Chemistry Education Research and Practice

Accepted Manuscript

Reinterpretation of students' ideas when reasoning about particle model illustrations.

A response to "Using animations in identifying general chemistry students' misconceptions and evaluating their knowledge transfer relating to particle position in physical changes" by Smith & Villarreal (2015)

Elon Langbeheim, Mary Lou Fulton Teachers College, Arizona State University.

1050 S. Forest Mall. Tempe, Arizona. 85287, USA

Email: elangbeh@asu.edu

Introduction

The article "Using animations in identifying general chemistry students' misconceptions and evaluating their knowledge transfer relating to particle position in physical changes" (Smith & Villarreal 2015) recently published in this journal, reported that a substantial proportion of undergraduate students expressed misconceived ideas regarding motion of particles in liquids and solids. The finding is not surprising in light of the abundance of studies that describe students' misconceptions about the particle model of matter (e.g. Johnson, 1998; Harrison and Treagust, 2002; Pozo & Gomez Crespo, 2005). However, the fact that the particle model of liquid and solid was presented to the students in the abovementioned study a short time before they expressed these seemingly erroneous ideas, mandates that they deserve deeper examination.

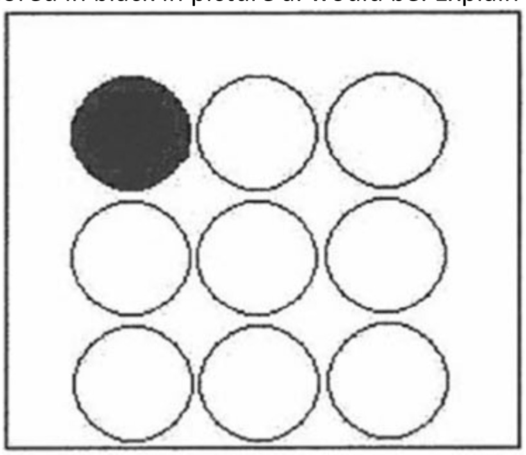
In many cases, the 'misconceptions' approach that views student ideas as stable cognitive structures, fails to capture the reasoning process through which these erroneous ideas actually form. According to an alternative view, concepts are not unitary cognitive entities, but rather structures that combine many knowledge resources (Taber & García-Franco, 2010). While in many cases the combined ideas that students express are incorrect, they may actually employ productive knowledge resources in the construction of these erroneous notions (Smith, diSessa et al 1992, Taber & García-Franco, 2010). Identifying the productive resources that students hold, instead of trying to refute the erroneous idea as a whole, can be conducive for developing a more sophisticated and nuanced scientific understanding and reducing other erroneous conceptions.

Viewing student conceptual reasoning as an actuation of various interrelated knowledge resources, also mandates a close examination of the context at which these pieces of knowledge were activated (Hammer et al., 2005). For example, when students in a pre-service teacher program were asked "How big a mirror do you need to see your whole body?" one student stated without hesitation that the mirror has to be (at least) "the same size as the body, because your whole body has to be able to fit in it."(ibid pp. 90) The same student owned a mirror roughly half her height at home, which shows a reflection of her whole body. She used the mirror every day, but did not use this knowledge resource. Similarly, research has shown that students who have an elaborate "street" mathematical knowledge do not use it in the classroom(Carraher, Carraher, & Schliemann, 1985), because these knowledge components are somehow not activated in the school context. Thus, in order to help students to transfer their productive knowledge resources, one needs to carefully examine the context at which a misconceived idea has emerged, especially if this idea is common among several students.

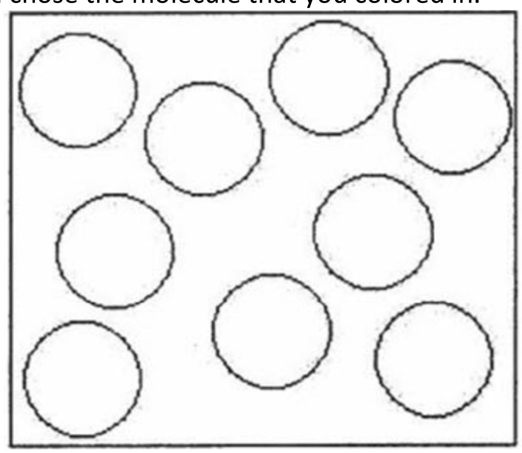
In my reinterpretation of the study, I claim that the illustration that accompanied the question in abovementioned study (Smith & Villarreal, 2015) was probably a major source for the seemingly incorrect reasoning that many students used. I also argue that a closer look at the question and student answers reveals they might have used productive 'mechanistic' knowledge resources that can be beneficial for explaining complex scientific phenomena.

A short summary of the study and results.

