

Students' Learning Trajectories in Developing Explanatory Models: Exploring Adaptive Scaffolding of Interactions with Online Science Simulations¹

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Explanatory models involving unobservable entities interacting in ways that explain observable phenomena, such as the particulate model of matter, have a central place in science and in science learning (Black, 1962; Coll & Lajium, 2011; Gilbert, 2004; Hesse, 1966; Nersessian, 2002, 2008, Brown, 1993, 1995a, 1995b; Cheng & Brown, 2010, 2015; Clement, 1989, 2008b; Clement & Brown, 2008). Dynamic computer simulations that make the interactions of these unobservable entities observable can help to support students' development of an understanding of these important explanatory models (Clark & Jorde, 2004; Linn & Eylon, 2011; Chang & Linn, 2013).

However, even though they can support such learning, the use of simulations as pedagogical tools in instructional situations can be hampered in several ways. If the simulations are employed without appropriate support, students may have difficulties knowing what controls to use to modify specific parameters, what to pay attention to, what questions the simulation can help them address, what manipulations are optimal for addressing these questions, what meaning to ascribe to the interacting elements, or how to formulate appropriate explanatory narratives about various interactions. While traditional classroom and online contexts may be able to support learning with simulations with worksheets and framing questions, such linear or *non-adaptive* framing treats all students the same, and it is often based on the teacher's or web page author's best guess of what will be helpful rather than on research on student learning with computer simulations.

In order to address these issues with linear or non-adaptive framing of learning with simulations, in this research we explore the possibilities for embedding *adaptive scaffolding* with the simulation interface. To this end we explore a microanalytical focus on student learning with simulations designed to help students develop explanatory models of molecular processes. The goal of this research is to *characterize the varied trajectories* by which students develop

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appropriate explanatory narratives about processes involving unseen molecules and molecular motion and to *identify effective pedagogical and technological supports* for adaptively scaffolding student understanding of these processes.

While a move toward online adaptive framing may seem similar to an intelligent tutoring environment in attempting to adaptively support student learning, it is not our goal to replace the teacher with an intelligent tutor. Rather, our goal is to replace linear framing of the simulations (e.g., through a worksheet or a linear sequence of web pages), with framing that is adaptive and based on prior detailed research on varied student learning trajectories. In what follows, we discuss the theoretical framing for this work and initial microanalyses that explore the varied learning trajectories of three individuals.

Explanatory models and narratives

For decades the essential role of models and modeling has been recognized in scientific thinking and reasoning (Black, 1962; Coll & Lajium, 2011; Gilbert, 2004; Hesse, 1966; Nersessian, 2002, 2008). While some scientific models focus on a precise articulation of patterns, an *explanatory model* is an imagistic representation of unseen interacting elements that provides mechanisms for the observed patterns. In producing an *explanatory narrative*, the student “runs” their (tenuous or fully developed) explanatory mental model in order to provide an explanation for some aspect of an observable phenomenon (e.g., here, why a blocked off syringe can be compressed, or why the syringe plunger moves back out when released). Through the development of appropriate explanatory narratives for various empirical patterns, students can construct robust explanatory models that can be applied more broadly (Cheng & Brown, 2015). Effectively supported dynamic simulations have the potential to help students in the articulation of these explanatory narratives.

Science Learning and Scaffolding with Computer Simulations

Simulations are computer models that permit users to manipulate their parameters and explore their implications (National Research Council, 2011). In their review of research on the learning effects of science education simulations, Rutten, van Joolingen, & van der Veen (2012) found robust support in the literature for simulations enhancing science instruction, complementing laboratory activities, and promoting learner construction of important science concepts. In

addition to practical benefits (safe, cheap, repeatable, etc.) there are also specific cognitive affordances for conceptual development and understanding, such as giving learners opportunities for personal experimentation consistent with constructivist pedagogies (e.g., de Jong & van Joolingen, 1998; Windschitl & Andre, 1998), exploiting spatial properties that facilitate more sophisticated knowledge representations (e.g., Dalgarno & Lee, 2010; Monaghan & Clement, 1999), and immersing them within the phenomena such that they adopt novel perspectives and important intuitions that cultivate more expert-like thinking (Clark & Jorde, 2004; Dede, 2009).

