivist perspective that knowledge and meaning is socially situated and collaboratively constructed (Lave & Wenger, 1991; Palincsar, 1998; Singer et al., 2000).

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.

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 as 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 a request to “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>Intentional</td>
<td>Explain why an investigation</td>
<td>“I think the advertisement is accurate, because I think</td>
</tr>
</tbody>
</table>

Question:
A company claims “…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…” Do you think their advertisement is accurate? Why or why not? Explain your reasoning, and provide evidence for your explanation.
is being carried out in terms of Nano technology can do all these things for the [solute] justifications, and intent. to help them dissolve faster.”

<table>
<thead>
<tr>
<th>Type</th>
<th>Explanation</th>
<th>Sample Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descriptive</td>
<td>Explain how a phenomenon behaves</td>
<td>“…they improved their [product] and now it desolve (sic) faster…”</td>
</tr>
<tr>
<td>Typifying</td>
<td>Explain 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>Causal / Predictive</td>
<td>Explains why a phenomenon behaves as it does, or what will happen in novel circumstances</td>
<td>“yes beacause (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>Teleological</td>
<td>Proposes that observed behavior is attributable to the purpose or identity of because] “Powder-like things such as 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>Observational principle-based</td>
<td>Refers to a principle abstracted from observations</td>
<td></td>
</tr>
<tr>
<td>Implicit: Principle implied in reasoning</td>
<td>“Since the crushed salt was smaller, it should dissolve (sic) faster.”</td>
<td></td>
</tr>
<tr>
<td>Explicit: Abstract, general principle directly stated</td>
<td>“My reasoning is that smaller things dissolve more faster, and if it is crushed it will dissolve faster…”</td>
<td></td>
</tr>
<tr>
<td>Mechanistic</td>
<td>Provides an underlying cause for behavior or characteristics related to the root interactions or structures (Russ et al., 2008)</td>
<td>“More surfaces of the Nanopran root breaks 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 decision-making and science, 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 particles (sic) are showing, <strong>so the water can reach them</strong>…”</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.

Analysis

*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, 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. For the understanding of sugar dissolving in water, our pre-post 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). 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 discrepancy can 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. 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. However, non-normative ideas constituted 29% of the responses chosen by the comparison group of students, indicating that, for some of the Academy students, changes in non-normative ideas may have been persistant (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. 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 timepoint, 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>Reasoning Type</th>
<th>Intentional</th>
<th>Descriptive</th>
<th>Typifying</th>
<th>Teleological</th>
<th>Causal - Principle</th>
<th>Causal - Explicit</th>
<th>Causal - Mechanistic</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>(SD=0.49)</td>
<td>(SD=0.32)</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=0.32)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post-Instruction</td>
<td>0.06***</td>
<td>0.16</td>
<td>0.23*</td>
<td>0.55***</td>
<td>(SD=0.43)</td>
<td>(SD=0.50)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(SD=0.24)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

Figure 2

Average Responses Pre- and Post- Instruction

![Changes in Student Explanations and Reasoning](image-url)
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). This suggests that Academy attendees may have integrated their particle model and principle-based reasoning to a greater degree than 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). 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

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

(*=p<0.05)
Figure 3

*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. (See Appendix III for a summary of this analysis.)

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 understandings of the observation-based principles of 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 context 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.

Conclusions 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 suggests that 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.

Students who successfully transitioned from descriptive explanations and implicit observation-based causal reasoning to more particle-based causal-mechanistic reasoning adopted a notion of solutes as materials whose surfaces are vulnerable to interactions with solvents. 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. We posit that studying surface-dependent properties specifically highlights this interaction between the solute and solvent, and provides a need-to-know about particles (M.
Suzanne Donovan & J.D. Bransford, 2005). In addition, 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.

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. The prevalence of this idea among students who successfully developed the target reasoning, and the absence of this idea among students who were not successful in developing this reasoning, suggests that a more direct focus on helping students hierarchically integrate these principles is essential to helping students develop more cohesive, usable principles and mechanistic understandings of the particle nature of matter and dissolution.

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 within one phenomena-based context relates to student reasoning about other contexts.

In conclusion, instructional strategies focused on investigating surface-dependent properties, and notions of dissolving that involve surface-based interactions between solute and solvent can help students develop mechanistic, particle-based reasoning about dissolution.
References


**Appendix I: Instructional Design**

*Construct map:*

**Student macroscale and sub-macroscale understanding 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*

---

Students with a nano-based, particulate explanatory model of the relationship between surface area, size, and rate of dissolution among samples of materials of identical substance and mass. Students’ models incorporate the importance of comparisons of surface area, edge, and corner particles.

Students are able to predict and explain different rates of dissolution among samples of materials of identical substance and mass. Student models use a particulate model to explain the importance of surface area, edge, and corner particles in rates of dissolution, and students are able to relate size of pieces of material to overall surface area of the sample.