The purpose of the study by Smith & Villarreal, (2015) as stated by the authors, was to "use illustrations to identify student views and misconceptions about the positions of particles during physical changes involving the liquid state". The students, enrolled in an introductory college chemistry course in the US were asked to identify the position of a particle in a solid after moving away from its original location during melting. The authors presented the sketches shown in Figure 1, and asked: "If the solid sample melts in a liquid as shown in picture b., color on picture b. where you think the molecule that was colored in black in picture a. would be. Explain why you chose the molecule that you colored in."



a.



b.

Figure 1: The problem scenario presented to the students in Smith & Villarreal (2015)

In a subsequent question, the students were asked about the particle trajectory after a reversal of the melting process. The students were shown a blank picture, similar to figure 1.a. and were asked "If the liquid in the previous (right) picture freezes to a solid, color in the picture below where you think the molecule that was colored black in the original picture would be. Explain why you chose the molecule that you colored in."

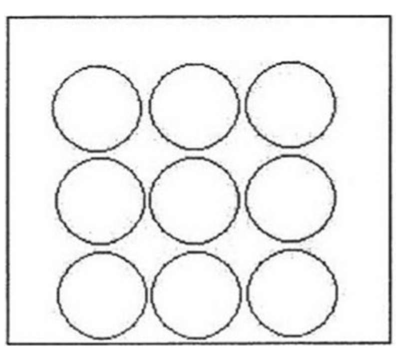


Figure 2: A snapshot of the system after re-freezing the liquid

The researchers presented the question to two groups of students after introducing the particle model in the course. The difference between the two groups was that in group 2 (N=107), the particle model was introduce using the PhET[1] dynamic simulation "Phases Of Matter" whereas in group 1 the model was introduced only using static pictures and diagrams. Despite this difference the overall performance of the two groups was quite similar: 69% of the first group (N=48) and 58% of the 2nd group (N=107) colored in black the molecule on the top-left corner of picture b, indicating that it maintained its original position relative to the other particles. About two thirds of the students who chose the top-left particle (approximately 43% of the overall student sample in both groups) explained that "The molecule doesn't move far from its original position". Only a relatively small proportion of students from both group (13-16%) held the correct conception - that the molecules move around within the entire volume occupied by the liquid and therefore the molecule could be at any location in figure 1b. Similarly, in the subsequent question most students (67%-80%) indicated that the molecule would move back to the upper left corner in picture c, and wrote that the molecule would move back to the same location in the solid or to a location near its' position in the liquid state shown in figure 1b.
The authors suggested that the students expressed a commonly documented 'misconception' – they attributed macro-level properties to the sub-microscopic particles. This type of erroneous reasoning represents an intermediate level of understanding of the particle model of matter, in which students acknowledge that matter is made out of particles (and is not continuous) but believe that the particles have the same properties (e.g. color) as the macroscopic material (Johnson, 1998). In a scientifically acceptable model of matter, the macro attributes are viewed as emerging from a collective summation of the individual particle properties, but the macro-state pattern does not necessarily resemble the property or behavior of the individual particles.

The authors report that the teachers explained the correct answer in the lesson after the administration of the question and that an isomorphic question was administered to the students four weeks afterwards. The isomorphic transfer question relied on very similar pictures of the solid and liquid particles but pertained to dissolving the solid rather than melting it. This time, approximately 30% of the students (about one half of the students who answered in this manner previously) predicted that the particle at the corner would not move far from its original location. This shows that a substantial percentage of the students held on to this misunderstanding and did not forego it easily.

A reinterpretation of the results

In my opinion, the authors' interpretation of student answers in this study could be missing an important resource that the students employed in answering the abovementioned questions. I suggest that the students might have invoked a dynamic, mechanistic form of reasoning (Russ et al., 2008) regarding the motion of the particles and furthermore, that these resources might have been activated by the pictures that were presented in the problem. The pictures in figure 1 and 2 present a two dimensional particle model of nine particles that are confined within a relatively small area. Analyzing the pixel level of the pictures using a graphics program I calculated that the particles occupy almost 50% of the entire area of the rectangle. This high density creates restrictions on the particle's motion, which, in my opinion, have led students to suggest that the particles would be confined to their original

[1] Produced at the University of Colorado at Boulder. URL https://phet.colorado.edu/en/simulation/states-of-matter

location. Obstruction of motion in two dimensional systems can induce solid-like behavior in which the particles stay confined to a small area because of mere geometric constraints. Computer simulations have shown that in an elastic hard-disc systems with no attractions between the particles, a liquid to solid transition appears at a density of d=0.7 (Alder & Wainwright, 1961). In addition, density plays an important role in melting/freezing transitions in two dimensional Lennard-Jones systems (Frenkel & McTague, 1979; Toxvaerd, 1980; Abraham, 1981).

