Expansive Modeling: Broadening the scope of modeling in K-12 education

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Abstract: Modeling is generally recognized as the core disciplinary practice of science. Through examinations of rich learning environments which expand the boundaries of modeling and the practices connected to it, researchers are broadening what modeling means in disciplinary settings. This interactive session brings together a diverse spectrum of scholars to share the practices they have used to expand modeling, how they were used in their curriculum, and the impact they had on learning. This session will serve as a rich opportunity for discussion to help advance the state of the field around what counts as modeling and the role it can play in learning.

Motivations and objectives

Since a fundamental objective of science is explaining phenomena through model construction, science educators and researchers have increasingly called for science instruction to be organized around models and modeling. These calls have rightfully emphasized directing learner's conceptual activity towards *disciplinarily accepted* forms of inquiry (Lehrer, 2009). However, more recently, scholars have begun to push on the boundaries of modeling to include learners' everyday practices and funds of knowledge. The papers in this symposium present work that expands what modeling can look like in formal and informal settings by drawing on a range of repertoires of practice including dance and movement (Vogelstein et al; DeLiema et al; Fridman et al), storytelling and drama (Reimers & Brady; Wagh & Dickes), discursive and linguistic resources (Farris et al; Pierson & Brady), and cultural and historical ways of knowing (Lam-Herrera et al). We collectively refer to this line of work as *expansive modeling* - broadening the ways we see value in modeling and the practices that can be connected to it. We see this work as critically important because it expands the field's understanding of what can count as modeling and the role it can play in sense-making thereby making it inclusive of and accessible to a wider range of learners. Themes explored include: (1) the practices which became an integral component of the modeling repertoire, (2) the curricular and methodological decisions taken to expand modeling, and (3) what impact these expanded practices had on learning. The goal of this symposium is to showcase how various efforts approach expansive modeling, its role on learning and to provide a knowledge base to build on and be inspired by.

Session format

To promote active and productive discussion, the symposium will be conducted as an interactive poster session. Following brief teaser introductions on each project, attendees will be invited to view presenters' posters. This will provide attendees ample opportunities to examine and discuss curricular and methodological decisions made by the presenters, and how they may be adapted for attendees' own designs in a way that traditional talks do not allow. The symposium will close with an open discussion, in which the discussant will engage presenters and attendees in discussion around the main themes and any areas of interest that emerge during the session.

Theatrical modeling of planetary systems: Expanding the role of perspective in modeling

Jackson Reimers & Corey Brady

We present results from design-based research investigating the potential of engaging students in embodied activities at the intersection of participatory theater and agent-based modeling, focusing on planetary systems phenomena. We were motivated to see how a group of students might come together to physically constitute a representational infrastructure for modeling that supports dynamic perspectival understandings (Greeno & van de Sande, 2007). We saw this possibility as especially propitious for the study of *planetary systems*, which afford a variety of meaningfully distinct perspectives yet can be captured using a relatively small number of interacting agents. Given these motivations, we drew inspiration from both participatory theater (e.g., *Theatre of the Oppressed* (Boal, 1985)) and agent-based modeling (Wilensky & Rand, 2015) as collaborative, socially distributed structures for engaging participants' perspectives in a sense-making endeavor.

Over six successive implementations of a planetary systems unit, designed and facilitated in partnership with a 5th grade STEM teacher, we explored this rich design space. Analyzing our designs, we have articulated initial principles of *theatrical modeling*. While these principles are still tentative, they suggest the power of theatrical modeling in itself and as an expansive addition to the multi-modal modeling enterprise. We identified activity designs that foster multiple modes of thought, ranging from *subjunctive, "What if?" thinking*, enlisting imagination, to *subjective, "What would it mean?" thinking*, enlisting story. These operate in flexible conjunction with the *objective "What is it?"* or *"How does it work?"* thinking more commonly associated with modeling practices, ultimately broadening what it means to know, ask, claim, and interpret in modeling practice.