Some science simulation researchers have sought explicitly to implement components of scaffolding within the simulations, such as metacognitive prompts (Fund, 2007), framing and focusing questions (Hmelo & Day, 1999), and visual representations that are grounded in a student's prior knowledge and experiences (Jackson, Stratford, Krajcik, & Soloway, 2004). The features of simulations that have been termed "scaffolds" are quite broad, but when Wood et al (1976) initially introduced the term, a central aspect of the concept was that of *adaptivity* (Pea, 2004). Puntambekar and Hubscher (2005) articulate this adaptivity by focusing on three central ideas: ongoing diagnosis, calibrated support, and fading. Thus, we use the term *adaptive scaffolding* to highlight these features, and we focus here on how to design adaptive scaffolding that specifically cultivates students' explanatory narratives.

Research Design

In a later phase of this research we will explore the feasibility of implementing adaptive scaffolds in an online context. However, before this can be done effectively, a great deal of research is needed exploring a variety of learning trajectories. The goals of this current phase of the research are twofold. First, we want to characterize the varied trajectories by which students develop appropriate explanatory narratives about processes involving unseen molecules and molecular motion. Second, we want to identify effective pedagogical and technological supports for adaptively scaffolding student understanding of these processes through the use of dynamic simulations.

In this work we take an approach complementary to that of focusing on learning progressions for groups of students (e.g., Smith et al, 2006; Stevens, Delgado, & Krajcik, 2010; Talanquer, 2009) by focusing on the specific learning trajectories of individual students (Simon, 1995) and instructional decisions and adaptive scaffolds that can best support each individual's

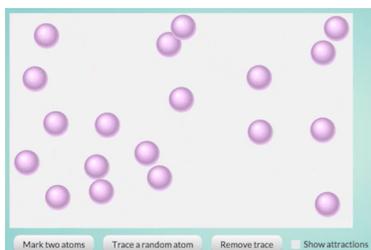
learning. For such a purpose, a microanalytical approach focusing closely on the learning of individual students is more appropriate than approaches focused on averages over large numbers of students. In microanalytical approaches, the focus is on looking in detail at the moment-by-moment interactions of students. For example, Roschelle (1998) looked closely at how a pair of students made use of a computer simulation. Through this focus, he was able to identify emergent categories of student thinking and interaction such as registrations, qualitative cases, and generative metaphors. Surprisingly, such a microanalytical focus on learning with simulations is comparatively rare in the literature. For our purposes of exploring in detail how different individuals learn from simulations, microanalytical methods are particularly appropriate. To assist us in these microanalyses, for each interaction we have two sources of video (the computer screen and the interviewer-interviewee interaction) as well as audio from the interviewee, the tutor, and any audio from the computer.

Microanalytical Vignettes

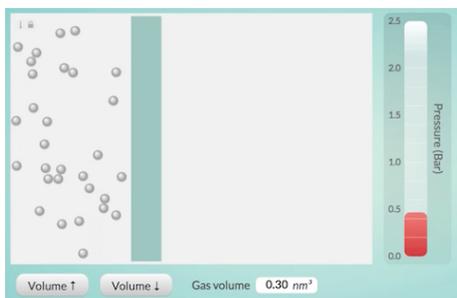
In the following cases, each interviewee was shown a syringe (for dispensing medicine orally) with the plunger pulled partially out and the end blocked off so that no air could escape even if compressed. They were asked to compose explanatory narratives for several observations: 1) why is it possible to compress the syringe, 2) why does it get harder as the syringe is compressed, and 3) why does the plunger move back out when released. The target narratives involve air molecules constantly moving in a background of empty space and causing pressure on the plunger by their collisions with the plunger.

