Cognitive Prosthetics for Fostering Learning: A View from the Learning Sciences

Janet L. Kolodner

■ *This article is aimed at helping AI researchers and practitioners imagine roles intelligent technologies might play in the many different and varied ecosystems in which people learn. My observations are based on learning sciences research of the past several decades, the possibilities of new technologies of the past few years, and my experience as program officer for the National Science Foundation's Cyberlearning and Future Learning Technologies program. My thesis is that new technologies have potential to transform possibilities for fostering learning in both formal and informal learning environments by making it possible and manageable for learners to engage in the kinds of project work that professionals engage in and learn important content, skills, practices, habits, and dispositions from those experiences. The expertise of AI researchers and practitioners is critical to that vision, but it will require teaming up with others — for example, technology imagineers, educators, and learning scientists.*

In its fall and winter 2013 issues, *AI Magazine* published a series of articles presenting some of the best current work at the intersection of artificial intelligence and education. The articles report on the newest in intelligent tutoring systems and resources (Bredeweg et al. 2013, Rus et al. 2013; Chaudhri et al. 2013), virtual humans and conversational agents (Swartout et al. 2013), assessment and student modeling for personalization (Conati and Kardan 2013, Koedinger et al. 2013), and intelligently controlled virtual environments (Lester et al. 2013). The final article in the set (Woolf et al. 2013), of which I am a coauthor, suggests needs and challenges facing STEM education (science, technology, engineering, and mathematics) that artificial intelligence might address — mentors for every learner, fostering learning of 21st-century skills, automating assessment in ways that support learning, universal access, and life-long and life-wide learning.

  ISSN 0738-4602

In this article, I aim to push artificial intelligence researchers and practitioners to consider an even broader range of ways technology might be used to foster learning. I want to help AI researchers imagine the roles intelligent technologies might play in the many different and varied ecosystems in which learning happens or could happen. My observations are based on what the learning sciences has learned about learning from experience over the past several decades, the affordances for fostering learning of new technologies of the last few years, as well as my experience as lead program officer for the National Science Foundation's Cyberlearning and Future Learning Technologies program[1] from August 2010 through July 2014.

The mindset of the learning sciences and of the cyberlearning program goes far beyond the notions of learning from the 1970s and 1980s that shaped intelligent tutoring systems and student modeling in artificial intelligence. We know now that understanding means far more than acquiring knowledge and involves complex considerations of what makes sense. Iterating toward understanding includes expressing, debugging, and refining one's understanding and self-explanations, often aided by interactions with peers and more knowledgeable others. Iterating toward development of masterful capabilities involves the same kinds of complex reasoning and interactions with others. Learning is not a solitary or purely cognitive activity (see, for example, Bandura [1986]; Rogoff [1990], Sfard [1998]; Vygotsky [1978]). As well, we now know that our bodies play powerful roles in helping us learn and in helping us express what we know, through the metaphors we use in understanding (Clark 1997; Lakoff and Johnson 1999), the gestures we use and observe others using to express meaning (Barsalou et al. 2003), our use of multiple senses as we experience scenarios and phenomena (Clancey 2013, Damasio 1999), and more — which we call embodied cognition. And because getting to deep understanding and masterful capabilities takes a long time and can be fraught with difficulties (and tedium), such deep learning can only happen if learners are motivated to sustain their engagement over long periods of time and through the hard parts.

Furthermore, we see in our schools on a regular basis that many students are turned off and tune out when they don't know why they need to learn something or how it will be important for their lives. We know, too, that well-meaning teachers (and I include many intelligent tutoring systems here) that violate the cultural norms of community members and make them feel that they are being talked down to turn them off and lead to attitudes of "not learning" (Kohl 1995).

In these situations, learners won't put in the time or energy to engage in sense-making activities and practice that are needed to develop understanding and capabilities. As well, what people need to learn in the 21st century, as trite as it sounds, is different from what they needed to learn in previous centuries. Communication and collaboration skills are more important than ever, as is the ability to be adaptive and flexible in the ways one uses what one knows and identifies what else one needs to learn. And learners, who are our citizens, need to both be competent and feel confident in these capabilities to succeed when required to perform outside of what they know well.

So the challenges in education, both formal (school) and informal (out of school) are not simply cognitive challenges; it is important, as well, to consider social, cultural, and volitional influences on individuals and collectives when designing ways to help them learn, and it is important to not only help learners know things but also to help them develop the skills, practices, attitudes, and dispositions they need to be productive and successful in our complex world. And, of course, sometimes, too, it is important to consider neurophysiological and other aspects of what is important for learning.

My thesis is that new technologies have potential to transform the possibilities for fostering learning in formal and informal learning environments, through making it possible and manageable for learners to engage in the kinds of project work that professionals engage in and to learn important content, skills, practices, habits, and dispositions from those experiences that are important for living a productive, healthy, and engaged life. The expertise of artificial intelligence researchers and practitioners, I believe, is critical to that vision, but it will require a mindset different than what many AI researchers are used to. Rather than thinking in terms of building standalone intelligent systems, it will require teaming up with others — for example, technology professionals, educators, and learning scientists — and integrating intelligent functionalities into the learning environments and ecosystems that are inhabited by learners over long periods of time. I highlight four technological parts of those ecosystems that AI can contribute to: (1) virtual and augmented environments that allow learners to play real-world roles as they interact with and manipulate phenomena, processes, or situations they otherwise could not experience, (2) cognitive prostheses that help learners to navigate such environments and benefit from such learning experiences, (3) cognitive prostheses and representational systems that foster sense making and expression, and (4) disciplinary platforms that are targeted toward particular types of content and skills and particular developmental stages. AI expertise will also be needed in the authoring systems for creating technologically-infused environments for learning that integrate the best in technology with the best in pedagogy.

Setting the Stage: A Broader View of Learning

In an effort to help readers develop imagination about what technology can be used for in fostering learning, I ask readers to think about the very best learning experiences you have had in your lives — the formal and informal ones, as children and as adults, as learners and as mentors or facilitators for others. When I have asked my undergraduate and graduate students to think of such experiences, they remember teachers who made content exciting and were available beyond the hours in the classroom; spending hours, days, months, or more making something work the way they wanted; some project they worked on that made them feel particularly accomplished when they looked back at what they had done, help and encouragement from people around them; pouring over books of chess plays to figure out what they could do better; aha's when they finally understand something and the recognition of the value in what they had been engaged in; exhibits in museums where the display made something particularly clear; taking a particular class to help them learn a particular craft skill they wanted to become good at; spending hours talking about big open questions; working in groups to solve hard math problems; math or science discussions (and jokes) around the dinner table; visiting their parents at work; really good stories; and so forth.

Over the many years I've asked my students this questions, I've rarely had any of them report about hours spent in lecture, with textbooks, and answering back-of-the-chapter problems. That's not to say that such hours are not important to learning, but it does suggest that single-minded focus on how to present content and on guiding learners through practice problems is insufficient or, worse, misguided. Those who put in time to deeply understand something or develop masterful skills do it because they are passionate about what they are learning and because they can predict that the tedium of practice will lead to big rewards and emotional highs in the end. People put energy and time into what they are interested in, and what they learn depends on what they already know, what resources they have available, and the help they can get from others (Bransford, Brown, and Cocking 1999; Sawyer 2006).

The big challenge, from this point of view, is how to design learning experiences that are motivating enough so that learners will want to put in effort over long periods of time, how to maintain the momentum over long time periods so that learners remain engaged, how to use what's known about social, cultural, embodied, motivational, and cognitive influences on learning to foster learning from those experiences, and how to make educational experiences with all of these qualities manageable.

There is agreement among those who are redefining what needs to be learned in school that depth of understanding should take precedence over lots of facts and that disciplinary practices should be learned along with getting to that deep understanding.[2] What is known about the cognition of learning tells us that deep understanding requires considerable time on task, abundant opportunities to try things out and get feedback, time for iteration toward understanding and capability, and revisiting of what has been learned over a variety of contexts (Anderson 1981; Bell, Davis, and Lynn 1995; Bransford, Brown, and Cocking 1999; Ericsson, Krampe, and Tesch-Romer 1993; Kolodner 1997; Schank 1982). We know, as well, that learners need to connect what they are learning to what they already know and have experienced; they can only build on the mental models they already have. How can we encourage learners to want to engage over the long periods of time needed for deep understanding? How can we make iteration toward understanding and capabilities flow naturally from activities rather than feeling tedious? How can we help learners appreciate the relationship between what they are learning and the world they live in and will live in as they mature?

An answer from long ago to these questions is to engage learners in activities where they play real-life (or imaginary) roles in realistic (or real) situations, taking on some mission that they are motivated to achieve, and engaging in the explorations, investigations, and syntheses needed for success (for example, Dewey [1938]). Luckily, technology affords making a wide range of role-play activities and taking on of missions possible — in the real world augmented by technology or in a virtual world (augmented by reality). Imagine learning in the context of taking on roles as scientists and engineers, policy makers, health-care professionals, pioneers moving west, blood cells, body organs, and so forth. Imagine being able to get inside a volcano or the core of the planet or an ecosystem or the sun or the circulatory system and being able to manipulate what is going on and sensing what happens.

Now imagine engaging in those activities along with others and the excitement and conversation and wonderment that might ensue. Once technology is used to afford the kinds of experiences that can foster engagement and make iterative refinement of understanding and capabilities feel natural, embedded cognitive prosthetics can be used for such functions as fostering observation, interpretation, explanation, exploration, feedback, collaboration, rigorous talk, and other cognitive and social behaviors that are essential for learning from experience. Such learning environments, when integrated well with reflective activities facilitated by a teacher, have potential for fostering very deep understanding indeed (Barron et al. 1998; Bell, Bareiss, and Beckwith 1994; Brown and Campione 1994; Cognition and Technology Group at Vanderbilt 2000; Kolodner et al. 2003).