In order to illustrate the motion restriction imposed by the high density of the system, I used a Lennard-Jones Molecular Dynamics Simulation similar to the one used in the PhET simulation. The simulation was based on the Verlet algorithm (Verlet, 1967) and portrays the scenario that was shown to the students in figure 1. At initialization, the particles were placed in a solid like lattice that resembles the structure of figure 1a with an overall density of d=0.48, and were given initial velocities with random headings as shown in the upper left snapshot of figure 3. The equilibrium state of 2D Lennard-Jones model at a density of 0.48 is liquid, a solid phase appears only at densities with d > 0.66 regardless of temperature (Abraham, 1981). The initial velocities were calculated based on the reduced temperature of T=0.45 which corresponds to a relatively high temperature of the liquid state (This is an arbitrary choice, so that one would not argue that the calculations result from a low temperature). Figure 3, shows a typical trajectory of the particle located initially at the upper-left corner at different times.

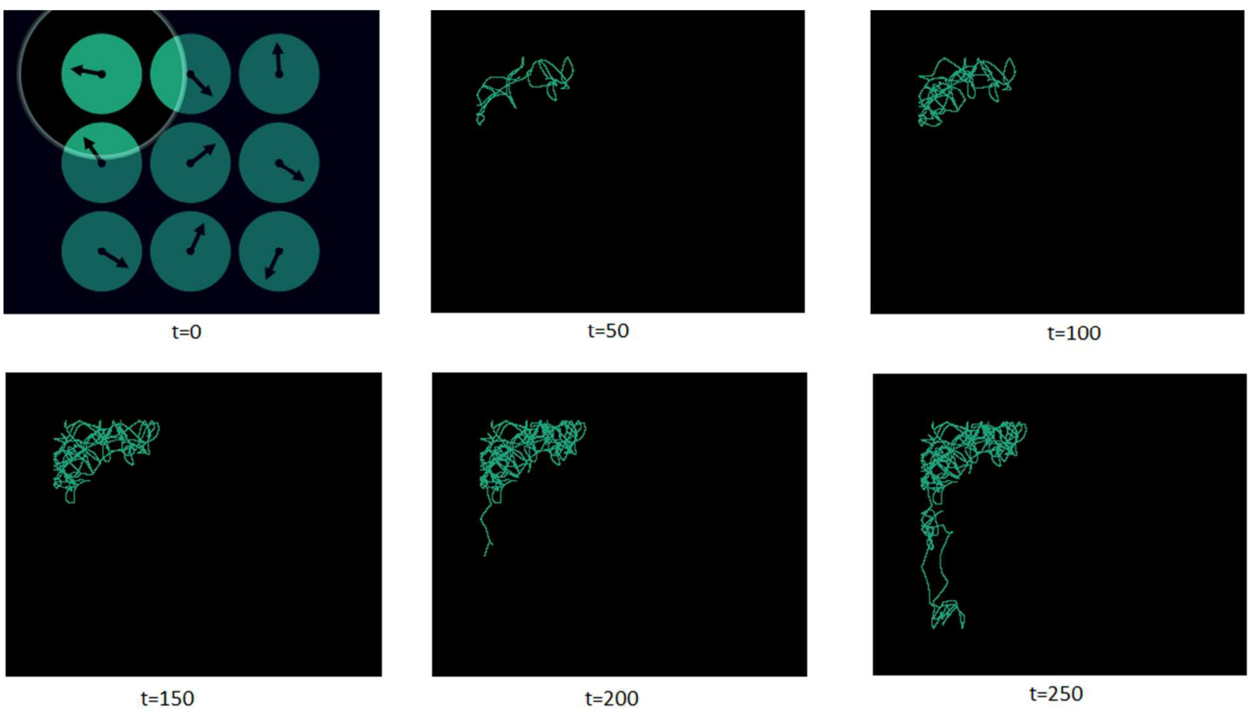


Figure 3. Snapshots of the trajectory of the upper-leftmost particle in two dimensional Lennard-Jones fluid. The trajectory was calculated using a molecular dynamics simulation of nine particles.

The simulation snapshots demonstrate that initially the particle moves in a relatively small area in the proximity of its original position. Only at around t=200 it moves downward, away from its original location. This is to show, that when students thought about the scenario portrayed in the figure 1, their reasoning correctly explains the phenomenon for short time scales. During the initial 180 time steps, the upper-leftmost particle was **indeed very close** to its original location, although it traveled a substantial distance overall. Of course, in this model, the time step is a reduced quantity which is much smaller than typical time scales for melting a macroscopic solid[2]. Therefore, after melting completed, a much longer time period has passed, and the particle could indeed be at any point in the liquid.