The interviewer or tutor then adaptively scaffolded their interactions with two dynamic simulations in order to help them construct appropriate explanatory narratives for each of these three questions. In what follows, we focus in somewhat more depth on the learning trajectory of a middle school girl, Jada, and, because of space constraints, much more briefly on two other learning trajectories in order to illustrate a variety of trajectories and adaptive scaffolds needed. In the final paper we will discuss a wider variety of trajectories in more depth, but these three trajectories illustrate rather clearly the need for such microanalyses to provide insights both for the specifics of adaptive scaffolds and the adjustments needed to simulation affordances in order to better support student construction of appropriate explanatory narratives.

A middle school student. When “Jada” was first asked to provide explanatory narratives for the three questions, she focused on “air,” sometimes as what would blow out of the end of the syringe if it weren’t blocked off, sometimes as empty space, and at other times as something inside the syringe represented using wavy lines in a drawing. Since she did not discuss air in any way as particulate, the tutor asked her to draw the air magnified using “magic glasses.” Jada said “I don’t know what air looks like, it’s just air.” The tutor interpreted that as effectively saying “no matter how closely you look, it will just look clear.” He made the decision to discuss the particulate ideas of another student and asked her what she thought of these. She had heard of atoms and molecules and said that view made sense. When the tutor then asked her to draw the air magnified, she drew circles to represent the particles, farther apart when the plunger is out and closer together when the plunger is compressed.



At this point the tutor introduced the first simulation (one of the Molecular Workbench [MW] simulations from Concord Consortium): “T: tell me what you notice about the simulation. J: It’s like if you have a box of balls and they’re like really tiny and they’re like a lot of, they’re really far apart and they have more space to move around. T: Does it make sense to think of air as molecules? J: No, because you usually think of air like there’s nothing, it’s like nothing.” She went on to say that there’s something in the syringe resisting the plunger, but she didn’t know what it was called. When asked if it was the air, she said “I think it’s the air, because it’s trapped in there.” The tutor went on to discuss situations in which air becomes perceptible, such as sticking a hand out of the window of a moving car or blowing on your hand, in order to further support this initially tenuous suggestion that air can have perceptible effects such as making the syringe hard to compress. When asked if thinking about air as molecules helped explain her observations, she replied that it did - when the syringe is pulled out the atoms are more spread out, when it’s pushed in, the atoms are closer together.



The tutor then helped her interact with the second MW simulation showing gas molecules moving around inside an adjustable volume. When asked why the pressure

measurement increases as the piston is moved to the left, she replied that the molecules are closer together and so are under more pressure. Since she was not explicitly focusing on the number of times the molecules strike the movable wall, he asked her about this. After some trial and error she was able to click on the Volume up and down buttons (she initially did not know what “volume” meant) to move the wall back and forth and to describe in some detail that when the wall is moved out, the molecules are hitting it much less frequently than when it is moved in. He then asked her how to explain why the plunger gets harder to push the more it is pushed in. She responded that it is because the molecules are closer together, and so are under more pressure. He then explicitly told her that the pressure measuring bar is measuring how often the molecules hit the piston. She responded “Ohhh” in a tone that indicated an aha. After this point she used this idea fairly consistently in future narratives.

After this interaction she was able to articulate a good explanatory narrative about increasing resistance as the plunger is compressed (“It gets harder and harder to push it in because the molecules are, there’s a lot more molecules hitting the barrier”), but she had some difficulty articulating why the plunger moves back out, focusing not on the molecules causing the plunger to move but rather that moving the plunger makes the molecules spread out and hit the plunger less frequently. On later reflection, we realized that the simulation supported the construction of the narrative about increasing pressure but not the narrative about why the plunger moves back out. The simulation interface allows the user to actively decrease the volume, similar to pushing the plunger in. But there is no control in the simulation allowing the user to “let go” of the wall - the user must actively move the wall back out by clicking the volume up button. This illustrates one kind of insight this research is designed to draw out - in what ways does the simulation support or not support student construction of various explanatory narratives?