In theatrical modeling, the modelers *are* the model. Participants simultaneously enact their understandings about the planetary bodies they represent, while also interpreting each others' enactments in this light. This setting is rich in opportunities for collective ideation, argumentation, contestation, and sense-making. Negotiating both "what we just did" and "how we can improve it" thus calls for coordination across perspectives. Theatrical modeling also blends process and product. The model (as product) is a coordinated performance, a collective action that is both a demonstration and a new occasion for question-posing. Re-enacting the model provokes inevitable variation and new observations. Thus, to instantiate a theatrical *model* is to engage in another round of model*ing*. Furthermore, participants' enactments are *polysemic*—they often express more or different ideas than the participant explicitly intends—and these "surplus" meanings fuel the interpretive work of the group, suggesting possible shifts in target phenomena or uncovering unexpected facets of planetary dynamics. These elements of theatrical modeling offer a new set of affordances and constraints for students' modeling practices. We see this most strongly in light of Goodwin's notion of a substrate for co-operative action (2018). Theatrical modeling engages students in using a broader set of semiotic resources, de-settling academic notions of legitimacy and subverting disciplinary boundaries at the interactional level.

Decolonizing complexity: An axiological reorientationfrom a Mayan perspective

Marilu Lam-Herrera, Women Weavers Community Council of Santo Domingo Xenacoj & Pratim Sengupta

In this research, we illustrate how agent-based modeling of emergent phenomena can be re-imagined through the lens of decolonization by partnering with Indigenous Mayan women weavers, high school teachers, and the Ixkoj Ajkem Council (Women Weavers Community Council) in Xenacoj, Guatemala. Research on complex systems emphasizes the importance of understanding emergent phenomena through building progressively complex relationships among individuals and between individuals and their environments (Dickes, et al., 2016; Wilensky & Resnick, 1999). However, modeling complex systems from embodied and agent-based perspectives can also be synergistic with Indigenous ways and forms of knowing and support interdisciplinarity in ways that value cultural historical forms of knowing (Aikenhead & Mitchel, 2011). Furthermore, partnering with Indigenous communities also call for an axiological reorientation of what forms of knowing are *valued* disciplinarily from the perspective of the community (Bang, 2020).

Through our ongoing partnership, we have been designing Grafemos (Lam-Herrera et al, 2019), a modeling environment for learning about emergence. The Grafemos modeling device is a physical "computer" in the shape of a dodecahedron, with slots for images that are soaked in ink and then imprinted on paper as the device is rolled. The images represent agents and interactions and are based on combinations of traditional Mayan motifs used in weaving practices. Modeling with Grafemos is also a communal activity, in which a small group must participate together, while each participant models from the perspective of a specific element in the system. Methodologically, we have adopted *Methodological Métissage* (Lowan-Trudeau, 2012), which is centered on: a) emphasizing Indigenous practices and traditions such as storytelling and symbolizing, and b) working with the elders and members of the community during all stages of the research. We believe that *Métissage* is foundational to enacting axiological reorientation of Western scientific approaches that largely dominate the Learning Sciences. Using the constant comparative method, we present an analysis of a month-long study in which we worked with six high school teachers and two members of the Ixkoj Ajkem Council in Xenacoj, Guatemala. Meeting 3-4 times a week, we worked together on modeling complex phenomena that the teachers and Council members identified as relevant to their lives as well as to the high school science curricula. We used Grafemos, embodied modeling activities, as well as the ViMAP (Sengupta et al., 2015) block-based programming environment. Data collected included video recordings of each session and participants' work.

Our analysis highlights a) how engaging in each form of modeling supported mid-level (Levy & Wilensky, 2008) and multi-level reasoning (Wilensky & Resnick, 1999), b) the axiological reorientation was evident in the kinds of phenomena (e.g., plastic contamination, systemic violence, etc.) that community members valued as scientific topics relevant to their lives as well as the curriculum, and c) how this axiological reorientation was supported through embodied and multimodal representations beyond the computer, that in turn, were intertwined with cultural forms (e.g., clotheslines and fabric motifs). Overall, our work illustrates how modeling with Grafemos offered a space for *Métissage* by bringing together cultural forms, participatory and embodied learning, as well as agent-based representations of complexity, while the axiological reorientation allowed teachers and community members to center events and concerns in their communities as topics of scientific and computational inquiry.

Storymaking and Storytelling: Exploring the affordances of narrative in computational modeling

Aditi Wagh & Amanda Dickes (equal contribution)

Jerome Bruner (2005; 2010) has argued that narrative, or story, is a uniquely human way of making sense of the world; an avenue to explore "possible worlds" and the vehicle through which we frame accounts of our own experience. In this sense, the act of storymaking and storytelling affords narrators opportunities to connect past, present and "imagined" worlds, and define relationships between seemingly disconnected events (Ochs & Capps, 1996). In this paper, we argue that storytelling and storymaking can provide a rich and meaningful context for theory building in science - particularly when situated within the medium of computational modeling - and potentially transform how students come to see and know in science. In particular, we draw on work that positions stories as "nascent theories" (Ochs et al, 1992) that scaffold and normalize practices such as perspective-taking, critical thinking, and abstraction; practices long argued as crucial components of scientific thinking and knowing.