To show how technology can make such learning experiences possible and manageable, I will present some of my favorite research projects as examples of the kinds of activities that foster learning and what technology can offer in making such activity possible. I am personally drawn to roles technology can play in immersing learners in situations and with phenomena they could not otherwise encounter (and helping them sense invisible phenomena, explore possibilities and experience effects of choices they make, explain and make sense, and learn from play as they engage in those immersions), and in helping learners gain masterful capabilities, express their own developing understanding and come to collective understanding with others, and develop appreciation of who they are and could be. Technology will need to play more prosaic roles as well for the vision I put forward to take hold — for example, helping learners self-assess, providing learning analytics for teachers, bringing people together, and making lectures and resources more widely accessible. As listed earlier, this article focuses in four areas: (1) virtual and augmented environments that allow learners to play real-world roles as they interact with and manipulate phenomena, processes, or situations they otherwise could not experience — I call this technology for fostering "being," (2) cognitive prostheses that help learners to navigate such environments and benefit from such learning experiences, (3) cognitive prostheses and representational systems that foster sense making and expression, and (4) disciplinary platforms that are targeted toward particular types of content and skills and particular developmental stages.

Environments for Role Play: Technology for Fostering "Being"

Schank et al.'s (1994) idea of goal-based scenarios was an early AI-based approach to supporting the doing and learning of learners as they take on real-world professional roles. In Sickle Cell Counselor (Bell, Bareiss, and Beckwith 1994), for example, learners take on the role of genetics counselor and make recommendations to couples worrying about whether their future children might be born with sickle-cell anemia. The software makes available offices and "equipment" for drawing blood, labs for blood analysis, resources to help with predicting the possibilities of sickle-cell, and an office for seeing their clients. Within each room are resources and experts available to answer questions and give advice. Learners are challenged by their clients to provide justifications for their advice, and they experience the reactions of their clients when advice is not well-justified or is well-received. The software's intelligence is in managing the scenario the learner is embedded in, identifying the best advice for embedded experts offer to learners, and identifying stories embedded experts might tell to help learners recover from their mistakes and make connections between what they are doing and what real-world genetic counselors do. In a museum environment where visitors normally spend almost no time at any one exhibit, the system kept visitors engaged for up to 20 minutes at a time and resulted in some sophisticated genetics learning. The system had to keep pretty tight rein on what learners were able to do in the environment so as to be able to give good advice, but with more sophisticated AI capabilities, one could imagine such immersive environments where characters in a scenario converse and interact more like human mentors would, taking into account not only the advice learners need to acquire the content but also to participate in sense-making and mentoring conversations.

In more modern immersive learning environments (but without intelligence), the environment provides a venue for exploration and investigation, sometimes by individuals and sometimes by learners working in groups. Sense-making conversations might happen within or outside the environment and both during immersive activities and after. In Tom Moher's RoomQuake (Moher 2006, 2008), for example, the elementary school classroom is outfitted with sensors, effectors, and equipment that allow students to be seismologists. The scenario controller keeps track of the locations of seismic plates in the classroom; it moves the plates to create "roomquakes," which the children experience as the noise of a big vibration and the classroom's seismographs coming to life. (The teacher can set the controller so that no earthquakes will happen during spelling tests.) Acting as seismologists, students read the seismograms, trilaterate epicenters, and calculate the intensity of each roomquake (as in figure 1). After several weeks of roomquakes, the class works together to identify where the "tectonic plates" in the classroom are. Sense making happens in small groups and as a class, and the computer is used for keeping track of data and helping learners develop representations that allow them to visualize the data in productive ways and make sense of it.

In Harvard's EcoMuve (Grotzer et al. 2013), learners immerse themselves in an ecosystem. The fish in the pond are dying, and it is their mission to figure out why. The graphics are quite sophisticated, and there is a feeling of being there. Learners walk around the watershed area to learn what activities in the neighborhood might be affecting the pond's chemistry, and they can have constrained "conversations" with those they encounter; a gardener, for example, tells them about the fertilizer he is putting down to keep the grass green. They can immerse themselves in the pond itself (at different levels and augmented with different magnifiers), and, using a microscope, they can examine the fish, plant life, and microorganisms under the water. They can magnify, measure, and count the organisms as well as watch them inter-

Figure 1. Participating in Roomquake Activities.

(a) Learners estimating roomquake wavefront speed using stopwatches and tape measures. (b) Learners examining a seismogram. (c) Learners exploring with a home-made seismograph and a shake table. Photographs by Brenda Lopez Silva. *Reprinted with permission from Tom Moher and Anthony Perritano, University of Illinois at Chicago.*

act with each other, and they can collect much environmental data — both current and past. The computer provides tools for visualizing what they can't directly see, taking measurements, and analyzing the data (see figure 2). They can share what they are finding online, but most sense-making discussions happen in small face-to-face groups and as a class.

An immersive environment might be mostly real world (as in roomquake), where learners play roles in an instrumented world. Or it can be virtual (as in EcoMuve). A virtual environment might surround the learners and engage multiple senses (imagine, for example, a room with touch-screen walls that puts you under the ocean or in the middle of a rainforest (Lui and Slotta 2013), or learners might immerse themselves as avatars (as in EcoMuve). Or the immersive environment might be augmented. EcoMobile (Kamarainen et al. 2013), for example, guides learners as they explore the pond modeled in EcoMuve. CI-SPY (Singh et al. 2014) is designed to help students learn the history of school segregation through visiting a local site, the Christiansburg Institute, important to that history. Using CI-SPY, they are able to examine what life was like in that place in previous generations and make observations and collect data from across historical eras to make sense of later. As historians do, they plan for data collection before going to the site, they collect data at the site, and they bring it back to examine and make sense of (as in figure 3). They might go back to the site another time after they identify what else they need to find out.

In a set of projects that help first and second graders learn from embodied role play, children act out such natural phenomena as the interactions of bees as they are gathering nectar (Peppler and Danish 2013) and the interactions of molecules in solids, liquids, and gases (Danish et al. 2015). In one version, the children don instrumented electronic hand puppets as they take on the roles of the organisms or objects they are learning about. In BeeSim (Peppler et al. 2010), for example, they play the roles of bees gathering nectar (figure 4). The instrumented e-puppets and other objects allow them to see flowers', bees', and the hive's levels of nectar as the children behave as bees moving around the classroom gathering nectar from flowers and returning to the hive. Displays on the bees, flowers, and hive show their nectar levels. Networking connections keep track of nectar levels and the travels of as many as 7 or 8 student bees at a time. Students play the role of entomologists, generating questions about bee behavior. Then they play roles as bees and get to directly experience the activity of bees and the emergent effects of nectar gathering. They reflect on that experience, again as entomologists, and they answer some of the questions they had generated and generate more; they go back to the bee role play to help them answer questions. For example, they might wonder, after acting once in the role of bees, how each bee

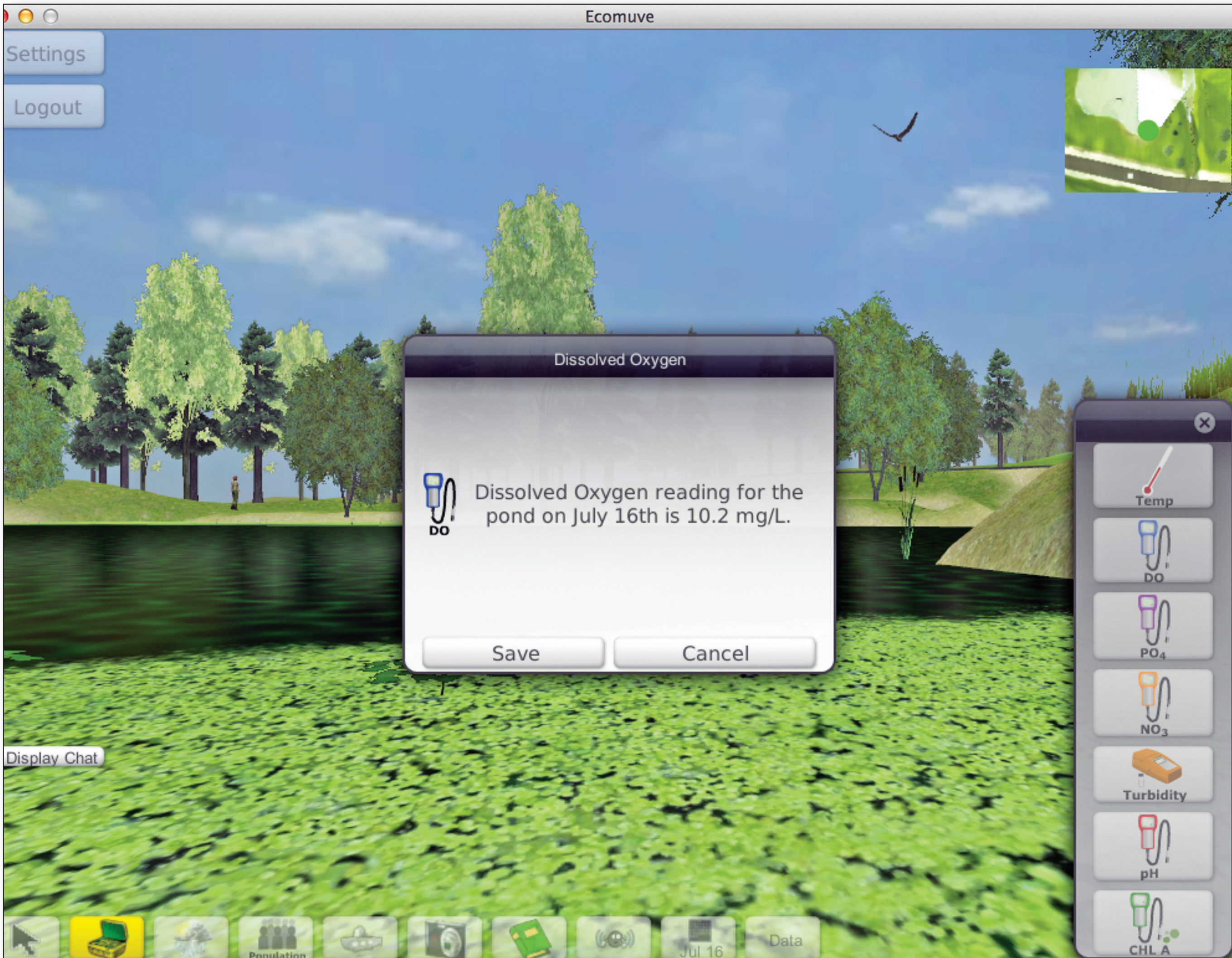

Figure 2. EcoMuve's Pond.