Students with a non-nano-based (exclusively-surface-area-focused) explanatory model of between surface area, size, and rate of dissolution among samples of materials of identical substance and mass.

Students are able to predict and explain different rates of dissolution among non-nanoscale samples of materials of identical substance and mass, including samples of different shapes and different-sized pieces. Student models consistently explain the importance of surface area in rates of dissolution, and students are able to relate size of pieces of material to overall surface area of the sample.

Students with an inconsistent model of the relationship between surface area, size, and rate of dissolution.

Students are able to predict different rates of dissolution among non-nanoscale samples of materials of identical substance and mass, including samples of different-sized pieces, but not samples of different shapes. Student can explain the importance of surface area in rates of dissolution, but can only apply it in certain circumstances, and students are able to recognize the importance of overall surface area of the sample, but are unable to apply the relationship to predict how substances in different shapes will dissolve, or are not able to identify the surface area of materials.

Students with a descriptive model of the relationship between size, and rate of dissolution that highlights the importance of being able to "get into" penetrate, or access the middle of the material.

Students use a “access” based model to predict and explain different rates of dissolution among non-nanoscale samples of materials of identical substance and mass, including samples of different-sized pieces, and/or samples of different shapes. Students explain the importance of mass and getting through a material in dissolution, but do not connect this to the overall surface area of the sample.

Students with a purely descriptive macroscopic model of the relationship between material size and the rate of dissolution.

Students are able to correctly identify the relationship between rate of dissolution and material size, asserting that, when a material is crushed or cut, it takes less time to dissolve than it does when it is intact. Explanation does not relate to surface.

*Direction of decreasing understanding of the relationship between a material’s surface and the rate of dissolution*
Construct map:

Student macroscale and sub-macro scale understanding of sugar dissolving into a 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.

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.

Students with a descriptive macroscopic model of the process of dissolution, focused on the solid.

Direction of decreasing understanding of the mechanism of dissolution
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.
Cahill — NARST

1. **Students 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:**
   
   o All matter is made up of particles. A solid material is made of a regular arrangement of particles stuck together.
   o 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.
   o 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:**
   
   o Only particles that are accessible on (on the surface of) solid materials are available to interact with liquid particles.
   o 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:**
   
   o 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:**
   
   o 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.
   
   o 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, & Krajick, in progress)

  o 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
1. The configuration of atoms in a molecule determines the molecule's properties... *Benchmarks* 4D/8 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; 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 experiences. 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 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 °C 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 dissolving 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 \( \text{H}_2\text{O} \) 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><strong>Initial explanations: Summary</strong></td>
<td><strong>Initial explanations: Summary</strong></td>
</tr>
<tr>
<td>10 (HG1)</td>
<td>13 (HG2)</td>
</tr>
<tr>
<td>Initial Explanations: why a material might not dissolve easily:</td>
<td>Initial Explanations: 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>Initial Explanations: On what one could do to improve how fast a material dissolves:</td>
<td>Initial Explanations: On what one could do to improve how fast a material dissolves:</td>
</tr>
</tbody>
</table>
| “Make it smoother.” (Descriptive, lacking reasoning): | n/a | “Make [it] smaller…” “any powder dissolves more faster…” | Student suggests to use a smaller amount or reduce the size, indicating the implicit observational principle that size is related to rate of dissolution. | Suggests changing the chemical composition to a material that dissolves more easily. | Student suggests to change the chemical composition of the solute to increase the rate of dissolution, indicates that pulverizing the material will help it dissolve faster. | Student suggests to change the chemical composition of the solute to make it “softer”.

Initial Ideas: On

<table>
<thead>
<tr>
<th>Initial Ideas: On</th>
<th>Initial Ideas: On</th>
</tr>
</thead>
<tbody>
<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>
</tbody>
</table>

55
<table>
<thead>
<tr>
<th>solid and liquid materials:</th>
<th>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.</th>
<th>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.</th>
<th>continuous, but water is depicted as H₂O molecules. Student did not make the connection that both solids and liquids are made of particles.</th>
<th>depicted as continuous, but water is depicted as H₂O molecules. Student did not make the connection that both solids and liquids are made of particles.</th>
<th>depicted as continuous, and no connection is made between the two.</th>
<th>depicted as continuous, and no connection is made between the two.</th>
</tr>
</thead>
</table>

**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:

- 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.
- Student may have a non-normative idea confounding melting and dissolution “It melts”. Student drew a descriptive diagram of dissolution, showing a solute getting gradual smaller until it disappears. Student diagram depicted the solute disintegrating as it dissolved.
- Student drew a descriptive diagram of dissolution, showing a solute getting gradual smaller until it disappears. Student diagram described the material “fizzing” as it smaller.
- Student drew a descriptive diagram of dissolution, showing a solute getting gradual smaller until it disappears. Student diagram indicates that a clear solution results from complete dissolution.