A less science-sophisticated adult. “Melissa” initially focused on the particulate nature of air, but she did not discuss these particles as in motion. When asked how the particle idea explains compression, she said that the particles or molecules are compressed into a smaller space than they want to be in and so push back. When asked how the molecules push back on the plunger, she replied “I don’t know.”

At this point the tutor showed her the first simulation with molecules moving around in a contained space. When asked what she noticed, she replied: “Molecules moving around randomly and there’s space in between - what is the space in between [the gray background]? What molecules are those, or are they just atoms [the simulation labels these as atoms]. So if these are atoms, they’re making up some sort of molecules, so the space in between is whatever takes up space within a molecule, the electron cloud or whatever.” This focus on the space between the atoms as something substantive was a continuing focus of her attention. This focus on the space between atoms as substantive is in sharp contrast to Jada’s conception of air as completely empty space and required significantly different scaffolding in order to focus Melissa’s attention on the motion of the air molecules in a background of empty space as explanatory. However, similar to Jada, the tutor had to directly focus her attention on the number of times the molecules struck the plunger.

After these interactions, Melissa discussed her explanatory ideas. Note the lingering focus on space as somewhat substantive (needing to be “squished out”), but in addition to important elements of the target model: “Molecules are obviously the same size, but they now have less space inside there because you’ve squished out the space, and so they are now pushing more often within their contained area, there’s less space between the molecules and so by their movement pushing back on this more, bouncing off of it more and so the pressure pushing back on this plunger is greater than it was here because now there’s less space and so these are now pushing to get back to where they were comfortable.”

A more science-sophisticated adult. When asked for explanations, “John” initially articulated ideas of air as composed of molecules in motion in empty space. However, while many elements of the target model were initially present, when asked how the motion causes the pressure, he focused on the frequency with which the molecules hit each other - the more they hit each other, the greater the pressure. When asked how this explained the increased pressure on the plunger when compressed, he realized that it did not, but he could not think of an alternative.

When working with the simulations, John continued to focus on the frequency of the molecules hitting each other. At this point the tutor gave a hint to focus on the number of times the molecules hit the plunger. This seemed to immediately click with John, and he used this idea very effectively in the remainder of the session.

When asked after the session how to explain what happens with the syringe, John articulated ideas essentially identical with the target model and was able to use this model flexibly for the different explanatory narratives (e.g., why the pressure on your finger gets greater as the plunger is depressed, why the plunger moves back out when released).

Discussion

These vignettes show the promise of this research for identifying student conceptions (e.g., air as nothing, pressure as how close the molecules are, etc.), example scaffolds that seemed to be effective (e.g., focusing attention on the number of times the molecules hit the wall), and example simulation modifications that may better support student construction of explanatory narratives (e.g., providing a way for the user to “let go” of the movable wall). These sessions also revealed some promising strategies for learning simulation designs that can be implemented as adaptive scaffolds. Certain aspects of the simulation interactions and controls could be highlighted, for example, based on individual student responses to the simulation. Three basic categories of potential supports that emerged from these cases are 1) modifying the simulation to better support identified issues with the construction of explanatory narratives (e.g., using sound or visual highlights to make salient the impact of atoms on the walls of the container as opposed to molecules hitting each other, providing a way for the user to “let go” of the movable barrier), 2) highlighting the links between simulation activity and data representations (e.g., making explicit the connection between the “pressure bar” and the frequency of atoms impacting the wall), and 3) prompting the student to consider the meaning of certain simulation characteristics and components (e.g., asking the student to reflect on what the “grey space” behind the atoms represents). These findings present an actionable path with which to create and test modified simulation environments that have the potential to better support student construction of powerful explanatory models.

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