Inserts show the tools available for taking measurements; the bar at the bottom shows tools available for moving around in the environment and taking notes. *Figure courtesy Shari Metcalf, Harvard University. Reprinted with permission.*

knows which flowers to go to. The teacher helps them figure out how bees might signal that to each other. They can then act out signaling and see how well that works. It would be time after that for the teacher to tell them about the bee dance or for them to see a video about it; the children could then figure out how to act out the bee dance, and then after playing bees again, they would have have had enough experience to discuss the extent of communication bees can have. The same e-puppets can be reconfigured as ants, and they can similarly study the behavior and communication of ants.

In STEP (science through technology enhanced play; Danish et al. [2014]), first and second graders interweave taking on the roles of disciplinary scientists and taking on the behaviors of organisms and objects interacting in an environment. Technology captures their movements as they behave like the organisms and objects, and they can see their interactions on a screen, sometimes with invisible phenomena embedded in those visualizations. As scientists, they discuss the ways they might act out the roles of organisms and objects they are modeling. Simultaneously, they try out different behaviors and see what they look like. In this play-as-modeling activity, they have a chance to act out and visualize pieces of the models they are working out as they generate those models. When they finish working out the rules for their models, they follow the rules they generated and act out the whole model, simultaneously following the rules for behavior of what they are modeling and examining the animated

Figure 3. Participating with CI-SPY.

(a) Groups of learners are all pointing their devices in the same direction, each seeing an overlay that corresponds to the historical era they are exploring. (b) A screen shot showing a facsimile of a downstairs classroom from 1960. *Figure courtesy Doug Bowman, CI Spy Project, University of Vermont. Reprinted with permission.*

Figure 4. Participating with E-Puppets.

(a) A young girl holds a bee e-puppet. (b) Learners are gathered around puppet flowers and the hive (large yellow blob at the bottom of the photo). *Figure courtesy Kylie A. Peppler, Indiana University. Reprinted with permission.*

model they have created. They step back from their modeling and can replay the animation as they reflect on it as student scientists. Figure 5 shows the setup of the room. In (a), children are playing the roles of objects in a landscape that has the sun shining on it. The ice will have to melt and turn into water; this doesn't quite work the way they have decided to set up their model. After some discussion, they decide to play the roles of molecules that make up the ice. In (b), they are close together, as in ice (a solid). In (c), they are playing the roles of those same molecules as the ice is melting. In a later implementation of the display, the forces between molecules can be seen in the display, allowing learners to see when they are getting too far away from the other molecules to still be part of the liquid, the cooccurrence of different states of matter, and the weakening of connecting forces as molecules move farther away from each other and the liquid turns into water vapor.

What is known about embodied cognition suggests that engagement with more senses and in a way that affects what one feels (physically or emotionally) or can do has potential to be more engaging, more memorable, and more powerful with respect to fostering understanding and long-term engagement. The feeling of being there also makes it easier to inspire awe. The more senses involved in sensing phenomena or affects, the more affordances for fostering deep knowing (Clancey 2012). Being immersed in a virtual ocean when a large animal swims by, for example, allows sensing the effects of the motion of the water and the reactions of the plant and animal life around it. While one perhaps cannot sense the forces themselves using current technology, the movements one senses all around oneself have more affordances for conveying the impression of that movement than does watching from the outside. Riding on a blood cell as it moves through the circulatory system affords experiencing the forces inside an artery or vein, the effects of plaques, the range of other things besides blood cells that are in the arteries and veins, and more. When a class of students is acting out the motion of molecules, they can feel the molecules colliding with each other, and the forces that are too small to feel otherwise become real to them; when they do the acting in the context of technology that allows them to see bonds between molecules getting stronger and weaker, they can begin to fathom that matter is made of these tiny components. And technology is moving forward; researchers at Northwestern University, for example, are working on haptic touch screens that allow feeling texture (Mullenbach et al. 2014). Others are working on odors, and so forth.

Where might artificial intelligence come in in the design and development of such environments? Lester et al. (2013) give a taste of that. In Crystal Island, learners are on a remote island where an infectious disease has been attacking the residents. They need to figure out the identity and source of the disease so that it can be treated. As in a goal-based scenario, they have available to them the tools and resources they need to address the challenge, and there are intelligent agents within the system to provide help and advice. The intelligence in the system keeps track of learners' goals as they are addressing the challenge, inferring what they might be as they move around the island looking for clues, so that it can provide help, advice, and answers to questions. It manages the story line to make sure the relevant content is encountered and relevant skills engaged in. And it keeps track of the understanding, capabilities, and level of engagement (affect, they call it) of the learners so that help can be provided at the right levels and learners challenged appropriately.

There is also much AI to bring to bear in the under-

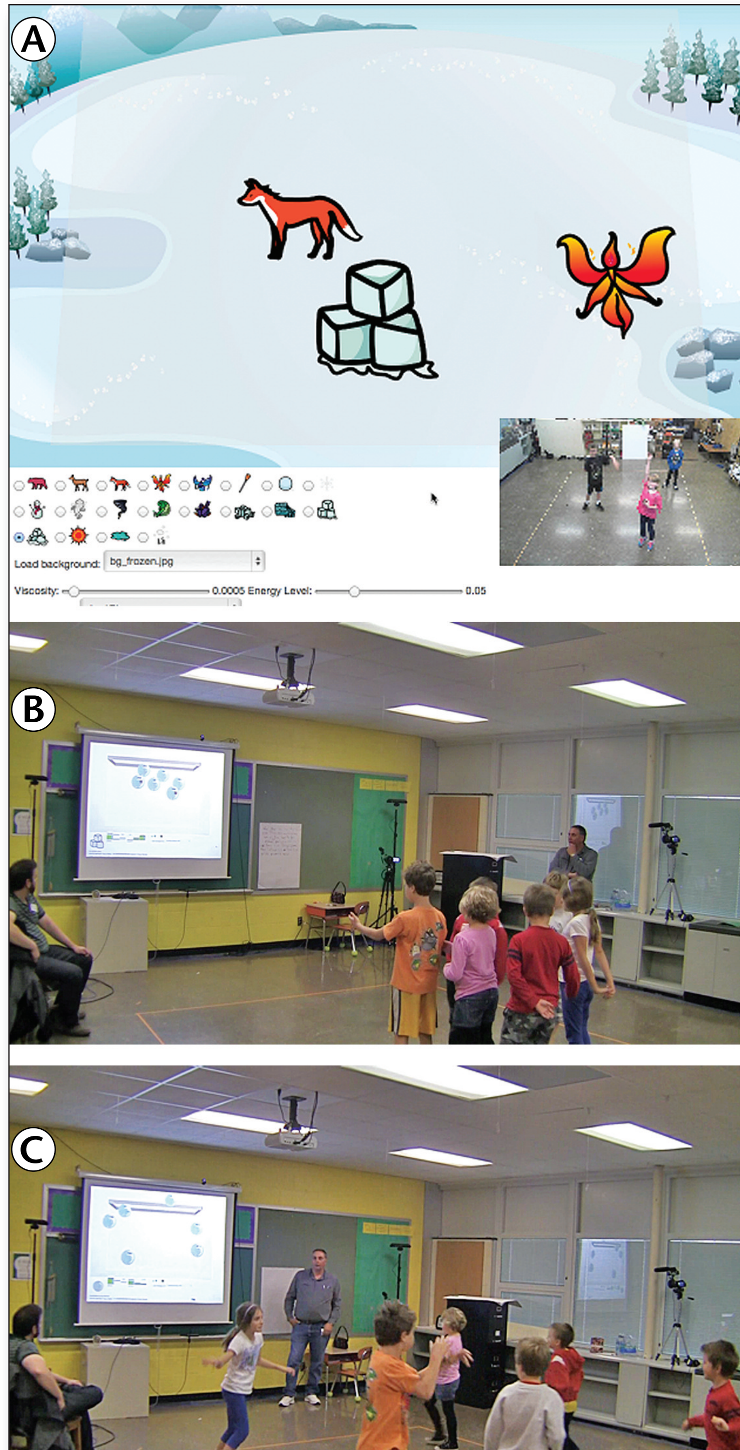

Figure 5. Participating with STEP.

(a) The insert shows children trying out at the macro level the way temperature affects the state of water. The screen shows what they see as they move around the room. In (b) and (c), they are acting out the molecular state of water. Each child acts as a molecule. In (b), they are acting as ice — huddled together close to each other but shaking in place. In (c), they are acting out the ways molecules behave in water (a liquid), moving around the room individually but staying fairly close together and organized. *Figure courtesy Joshua Adam Danish, Indiana University. Reprinted with permission.* (Danish et al. 2015).