**Formative Explanations:**

Addressing the principle: Smaller grain-sizes of materials dissolve faster than larger grain sizes:

- 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 evidence described, implicit statements predicting and providing evidence that smaller things dissolve faster. Student artifacts indicate that the student connects smaller size to increased surface area after completing a lesson on the relationship between surface area and rates of dissolution, but only with scaffolding. Without scaffolding, in subsequent responses, student does not indicate this relationship.
- Implicit and explicit statements predicting and providing evidence that smaller things dissolve faster. Student artifacts indicate that the student connects smaller size to increased surface area after completing a lesson on the relationship between surface area and rates of dissolution.
- Student makes the implicit statements predicting that smaller materials will dissolve faster than bigger materials several times, but never states the principle explicitly. Student artifacts indicate that the student never connects smaller size to increased surface area.
- Implicit and explicit statements predicting and providing evidence that smaller things dissolve faster. Student artifacts indicate that the student never connects smaller size to increased surface area.
- Implicit and explicit statements predicting and providing evidence that smaller things dissolve faster. Student artifacts indicate that the student never connects smaller size to increased surface area.
but no revision of principles expressed.

### Formative Explanations:

Addressing the principle: Differently shaped materials that are otherwise identical can dissolve at different rates due to differences in surface area.

|   | After several learning activities, a new implicit principle seems to emerge: the more exposed a material, the faster it dissolves. | First focuses on the idea that some different shaped materials seem to be fragile and falling apart, thus will dissolve faster. 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. | 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.” | 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 uses the principle that smaller sizes of materials dissolve faster to respond to questions about different shapes of materials, predicting that different shapes of materials will dissolve at different rates because they appear smaller. In other activities, student uses the principle that the number of particles is the only factor important in determining rates of dissolution, suggesting a fragmented understanding the relationship between size and shape and rates of dissolution. | 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. | 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. |
The student reiterates this principle several times throughout the remainder of the instructional unit, supporting it with the reasoning that the solvent particles need to be able to access the solute for dissolution to occur. 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:**

**Addressing the principle:** Identical masses of solute result in identical concentrations of solutions under identical conditions.

<table>
<thead>
<tr>
<th>Prior to instruction, the student believes 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, there is a smaller total amount (mass) of them, or 3. That he</th>
<th>Prior to instruction, the student believes 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.</th>
</tr>
</thead>
<tbody>
<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>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 “puts concentration in your body faster”</td>
</tr>
<tr>
<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>
<td>Prior to instruction, student believes that crushed materials will dissolve faster and have a faster increase in concentration than intact materials, but will have a lower final concentration than intact materials. This suggests that the student understands the relationship between rate of dissolution and increase in concentration, but does not grasp the relationship between the mass of material and</td>
</tr>
</tbody>
</table>
Cahill – NARST

| Final reasoning and explanations: summary | Connections among principles that smaller things dissolve faster, the principle that smaller things are more exposed, and the process of dissolution are referenced by the student. | Connections among principles that smaller things dissolve faster, the principle that smaller things are more exposed, and the process of dissolution are referenced by the student. | Uses particles of solvent and solute, agency, association between solute and solvent, and process to describe dissolution. | Uses particles of solvent and solute, agency, association between solute and solvent, and process to describe dissolution. | Uses particles of solvent and solute, agency, association between solute and solvent, and process to describe dissolution. | Uses particles of solute and solvent, agency, association between solute and solvent, and process to describe dissolution. | 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. | 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. | Student provides a descriptive, non-particle-based explanation of dissolution, emphasizing the importance of the spatial association between the solute and solvent. | Student maintains the implicit and explicit use of the principles that crushed materials dissolve faster than uncrushed materials, and that final concentration is related to the initial mass of the solute rather than surface area is related to rate of dissolution, but does not connect |
|---|---|---|---|---|---|---|---|---|---|---|---|
| • Representation of particle-based mechanistic model detailing specific interactions between particles of solute and solvent - approaching target normative understanding | • Connections among principles that smaller things dissolve faster, the principle that smaller things are more exposed, and the process of dissolution are referenced by the student. | • Uses particles of solute and solvent, agency, association between solute and solvent, and process to describe dissolution. | • Maintainence of a usable mechanistic, particle-based understanding of dissolution and factors in determining the | • Maintainence of a usable mechanistic, particle-based understanding of dissolution and factors in determining the | • Maintainence of a usable mechanistic, particle-based understanding of dissolution and factors in determining the | | | | | |
| | | | | | | | | | | | |
• 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.”

rate of dissolution.

• 6-months post-camp assessment: The student indicated that he believed a long, narrow object would dissolve faster than a cubic object “because more surface is showing. The more surface, the faster it dissolves.”, indicating that the student maintained the explicit principle that dissolution rate is related to surface area.

rate of dissolution

rate of dissolution

the rate of dissolution.

the two principles.