Indeed, the picture in the Smith and Villarreal study was said to represent "nine molecules of the solid sample"; - that is, only part of the solid; however, the particles were drawn inside a rectangular frame, as a confined, standalone system. The picture implies that the particles are *not* part of a continuous, macroscopic solid, rather, a nano-system of nine particles kept in some kind of cavity. Such systems behave quite differently from macroscopic solids, and their melting time is in the order of magnitude of pico-seconds (El-Sayed, 2001) similar to the time required by the particle to move away from its' original location in the simulation.

Therefore, it is possible that the confusion between the macroscopic level and particle level in the students' answers was rooted in the problem scenario itself. If this analysis is correct, then the students would have answered differently if the picture would not imply a strong confinement of the particles, or if the question would have indicated that the process of melting takes a long period of time. Mentioning the time scale in the question, can invoke a more careful examination of the particle's motion and a realization that the particles might have sufficient space to slide around each other and bypass the seeming obstruction.

This interpretation is just one among many possible explanations of the students' answers, and without additional data it is difficult to know what type of reasoning the students actually used to claim that the black particle would not move far from its initial position. It is possible that students employed a dynamic view of matter as suggested above, but it is also possible that they have had a very static view of the system and thought of the particles as not moving at all. As Smith & Villarreal suggested, in-depth data from interviews (or other sources) is necessary for further exploration of the ideas that students have used.

Assuming that students used a dynamic view of the melting process, this resource can be used for a better understanding of the differences between liquids and solids in relation to the particle level structure. For example, students can apply their reasoning to explain why liquids that are subject to strong forces at short times scales(e.g. water droplets that hit a solid surface at a high speed), may act like elastic solids(the water droplets may bounce off like rubber balls). Using the idea that at short time scales atoms remain "caged" like in a solid, one can understand why a quick compression of the droplet gives rise to an inter-particle repulsion force that pushes back on the liquid particles as in the retraction of an elastic solid.

Student knowledge resources may playout in different ways when they tackle conceptual questions, sometimes leading to erroneous answers. The interpretation outlined above shows that sometimes, incorrect answers stem from productive reasoning resources, which can be harnessed for conveying a more sophisticated understanding of the scientific models involved.

Summary.

[2] For Argon, each reduced time unit is approximately $10^{-13} sec$ in real time whereas melting processes last for much longer time scales.

The students in the study by Smith & Villarreal (2015) might have utilized appropriate mechanistic reasoning, reacting to the seeming obstruction of motion that the picture presented. As demonstrated with the simulation, such reasoning correctly predicts the behavior of the system for short time scales. Therefore, the students' erroneous responses should not be dismissed as mere misconceptions, rather, teachers and educators should look for productive reasoning resources in students' thinking to develop a more nuanced view of the difference between liquids and solids.

Acknowledgements

I thank Prof. Samuel A. Safran and the two anonymous referees for their insightful comments.

References.

Abraham, F. F. (1981). The phases of two-dimensional matter, their transitions, and solid-state stability: a perspective via computer simulation of simple atomic systems. *Physics Reports*, *80*(5), 340-374.

Carraher, T. N., Carraher, D. W., & Schliemann, A. D. (1985). Mathematics in the street and in school. British Journal of Developmental Psychology, 3, 21-29.

El-Sayed, M. A. (2001). Some interesting properties of metals confined in time and nanometer space of different shapes. *Accounts of chemical research*,*34*(4), 257-264.

Hammer, D., Elby, A., Scherr, R. E., & Redish, E. F. (2005). Resources, framing, and transfer. *Transfer of learning from a modern multidisciplinary perspective*, 89-120.

Harrison, A. G., & Treagust, D. F. (2002). The particulate nature of matter: Challenges in understanding the submicroscopic world. In J. K. Gilbert (Ed.), *Chemical education: Toward research based practice* (pp. 189–212). Dordrecht, The Netherlands: Kluwer Academic Publishers.

Johnson P (1998) Progression in children's understanding of a 'basic' particle theory: a longitudinal study. *Int J Sci Educ*. 20:393–412

Russ, R. S., Scherr, R. E., Hammer, D., & Mikeska, J. (2008). Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science. *Science Education*, *92*(3), 499-525.

Pozo, J. I., & Gomez-Crespo, M. A. (2005). The embodied nature of implicit theories: The consistency of ideas about the nature of matter. *Cognition and Instruction*, 23(3), 351-387.

Smith, K. C., & Villarreal, S. (2015). Using Animations in Identifying General Chemistry Students' Misconceptions and Evaluating their Knowledge Transfer Relating to Particle Position in Physical Changes. *Chemistry Education Research and Practice*.

Taber, K. S., & García-Franco, A. (2010). Learning processes in chemistry: Drawing upon cognitive resources to learn about the particulate structure of matter. *The Journal of the Learning Sciences*, *19*(1), 99-142.

Verlet, L., (1967) Computer "experiments" on classical fluids I. Thermodynamical properties of Lennard-Jones molecules. *Physical Review*, 159, 98-102