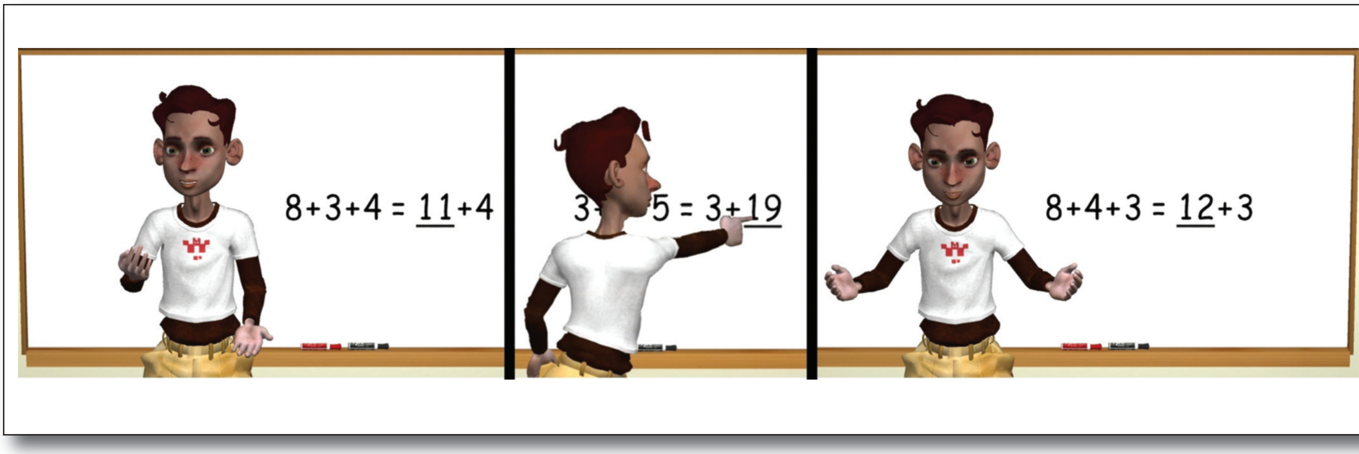

Figure 6. Frames from Mathematical Equivalence Lesson Delivered by an Instructor Avatar.

The avatar makes embodied explanatory gestures (the balance gesture in left frame), deictic gestures (pointing in middle frame), and charisma gestures (parallel outward-focused gesture in right frame). *Figure courtesy, Voicu S. Popescu, Purdue University. Reprinted with permission.*[3]

pinnings of such environments. The more things happening in an environment, the more there is to keep in sync, and AI's qualitative methods for reasoning about causality have a big role to play. As well, an intelligent controller might allow experiments, exploration, and other types of investigations in copies of an immersive environment or might allow reconfiguring a copy of the environment and allow investigation of alternative worlds, keeping track and allowing access back to those possible worlds. Using these intelligent technologies to afford engaging immersive learning experiences might be possible with existing AI technologies; I am guessing that there are new challenges that will arise that have not shown up in the scientific, business, health, and entertainment contexts many AI researchers use as prototypes for their technologies. And learning analytics might be used to help a teacher, mentor, or facilitator keep track of the achievements and challenges of groups of students. While the AI community has uncovered many approaches to keeping track of the cognitive capabilities of learners who are interacting individually with the computer, there are still open challenges in interpreting the understanding, interests, and engagement of learners and groups of learners when their interactions are with each other and continue over long periods of time that interweave having experiences with reflecting on them and making use of what is learned. Another challenge is determining the kinds of summary materials and how to create such materials that might help a teacher or facilitator remain aware of student activity and learning when learners are engaging in active and collaborative activities.

Cognitive Prosthetics and Systems of Cognitive Prosthetics in Support of Sense Making

We know that simply having experiences does not guarantee learning from them, and certainly having experiences does not guarantee learning of the content and skills that are targeted in a curriculum or by a teacher. As well, the richer the experience of the learner, and the more they can sense or manipulate, the more chance there is for learners to be overwhelmed. Learners often need help with focus, and cognitive protheses can help. Cognitive prostheses embedded into learning environments might directly help a learner focus, might more indirectly help the learner direct his or her gaze, might show invisible forces or phenomena, might suggest what to do next or provide help doing it, and might provide other aid so that learners can successfully dig deeper, focus, or notice more while they are engaged in immersive learning activities. While learners are reflecting on their experiences, cognitive prostheses might participate in sense-making discussions, help with data analysis, and/or help learners connect what they are learning to the real world they live in.

Consider, for example, the roles cognitive prostheses might play while learners are analyzing earthquakes. A cognitive prosthetic acting as a tutor could provide help as groups of learners are making sense of data they collected; one acting as an expert seismologist could tell stories at appropriate times in sense-making deliberations to help learners recognize the relationship between what they are doing and what real seismologists do. Or, as Feltovich, Coulson, and Spiro (2001) have suggested, a cognitive prosthetic could engage with a group of learners as a slightly more-sophisticated group member scaffolding their sense making while participating as a peer. This last capability would require full conversational and social capabilities. Perhaps the seismologist and peer would be represented as avatars on the computer screen and would use both engaging and explanatory gesture (as in figure 6); more research is needed to understand how to coordinate such gesture to foster learning. Perhaps, as well, a "facilitator" would join the group from time to time and offer the group the help they need to engage in productive conversation (called "accountable talk," to be discussed later).

Other cognitive prosthetics could allow technology to play a more active role in shaping the experiences of learners with the aim of making those experiences both more engaging and more productive. A cognitive prosthetic in the EcoMuve environment, for example, where there is so much going on, might highlight phenomena that are important to sense or make personalized suggestions about where to focus or what to focus on. One for learning about forces might show the invisible forces at work in what learners are observing (as, for example, in figure 7). As imagined for roomquake, expert, peer, and facilitator avatars might participate in sense-making discussions.

It will be important, of course, that cognitive prosthetics add to learning experiences in engaging ways; much research and practical investigation is needed, for example, to understand how to embed conversational agents without getting in the way of the engaging experience. Immersive and role-playing environments might also have a set of narrowly-focused tutoring systems that help learners understand concepts they are having trouble with or help them gain experience and capabilities with necessary skills or practices. The conception here is quite different from the current conception of intelligent tutoring systems. Current systems act as experts to teach learners large pieces of a discipline; the suggestion here is that their use would be more piecemeal, helping learners address learning goals as those goals arise. Such resources are quite different, too, from the kinds of systems that provide short lectures (for example, Khan Academy)[4] or answer questions (for example, Inquire Biology [Chaudhri et al. 2013]), as they would be designed to take into account what the learner already knows and is capable of and help them connect with, refine, and expand what they already know.

Scenarios for learning might also include embedded modeling (for example, NetLogo, Wilensky and Jacobson, in press)[5] and simulation (for example, Phet)[6] tools that allow learners to model and explore their ideas and explanations and see what happens under several conditions in situations that are not as complex as a dynamically changing ecosystem. While simulation tools can help learners find out what happens in different situations, modeling tools have the added benefit of requiring from learners that they consider what all the components are of the phenomena or scenarios they are modeling and how those components are connected to and influence each other to generate the behaviors they observe. Learners often need help in engaging in such modeling and deciding which possibilities to try out as they are running simulations.

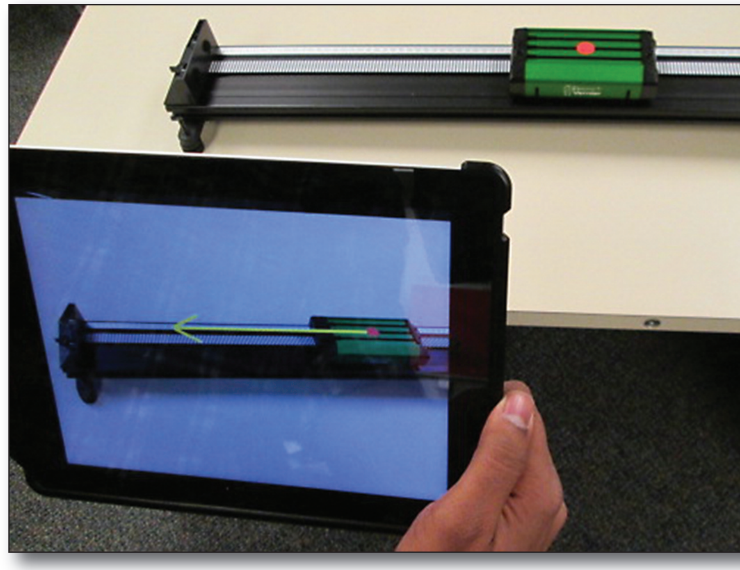

Figure 7. An Augmented Reality Application Tracks Objects of Interest Using Colored Markers.

The theoretical context of the experiment is programmed into the application, which can then overlay information such as velocity or forces on the view of the real-world experiment. *Figure courtesy David E. Johnson, University of Utah. Reprinted with permission.*

Cognitive Prostheses and Representations for Fostering Sense Making and Expression

Two areas of particular importance for cognitive prostheses that offer interesting challenges for AI researchers are guiding sense making and facilitating expression. Sense making is the reflective activity learners do while in the midst of learning activities and afterwards. (Think here about Schön's "reflection-in-action" and "reflection-on-action" [Schön 1983].) Facilitating sense making means helping learners grapple with the ins and outs of interpreting what they are or have just experienced in ways that will lead toward increased understanding or capability. It includes, among other things, identifying what is happening or happened and explaining why it is happening or happened, identifying effects of actions and what explains those effects, figuring out what one doesn't understand, and identifying what to do next time — the things cognitive science includes under the labels interpretation, reflection, and self-explanation.

The sociocognitive literature points out how messy sense making is in the real world. The messiness is partly cognitive, as sense making can involve a huge variety of considerations as learners are thinking about options and rightly or mistakenly discarding some, accessing (or not) prior knowledge that can be brought to bear, expressing themselves so others can understand, moving from opinion to informed justification, and iterating toward precision and precise language. But much of the messiness is also social and cultural and includes such things as identifying what others in a conversation know and don't know, making room (or not) for others to speak, and the consequences of not feeling that one's voice is welcome or not having a way of making one's voice heard. The richness of experience while collaborating around role play and immersive learning experiences affords rich sense making but means that our intelligent technologies will have less control over exactly what is expressed than when learners are having less rich learning experiences. There are AI challenges both in understanding and keeping track of ongoing sense making and in choosing ways of helping learners reflect productively. This is made particularly difficult by two tensions — (1) between guiding learners toward making sense and ceding to them the control they need over their reflection and discussion to remain engaged and feel heard (citations), and (2) the need to not interrupt engaging experience but to somehow make sure attention is focused well. Also, making choices about highlighting, facilitation, conversational, and mentoring roles in these circumstances requires more power than is present in current language processing and conversational agents.