We identify four narrative discursive practices that we believe can be useful in science learning: (1) Employing figurative language, specifically metaphor, as a tool to illuminate qualities of less understood objects (or natural phenomena) by drawing lines of association between the unknown object and objects that are already understood (Quale, 2002); (2) Considering and reconciling competing perspectives by coordinating between different understandings to identify solutions to confusing and challenging narrative problems (Ochs & Capps, 1996); (3) Identifying and contextualizing narrative problems along a temporal dimension to construct a theory of events for how and why problems emerge and how they might impact future events (Ochs & Capps, 1996); and (4) Constructing collaborative meaning through co-authorship, interpretation, and multiple retellings of narrative events. We see these practices as congruent and complementary with the practice of modeling in science and conjecture that the inclusion of narrative as a parallel practice in investigations of natural systems can scaffold learners' use and interpretation of computational models which represent those systems.

In this session, we report on a pilot design study which follows a group of upper elementary grade students' explorations of an invasive species and its impact on local species within the Gulf of Maine through parallel storymaking, storytelling and computational modeling activity. Our analysis describes how students drew on narrative practices, such as temporal fluidity and metaphor, to cohere the disparate elements of the natural system into a "plot" comprising character and conflict, and the role that this narrative work played in supporting their work on modeling that same system. Finally, we discuss the tensions that arose between employment of a narrative frame and more normative scientific frames, and how those tensions were reconciled.

Expansive embodied modeling: Inviting and leveraging students' ideas and linguistic resources

Ashlyn Pierson & Corey Brady

Computational modeling is a powerful tool for helping K-12 students explore and learn about complex systems (Dickes et al., 2013; Sengupta et al., 2013; Wilensky & Reisman, 2006). Yet due to barriers arising both from the syntax and concepts of computational representations, computational thinking and modeling can be challenging for both students and teachers. In response, researchers have worked to design programming environments and learning activities that make computational modeling more accessible. One such approach to support computational modeling is embodiment or enactment. In an embodied model, students role-play agents in a system (e.g., plants and animals in an ecosystem) to explore agent actions and interactions as well as system-level, emergent phenomena from the perspective of these agents (Danish, 2014; Forrester, 1961). To enact agents, students typically follow rules, which are sometimes framed as the "code" or "program" for the agents in the embodied model.

In addition to these affordances of embodied modeling, we propose that embodied modeling activities could be designed to invite and leverage students' linguistic resources and multimodal representations, in turn supporting learning and participation particularly for students classified as English Learners (ELs). Research in bilingual education and science education shows that multilingual students benefit from deploying their full range of meaning-making resources in classrooms (García & Kleyn, 2006), including linguistic resources as well as other semiotic resources (nonlinguistic modes, like images, gestures, actions, symbols; Blackledge & Crease, 2017; Li, 2018). Building upon this work, we explored how embodied modeling activities could be enriched with additional representations beyond embodied actions, including both canonical representational forms (e.g., Cartesian graphs) and students' everyday resources (e.g., gestures, student-generated language), along with social interactions.

In the context of an iterative design-based research project in a 6th grade STEM classroom studying ecosystems and population dynamics, we explore how embodied modeling can expand opportunities for participation and for learning about complex systems. We illustrate how embodied modeling activities were refined with each cycle of our design to offer students distinct ways of understanding their computational models and the ecosystems they represented. We describe three iterations of the design, which positioned embodied modeling successively as: (1) a rehearsal for the computational model, in which each students' unique contributions and perspectives were essential for shared meaning-making, (2) a space for active and collective modeling, as students "remixed" (modified) the code to test their own ideas, and (3) a full-fledged component of the classroom's system of models of ecological phenomena, supported by linked representations drawn from their computational models and from students' everyday linguistic resources. We argue that these approaches to augmenting embodied modeling show promise for supporting participation and complex systems learning, particularly for students classified as ELs.