Teachers, too, have a hard time facilitating discussions in these situations, and there are two complementary approaches to helping teachers learn these skills — (1) providing guidance in teacher materials about specific issues that will arise, how to recognize those, and suggestions about how to use those to move a conversation forward, and (2) helping teachers learn to facilitate what is called accountable talk (Michaels, O'Conner, and Resnick 2008). In facilitating accountable talk, teachers insist that students ask each other for evidence of their statements. The teacher models both sides of this for students, and the students soon take over playing facilitation roles for each other. Talk becomes rigorous and focused on important concepts. As with other strong and weak approaches within AI, the two are necessarily complementary. Good sense-making facilitation will both need to help learners participate in rigorous disciplinary expression and be done in a way that leads learners toward justifying ideas and participating well in collaborative sense-making conversations. Ultimately, giving intelligent conversational agents these capabilities will require nuancing our intelligent language understanding and generation technologies with what is being learned in the collaborative learning and sociocognitive research communities about managing agency and positioning among groups of learners and facilitators and adapting conversational moves for the cultural expectations of different groups of learners (Clarke, Resnick, and Rosé, in press).

Right now, several projects are carrying out research moving in those directions. Carolyn Rosé (Adamson et al. 2014) is working on automating the facilitation moves in accountable talk so that small groups of learners will have productive discussions even when a teacher is not available, as shown in figure 8. Figure 6 (earlier) shows gestures an avatar might make to help learners feel comfortable as they make sense of difficult content while at the same time using content-related gestures to help them move forward with their understanding. Several researchers are just beginning to explore the power of crowdsourcing to help learners make sense; it still is not exactly clear yet what intelligent roles technology might play in managing sense making in those situations. Others are working on how to represent what learners have experienced so that learners have something concrete available to guide their discussions. Tom Moher is exploring that issue in the context of bringing the field into the classroom. Noel Enyedy and Joshua Danish are using STEP as a vehicle for exploring how to help learners revisit their enactments of bee or molecule behavior. More research is needed to understand exactly the qualities such representations need to have so that learners can make sense with them.

Of course, sense making cannot happen without expression — representing one's ideas in ways that allow them to be examined and understood by oneself and others and refined transitively by oneself and others. Expressive technologies provide tools to learners that they use to express their understanding, ideas, or intentions. When learners have a chance to express themselves concretely, there is also a chance for them and others to treat what was expressed as an object for examination, discussion, and refinement (Scardamalia and Bereiter 2006). When a point is expressed concretely (using some medium) and not simply spoken, it allows better refinement and debugging of understanding, by an individual learner or by collaborators. And when what is expressed is kept around and linked to refinements, opportunity is afforded for examining how one's or a collective's understanding has evolved over time, for remixing and building upon the expressions/ideas of others, for noticing and connecting ideas across time and across topics and conversations, and more.

One well-known expressive technology that teachers and young people use a lot is Scratch

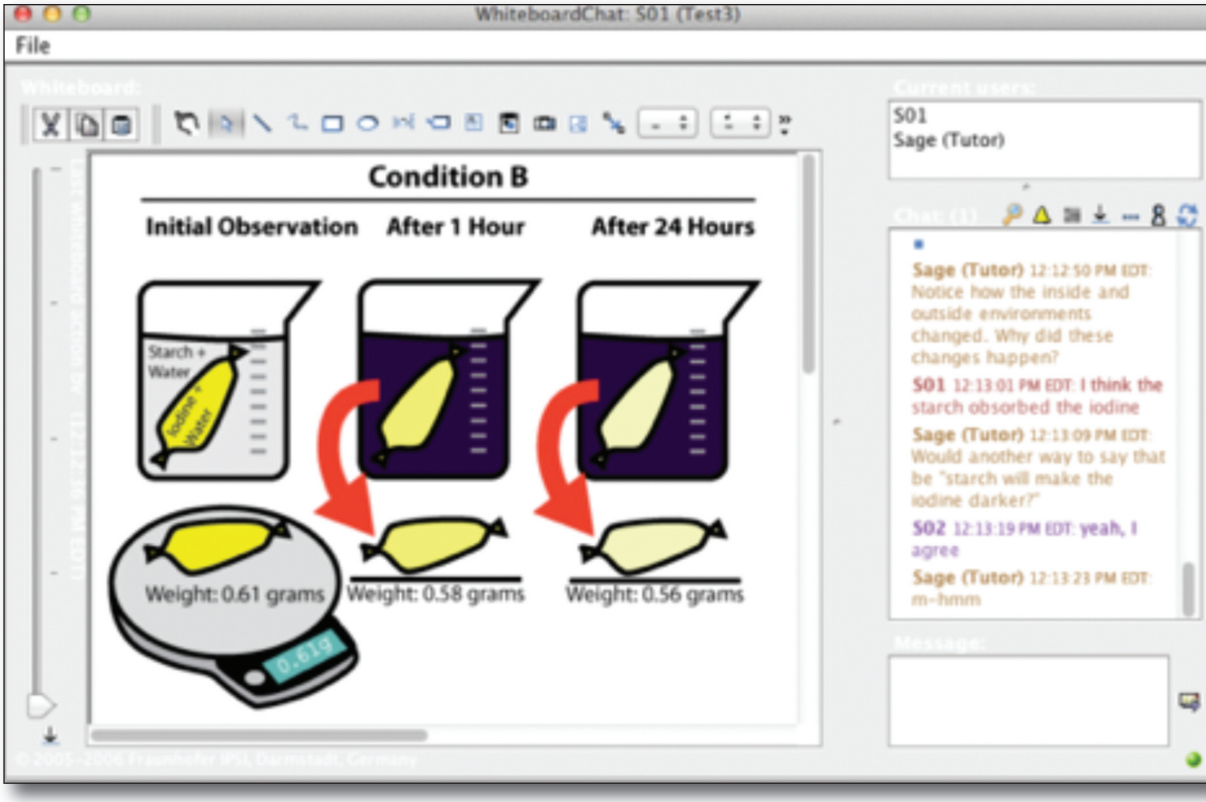

Figure 8. Exploring Diffusion Through Cell Models.

This screen shot illustrates students from ninth grade biology working through a lab in which they explore the concept of diffusion through cell models. Sage, the conversational agent, uses a Revoicing move to engage the students in idea improvement on S01's original statement about the effect of iodine when it is absorbed by starch. From Adamson et al. 2014. Used with permission.

(Resnick et al. 2009),[7] a computational system for expression that provides easy ways in to creating animations. When teachers have students develop animations using Scratch to put into reports, they grapple with making the animations match what they mean; the process of doing that helps them, as modeling helps scientists and engineers, make their understanding more refined. Scratch is also used at home and in libraries by a large community of learners around the world (over a million). They design and build animations — sometimes as art, sometimes as explanation, sometimes as functional apps for someone else to use — and post them for the rest of the Scratch community to see. Scratchers (as community members are called) reuse, refine, and remix the creations of others for their own purposes. In some cases, Scratchers have created online companies with others who have different expertise to create animations that others might want on their web pages or as parts of their creations. Scratchers express themselves through their animations, share their animations and discuss their intentions and how they went about building them with others, watch and sometimes help as others borrow and refine their expressions, help each other get to more efficient implementations, and so forth, and eventually some of them learn a lot about programming and some about the particular disciplines they are working in (for example, music composition) and some both.

It is not always easy to express oneself, nor is it always easy to critique what someone else has added to a conversation. Those who created Scratch designed the software to provide an infrastructure for expression, sharing, and discussion; the community around Scratch provides the help participants need to become better at expression and animation. But another way to address this set of challenges is to embed that help in the computer system. Conversational help may be provided, representational help might be provided, or access to those who can help might be provided.

One particular expressive challenge for learners, especially young learners, is moving from commonsense understanding of phenomena to scientifically grounded understanding, especially when there is so much that is invisible in natural phenomena (Frederiksen and White 1992; Gravel, Scheuer, and Brizuela 2013; Schwarz et al. 2009). In their SiMSAM project (Wilkerson-Jerde, Gravel, and Macrander 2013), Michelle Wilkerson-Jerde and Brian Gravel

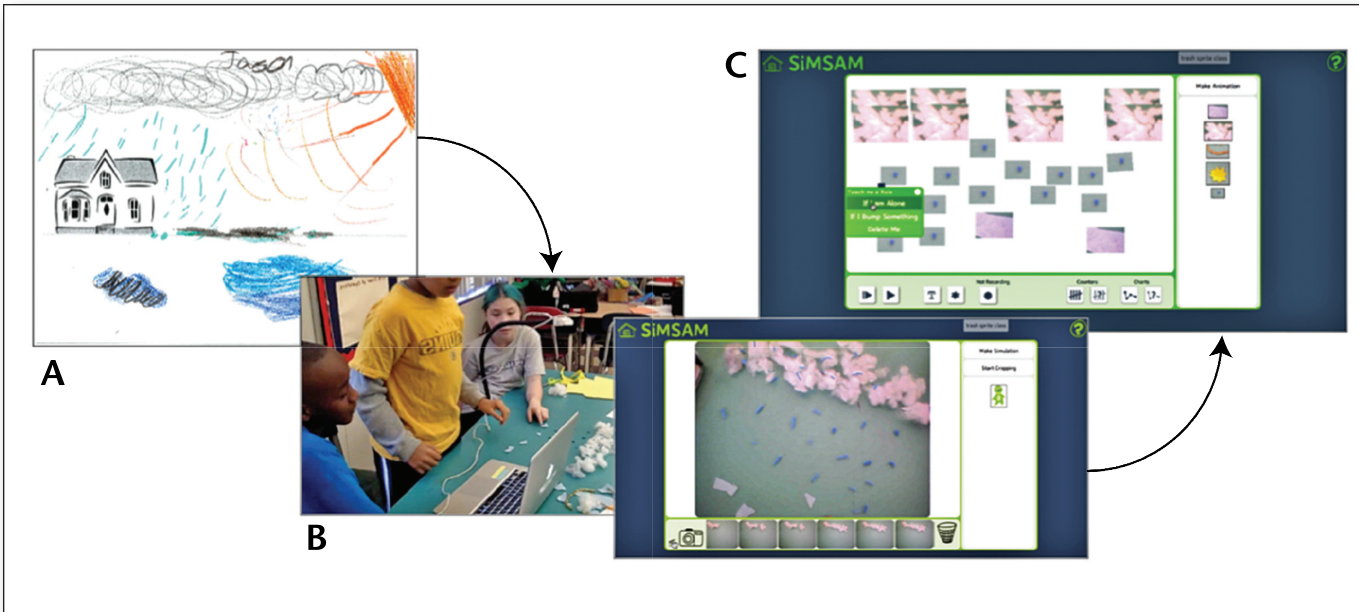

Figure 9. SimSAM.

After creating grounded representations of scientific processes (in this case, evaporation) (a), SiMSAM allows learners to generate stop-motion animations using drawings or craft materials (b), which then serve as a basis to construct testable computer simulations (c). *Figure courtesy Michelle H. Wilkerson-Jerde, Tufts University. Reprinted with permission.*

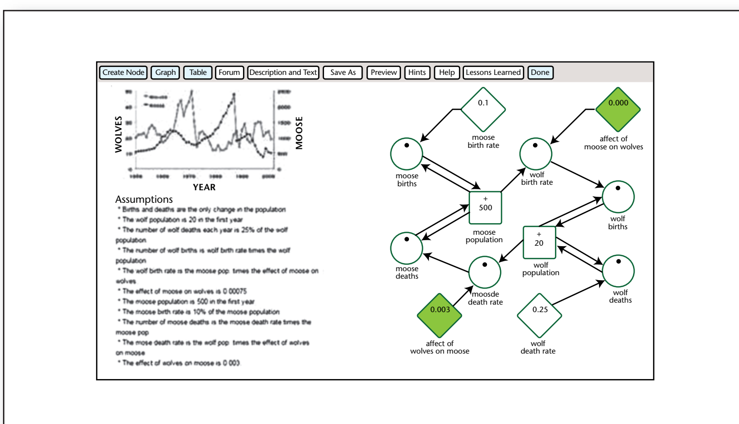

Figure 10. A Predator-Prey Ecosystem Model Expressed in the Dragoon System.

Figure courtesy, Kurt VanLehn, Arizona State University. Reprinted with permission.

have created tools to help middle schoolers move from seeing the world and expressing what they are understanding in everyday informal ways to disciplinary expression and understanding. In the process of making sense of scientific phenomena, middleschoolers begin by creating (through drawing, taking pictures of, or reproducing with craft materials) grounded-in-the-real-world representations of processes they are observing and imagining that they then animate with stop-action animation. They then crop objects from their animation to populate a modeling environment and define rules and interactions for those objects to create models of phenomena they are learning about using those representations. The system animates the models they create (runs them as simulations), affording sense making that brings together the intuitions they used as they created their stop-action animations and models with the output of those models. In this way, they aim toward helping learners ground their scientific understanding in what is familiar to them, come to recognize the relationship between scientific models and the phenomena they are modeling, and leverage familiar experience as they engage in scientific sense making (Wilkerson-Jerde, Gravel, and Macrander 2014). The teacher guides whole-class discussion that helps small groups go beyond what they can make sense of on their own, though one could imagine cognitive prosthetics that help learners through some of the challenges.

Van Lehn's Dragoon system (figure 10)[8] addresses challenges of facilitating expression by combining representational help with access to others. In the context of learning environmental science, learners are asked to create models for others to learn from. Others then examine and run those models to help them understand some new concept or process. As those others have questions, they turn to their peer who created the model, and together the two learners debug the model that was created, the model creator providing explanations and descriptions of

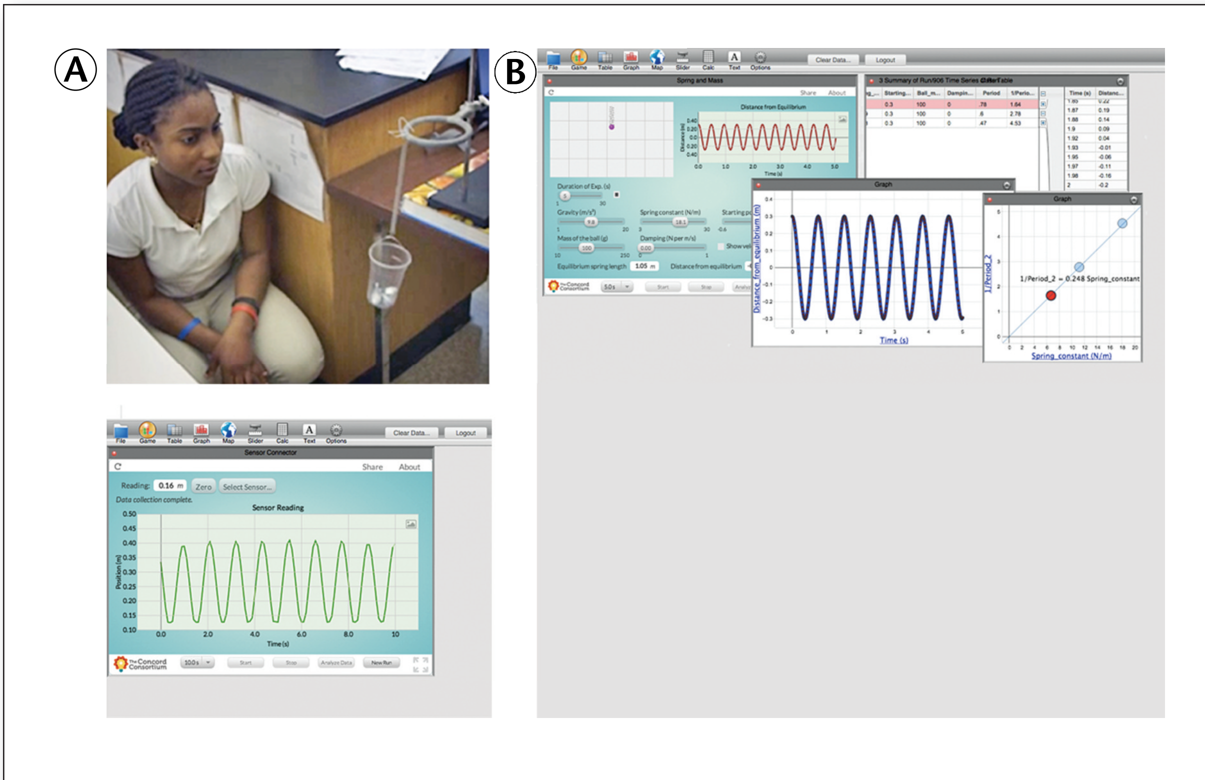

Figure 11. Scientific Inquiry with InquirySpace.

Students collect data from a physical system using probes and sensors (a), then compare to a wider range of data collected from a simulation. Students analyze and compare the data within the Common Online Data Analysis Platform (CODAP) (b) to discover and explore patterns and relationships between variables. This integration enables students to move back and forth between the physical system and comparisons with a simulation. In the process, they exercise parameter-space reasoning, the process of identifying relationships within and across hierarchical data from multiple experimental runs. *Figure courtesy Chad Dorsey, The Concord Consortium. Reprinted with permission.*

what he or she intended, and the one using it asking questions and pointing out deficiencies, and together, making sense of how to make the model consistent with the concepts or phenomena it is modeling. The software provides a language for model creation, an infrastructure for trying out and running models, and communication infrastructure for making sense of, debugging, and refining the model.

In Kevin Ashley's, Diane Litman's, and Chris Schunn's ArgumentPeer project (Nguyen, Xiong, and Litman 2014; Falakmasir, Ashley, and Schunn 2013), the computer shares responsibility with peers and teacher for helping learners across disciplines (law, science) construct well-warranted arguments. The software provides infrastructure for structuring an argument and can automatically provide feedback about the argument's structure and what might be missing, and peers critique the content of arguments in progress. When the argument structure looks right, learners turn it into prose. The system knows language conventions of arguments and can thus do some of the critiquing of the expression of the argument in natural language; peers, teaching assistants, and teacher critique the nuances of expression. Such a setup could be used for aiding with expression of explanations and other well-structured genres of expression as well.

Discipline-Specific Platforms

Earlier in this article, I urged AI and education researchers to think in terms of integrating what they are doing into larger wholes that support having the kinds of engaging experiences that will encourage motivation to continue to engage over the long periods of time in productive learning activities. Such long-term engagement is helped when it is easy to move fluidly between activities. Many in the learning technology community talk about the need for interoperable learning technologies so that technologies with different functions can exist together on platforms. But in addition to technical interoperability, we need to be thinking about how the functions integrated on a platform can share data and how platforms can support the kinds of help learners need in knowing what to do next. Rather than thinking simply about technical interoperability, I want to urge researchers and developers to aim toward the kinds of integrations that support learning in targeted disciplines and domains and that are appropriate to particular populations of learners; for example, an integration might include tools needed to do history inquiry at the middle-school level, and a different integration would include tools for elementary school history; a different integration would be appropriate to middle-school project-based science, and some variation of that would be appropriate for middle-school engineering; an integration of tools with similar functions but that easily supports more sophisticated reasoning would be aimed at high-school biology and a different one at chemistry and a different one at environmental science. And perhaps a completely different set of tools is needed to help youth learn prosocial behaviors or healthy living practices. We need to make sure these integrations support having experiences that afford learning as well as reflective practices needed for sense making and putting understanding into action. InquirySpace (inquiry space.concord.org; figure 11), from the Concord Consortium is an early example of one of these integrations. By fusing several software elements, it unites and streamlines the process of scientific experimentation, data collection, and data analysis, fostering extended scientific inquiry.

An Aside: Support for Authoring Learning Experiences

A huge issue with respect to technologies for fostering and assessing learning, as for the wide variety of intelligent systems that require depth of understanding and nuanced interpretation and decision making to do their jobs, is building the full range of systems that will make it easy for teachers to integrate active learning activities into their classrooms and for learners of all ages to engage in learning activities in the areas they are interested in (inside or outside the classroom). For this, a full range of authoring systems are needed — those that allow developers to specialize immersive environments and cognitive prostheses to particular content and skills and those that help developers integrate components together to create coherent wholes. Designing these well will require capturing the nuances that need to be considered in helping learners learn and helping designers design for these nuances — no easy task. This is not a challenge for the present. However, when we know more about how to integrate pieces to create intelligent immersive and role-playing environments, impact will require that such authoring systems be developed.

Final Words

I imagine classrooms of the future as places to achieve challenges together rather than as places where teachers teach and students listen and do problem sets. The challenges could take the form of design challenges, local or community problems that need solving, fantasy problems, and big wonderment questions. Groups of learners, who may be colocated or not, will work together on challenges. Small groups will engage in activities and talk that help them imagine and figure out; whole-class discussions will help learners extract from their experiences both the knowledge and skills that can be learned. Activities will be varied; long lectures will be rare and short ones as needed; reading will be accompanied by the kinds of help learners need to understand; peers will share responsibility with the teacher and with technology for fostering understanding. Learning will feel purposeful to learners, as they will be learning in the context of achieving goals they have bought into.

Such education will ready students to live in the world around them, as it will engage them in solving the kinds of problems and achieving the kinds of goals that will come their way in life. Opportunities for learning will be pulled from the experiences learners are having in and out of school. Assessment will be purposeful also — not simply for purposes of accountability but rather for purposes of knowing how to best provide the right kinds of help to learners so that they can be successful. Learning technologies will be used for a whole variety of purposes and integrated into learning activities in purposeful ways, as suggested above and in ways that cannot yet be imagined.

This vision does not rule out a place for traditional intelligent learning technologies, for example, intelligent tutoring systems and other systems that provide and guide practice of skills. It does suggest, however, that rather than thinking primarily about computers as teaching machines that focus on individual learners, we need to think about the roles technology might play in the environments where people learn and how to distribute responsibility for fostering and assessing learning across learners themselves, peers, mentors, parents, teachers, technology, and the rest of the agents in learners' lives. What might technology do to foster self-reflection or self-explanation? How can it be used to help a collective move forward in their understanding and capabilities? When and how should it provide hints or coaching or modeling? How can it make the activities of learning more productive or easier to carry out? How can it be used to entice learners so that they will engage over long enough periods for deep understanding? Perhaps technology can help facilitators or teachers or mentors or parents become better at helping others learn?

Addressing this set of challenges means going beyond the idea that a single researcher or discipline can create methods and tools for fostering learning and assessing learners. Addressing these challenges requires the combined efforts of (at least) those who can imagine new technologies and the roles they might play in fostering learning, those who are expert at particulars of how people learn, those who understand the big picture of learning and living as it happens well or not as well in the world, those who are expert technology inventors and developers, those who are expert at experience design, and those who know how to put themselves inside the heads of targeted learner populations.

This requires more of a collaborative work style than is traditionally valued in academia but has potential to result in discoveries in Pasteur's Quadrant (Stokes 1997) and beyond — discoveries that explain learning as it happens (or fails to happen) in all its messiness, and products and new approaches that foster learning more effectively than anybody knows how to do now and allow assessment of the kinds that can lead to providing help that individuals and groups need as they are developing capabilities, expertise, and self-awareness. More artificial intelligence researchers working along with those who understand learning more broadly and who have expertise in designing for learners (as they are, warts and all) is key to achieving those goals.

The future for intelligent learning technologies and cognitive prostheses, then, lies in (1) addressing these issues in the context of immersive and expressive technologies for learning and pedagogies those afford and (2) working in interdisciplinary teams to integrate what AI can provide into more sophisticated and learner-oriented learning environments than any of us alone can imagine or build.

Notes

1. See www.nsf.gov/funding/pgm_summ.jsp?pims_id=504984; originally named Cyberlearning: Transforming Education (www.nsf.gov/funding/pgm_summ.jsp?pims_id=503581).

2. See www.corestandards.org/read-the-standards/ (math and language arts), www.nextgenscience.org/ (science), and www.socialstudies.org/c3 (social studies))

3. www.cs.purdue.edu/cgvlab/avatar.

4. www.khanacademy.org.

5. ccl.northwestern.edu/netlogo.

6. phet.colorado.edu.

7. scratch.mit.edu.

8. dragoon.asu.edu.

References

Adamson, D.; Dyke, G.; Jang, H. J.; Rosé, C. P. 2014. Towards an Agile Approach to Adapting Dynamic Collaboration Support to Student Needs, *International Journal of AI in Education* 24(1): 91–121. dx.doi.org/10.1007/s40593-013-0012-6

Anderson, J. R. ed. 1981. *Cognitive Skills and Their Acquisition*. Hillsdale, NJ: Erlbaum.

Bandura, A. 1986. *Social Foundations of Thought and Action: A Social Cognitive Theory*. Englewood Cliffs, NJ: Prentice Hall.

Barron, B. J.; Schwartz, D. L.; Vye, N. J.; Moore, A.; Petrosino, A.; Zech, L.; and Bransford, J. D. 1998. Doing with Understanding: Lessons from Research on Problem and Project-Based Learning. *Journal of the Learning Sciences* 7(3–3): 271–265.

Barsalou, L. W.; Niedenthal, P. M.; Barbey, A. K; and Ruppert, J. A. 2003. Social Embodiment. *Psychology of Learning and Motivation* 43(1): 43–92. dx.doi.org/10.1016/S0079-7421(03)01011-9

Bell, B.; Bareiss, R.; and Beckwith, R. 1994. Sickle Cell Counselor: A Prototype Goal-Based Scenario for Instruction in a Museum Environment. *Journal of the Learning Sciences* (3(4): 347–386. dx.doi.org/10.1207/s15327809jls0304_3

Bell, P.; Davis, E.; and Linn, M. C. 1995. The Knowledge Integration Environment: Theory and Design. In *Proceedings of the Computer Support for Collaborative Learning Conference*. Mahwah, NJ: Lawrence Erlbaum Associates, Inc. dx.doi.org/10.3115/222020.222043

Bransford, J. D.; Brown, A. L.; and Cocking, R. R., eds. 1999. How People Learn: Brain, Mind, Experience, and School. Washington, DC: National Academy Press.

Bredeweg, B.; Liem, J.; Beck, W.; Linnebank, F.; Gracia, J.; Lozano, E.; Wifsner, M.; Buhling, R.; Salles, P.; Noble, R.; Zitek, A.; Borisova, P.; and Mioduser, D. 2013. DynaLearn — An Intellient Learning Environment for Learning Conceptual Knowledge. *AI Magazine* 34(4): 46–65.

Brown, A. L., and Campione, J. C. 1994. Guided Discovery in a Community of Learners. In *Classroom Lessons: Integrating Cognitive Theory and Classroom Practice,* ed. K. McGilly. Cambridge, MA: The MIT Press.

Chaudhri, V. K.; Cheng, B. H.; Overholtzer, A.; Roschelle, J.; Spaulding, A.; Clark, P.; Greaves, M.; and Gunning, D. 2013. Inquire Biology: A Textbook that Answers Questions. *AI Magazine* 34(3): 55-72.

Clancey, W. J. 2012. Working on Mars: Voyages of Scientific Discovery with the Mars Exploration Rovers. Cambridge, MA: The MIT Press.

Clark, A. 1997. *Being There: Putting Brain, Body, and World Together Again*. Cambridge MA: The MIT Press.

Clarke, S.; Resnick, L.; and Rosé, C. P. 2016. Academic Dialogue, Teaching, and Learning. In the *Handbook of Educational Psychology on Classroom Teaching*. New York: Routledge.

Cognition and Technology Group at Vanderbilt. 2000. Adventures in Anchored Instruction: Lessons from Beyond the Ivory Tower. In *Advances in Instructional Psychology, Educational Design, and Cognitive Science, Volume 5,* ed. R, Glaser. Mawah, NJ: Erlbaum

Conati, C., and Kardan, S. 2013. Student Modeling: Supporting Personalized Instruction, from Problem Solving to Exploratory Open-Ended Activities. *AI Magazine* 34(3): 13–26.

Damasio, A. 1999. The Feeling of What Happens: Body and Emotion in the Making of Consciousness. New York: Houghton Mifflin Harcourt.

Danish, J.; Enyedy, N.; Saleh, A.; Andrade-Lotero, A.; and Lee, C. 2015. Science Through Technology Enhanced Play: Using Play and Embodiment to Promote Reflection About States of Matter. Paper presented at the Annual Meeting of the American Educational Research Association, April 16, Chicago, IL.

Dewey, John. 1938. *Experience and Education.* New York: Macmillan.

Ericsson, K. A.; Krampe, R. T.; and Tesch-Romer, C. 1993. The Role of Deliberate Practice in the Acquisition of Expert Performance. *Psychological Review* 100(3): 363–406. dx.doi.org/10.1037/0033-295X.100.3.363

Falakmasir, M. H.; Ashley, K.D.; and Schunn, C. D. 2013. Using Argument Diagramming to Improve Peer Grading of Writing Assignments. In *Proceedings of the Workshops at the 16th International Conference on Artificial Intelligence in Education.* Aachen, Germany: RWTH Aachen University.

Feltovich, P. J.; Coulson, R. L.; and Spiro, R. J. 2001. Learners' (Mis)Understanding of Important and Difficult Concepts: A Challenge to Smart Machines in Education. In *Smart Machines in Education: The Coming Revolution in Educational Technology,* ed. K. D. Forbus and P. J. Feltovich. Cambridge, MA: The MIT Press.

Frederiksen, J. R., and White, B. Y. 1992. Mental Models and Understanding: A Problem for Science Education. In *New Directions in Educational Technology,* ed. E. Scanlon and T. O'Shea, 211–226. Berlin Heidelberg: Springer-Verlag. dx.doi.org/10.1007/978-3-642-77750-9_18

Gravel, B. E.; Scheuer, N.; and Brizuela, B. M. 2013. Using Representations to Reason About Air and Particles. In *Show Me What You Know: Exploring Representations Across STEM Disciplines,* ed. B. M. Brizuela and B. E. Gravel, 163–182. New York: Teachers College Press.

Grotzer, T.; Kamarainen, A.; Tutwiler, M. S.; Metcalf, S.; and Dede, C. 2013. Learning to Reason About Ecosystems Dynamics over Time: The Challenges of an Event-Based Causal Focus. *Bioscience* 63(4): 288–296. dx.doi.org/10.1525/bio.2013.63.4.9

Kamarainen, A. M.; Metcalf, S.; Grotzer, T.; Browne, A.; Mazzuca, D.; Tutwiler, M. S.; and Dede, C. 2013. EcoMOBILE: Integrating Augmented Reality and Probleware with

Environmental Education Field Trips. *Computers, and Education* 68 (October): 545–556. dx.doi.org/10.1016/j.compedu.2013.02.018

Koedinger, K. R.; Brunskill, E.; Ryan S.; Baker, J.; McLaughlin, E. A.; and Stamper, J. 2013. New Potentials for Data-Driven Intelligent Tutoring System Development and Optimization. *AI Magazine* 34(3): 27–41.

Kohl, Herbert R. 1995. *I Won't Learn from You: And Other Thoughts on Creative Maladjustment*. New York: New Press.

Kolodner, J. L. 1997. Educational Implications of Analogy: A View from Case-Based Reasoning. *American Psychologist* 52(1): 57–66.

Kolodner, J. L.; Camp, P. J.; Crismond D.; Fasse, B.; Gray, J.; Holbrook, J.; Puntambekar, S.; Ryan, M. 2003. Problem-Based Learning Meets Case-Based Reasoning in the Middle-School Science Classroom: Putting Learning by Design into Practice. *Journal of the Learning Sciences* 12(4): 495–548. dx.doi.org/10.1207/S15327809 JLS1204_2

Lakoff, G., and Johnson, M. 1999. *Philosophy in the Flesh: The Embodied Mind and Its Challenge to Western Thought*. New York: Basic Books.

Lester, J.; Ha, E. Y.; Lee, S. Y.; Mott, B. W.; Rose, J. P.; and Sabourin, J. L. 2013. Serious Games Get Smart: Intelligent Game-Based Learning Environments. *AI Magazine* 34(4): 31–45.

Lui , M., and Slotta, J. D. 2013. Immersive Simulations for Smart Classrooms: Exploring Evolutionary Concepts in Secondary Science. *Technology, Pedagogy, and Education* 23(1): 57–80. dx.doi.org/10.1080 /1475939X.2013.838452

Michaels, S.; O'Connor, C.; and Resnick, L. 2008. Reasoned Participation: Accountable Talk in the Classroom and in Civic Life. *Studies in Philosophy and Education* 27(4): 283–297. dx.doi.org/10.1007/s11217-007-9071-1

Moher, T. 2006. Embedded Phenomena: Supporting Science Learning with Classroom-sized Distributed Simulations. In *Proceedings ACM Conference on Human Factors in Computing Systems,* 691–700. New York: Association for Computing Machinery.

Moher, T. 2008. Learning and Participation in a Persistent Whole-Classroom Seismology Simulation. *Proceedings International Conference of the Learning Sciences* (ICLS 2008), 82–90. Seattle, WA: International Society of the Learning Sciences. dx.doi.org/10.1145/1124772.1124875

Mullenbach, J.; Shultz, C.; Colgate, J. E.; and Piper, A. M. 2014. Exploring Affective Communication Through Variable-Friction Surface Haptics. In *Proceedings of ACM Conference on Human Factors in Computing Systems 2014,* 3963–3972. New York: Association for Computing Machinery. dx.doi.org/10.1145/2556288.2557343

Nguyen, H.; Xiong, W.; and Litman, D. 2014. Classroom Evaluation of a Scaffolding Intervention for Improving Peer Review Localization. In *Intelligent Tutoring Systems*, Lecture Notes in Computer Science Volume 8474, 272–282. Berlin: Springer.

Peppler, K., and Danish, J. 2013. E-Textiles for Educators: Participatory Simulations with e-Puppetry. In *Textile Messages: Dispatches from the World of e-Textiles and Education*, 133–141. New York: Peter Lang Publishing.

Peppler, K.; Danish, J.; Zaitlen, B.; Glosson, D.; Jacobs, A.; and Phelps, D. 2010. BeeSim: Leveraging Wearable Computers in Participatory Simulations with Young Children. Paper presented at the 9th International Conference on Interaction Design and Children, Barcelona, Spain, 9–12 June. dx.doi.org/10.1145/1810543.1810582

Resnick, M.; Maloney, J.; Monroy-Hernández, A.; Rusk, N.; Eastmond, E.; Brennan, K.; Millner, A.; Rosenbaum, E.; Silver , J.; Silverman, B.; and Kafai, Y. 2009. Scratch: Programming for All. *Communications of the ACM* 52(11): 60–67. dx.doi.org/10.1145/1592761.1592779

Rogoff, B. 1990. *Apprenticeship in Thinking: Cognitive Development in Social Context*. New York: Oxford University Press.

Rus, V.; D'Mello, S.; Hun, Z.; and Graesser, A. C. 2013. Recent Advances in Conversational Intelligent Tutoring Systems. *AI Magazine* 34(3): 42–54.

Sawyer, K. R., ed. 2006. *The Cambridge Handbook of the Learning Sciences*. Cambridge, UK: Cambridge University Press.

Scardamalia, M., and Bereiter, C. 2006. Knowledge Building: Theory, Pedagogy, and Technology. In *The Cambridge Handbook of the Learning Sciences,* ed. K. R. Sawyer. Cambridge, UK: Cambridge University Press.

Schank, R. C. 1982. *Dynamic Memory.* New York: Cambridge University Press.

Schank, R. C.; Fano, A.; Bell, B.; and Jona, M. 1994. The Design of Goal-Based Scenarios. *Journal of the Learning Sciences* 3(4): 305–346. dx.doi.org/10.1207/s15327809jls0304_2

Schön, Donald A. 1983. *The Reflective Practitioner — How Professionals Think in Action*. New York: Basic Books.

Schwarz, C. V.; Reiser, B. J.; Davis, E. A.; Kenyon, L.; Acher, A.; Fortus, D.; et al. 2009. Developing a Learning Progression for Scientific Modeling: Making Scientific Modeling Accessible and Meaningful for Learners. *Journal of Research in Science Teaching* 46(6): 632–654. dx.doi.org/10.1002/tea.20311

Sfard, A. 1998. On Two Metaphors for Learning and the Dangers of Choosing Just One. *Educational Researcher* 27(2): 4–13. dx.doi.org/10.3102/0013189X027002004

Singh, G.; Bowman, D.; Hicks, D.; Cline, D.; Ogle, J.; Johnson, A.; Zlokas, R.; and Ragan, E. 2014. CI-Spy: Using Mobile-AR for Scaffolding Historical Inquiry Learning. In *Proceedings of 2014 IEEE International Symposium on Mixed and Augmented Reality* (ISMAR), 73-74. Piscataway, NJ: Institute for Electrical and Electronics Engineers. dx.doi.org/10.1109/ISMAR-AMH.2014.6935444

Stokes, D. E. 1997. *Pasteur's Quadrant — Basic Science and Technological Innovation*. Washington, DC: Brookings Institution Press.

Swartout, W.; Artstein, R.; Forbell, E.; Foutz, S.; Lane, H. C.; Lange, B.; Morie, J.; Noren, D.; Rizzo, S.; and Traum, D. 2013. Virtual Humans for Learning. *AI Magazine* 34(4): 13–30.

Vygotsky, L. S. 1978. Mind in Society: The Development of Higher Psychological Processes. Cambridge, MA: Harvard University Press.

Wilensky, U., and Jacobson, M. 2014. Complex Systems in the Learning Sciences. In *The Cambridge Handbook of the Learning Sciences,* 2nd Edition. Cambridge, UK: Cambridge University Press. dx.doi.org/10.1017/cbo9781139519526.020

Wilkerson-Jerde, M.; Gravel, B.; and Macrander, C. 2013. SiMSAM: An Integrated Toolkit to Bridge Student, Scientific, and Mathematical Ideas Using Computational Media. Paper presented at the 10th International Conference of Computer Supported Collaborative Learning, Madison, WI, USA. June 16–19.

Wilkerson-Jerde, M. H.; Gravel, B. E.; and Macrander, C. A. 2014. Exploring Shifts in Middle School Learners' Modeling Activity While Generating Drawings, Animations, and Computational Simulations of Molecular Diffusion. *Journal of Science Education and Technology* 24(2–3): 396–415. dx.doi.org/10.1007/s10956-014-9497-5

Woolf, B. P.; Lane, H. C.; Chaudhri, V. K.; and Kolodner, J. L. 2013. AI Grand Challenges for Education. *AI Magazine* 34(4): 68–84.

Janet L. Kolodner is chief learning scientist at the Concord Consortium and Regents' Professor Emerita in Computing and Cognitive Science at the Georgia Institute of Technology. From August 2010 through July 2014, she was lead program officer of the National Science Foundation's Cyberlearning and Future Learning Technologies Program. Her research over the past four decades has addressed a variety of issues related to learning from experience and fostering learning from experience, both in people and in machines..