Meadow bees, hive bees, and a moving sun: Tensions and affordances in learning between embodied point of view and spatial frames of reference

David DeLiema, Noel Enyedy, Joshua Danish, & Francis Steen

A robust educational research literature around complex systems documents how reasoning about systems involves a delicate act of balance between agent perspectives (e.g., viewing the scene from the perspective of one component) and aggregate perspectives (e.g., pulling back to see patterns among multiple components) (Wilensky & Reisman, 2006). Even with third-person, cartesian graphs in mathematics, students might spontaneously embody in gesture the first-person viewpoint of a graphed component (Nemirovsky & Monk, 2000). More recently, with augmented reality technologies that track and display full body movement (Danish et al., 2020), the dynamic of being multiple components in a model all while tracking aggregate connections creates a public process of *coordinating point of view and spatial reasoning*.

Building on a case study of the friction that arises during this coordination process (DeLiema & Steen, 2014), we examine the Science through Technology Enhanced Play's (STEP) unit on bees to document how 1st and 2nd graders and their experienced teacher navigate multiple points of view (bees in the hive; bees in the meadow) and spatial reasoning (bee waggle dance identifying location of valuable flowers). To anchor our multimodal interaction analysis, we draw on gesture research around character and observer *points of view* (Stec, 2012), the notion of layered or *laminated* semiotic resources in interaction (Goodwin, 2018), and *spatial frame of reference* terms such as figures, anchors, and grounds (Levinson, 1996). We strategically selected one video-recorded episode from the six-session unit in which the teacher and two students encounter spatial (in)congruence at the intersection of multiple points of view in order to investigate how participants *notice* this tension between viewpoints within a system and how they *publicly draw on* embodied, material, and interactional resources to resolve the tension.

The analysis documents why material infrastructure (e.g., a flower icon on the floor) that grounds imaginative play across points of view at once *confounds* (e.g., a bee in the hive could never presently see a meadow flower) and *supports* (e.g., a meadow bee can now see it would not arrive at a flower) complex systems reasoning. In addition, the analysis examines how the participants' public efforts to make spatial anchors and grounds more explicit surfaces friction between viewpoint and spatial reasoning, and then become the very resource that clarifies the participants' inquiries (e.g., the bee's "diagonal to the left" flight starts "*from there*"). These clarifying moves laminate gesture, full body movement, talk, and material and imagined objects in sequences of conversational repair to help the participants converge on their understanding of the system. This analysis raises key considerations for designers of material and embodied spaces in which students move across roles or viewpoints in the setting. Most importantly, the analysis shows that tensions between spatial reasoning and viewpoint are not a deficit, but rather, an inherent part of modeling that participants can notice, argue about, and clarify to arrive at a shared understanding of the system.

The collective and discursive nature of model-based reasoning: Discussion as means for thinking together in preservice professional learning and elementary mathematics education

Amy Voss Farris, Rachel Wolkenhauer, Gwendolyn Lloyd, & P. Karen Murphy

Engaging in model-based reasoning is fundamentally interdependent with generating explanations that are justifiable and critiqued by others. Models are a type of purposeful explanation of some phenomenon or process and make reasoning evident by way of letting one thing "stand in" for something else (Lehrer & Schauble, 2010). However, what counts as acceptable forms of evidence and reasoning in particular disciplines is often not made explicit to educators or to students (Manz et al., 2020). Our focus in this poster is on how teacher educators and preservice teachers (PSTs) engaged in discussion-based pedagogy to support authentic forms of questioning and argumentation in three cross-disciplinary contexts: (1) a course called Classroom Learning Environments, which focuses on teachers' inquiry and equitable pedagogical praxis in contexts of complex social and political discourses, (2) a methods course for elementary mathematics, and (3) PSTs' facilitation of mathematics discussions with children in their field classrooms. We argue that explicit attention to questioning and argumentation in discussion-based pedagogy across disciplines supported PSTs' early facilitation of mathematics discussions in their field placements.

We partnered with teacher educators within the Penn State Professional Development School (PDS) to adapt and enact the *Quality Talk* discussion approach. Quality Talk is a small-group, teacher-facilitated discussion approach that has been shown to foster K-12 students' reasoning and content-area learning (Murphy & Firetto, 2017). Teacher educators learned to use Quality Talk discussions to support preservice teachers (PSTs) in methods coursework so that, in turn, PSTs can use the approach in discussions about pedagogy and mathematics and while teaching mathematics in their field experiences. Expectations included eliciting student-generated questions about mathematics, student-initiated responses to peers' questions that include evidence or mathematical reasoning, and collective sensemaking about mathematical tasks. The authors and other PDS school- and university-based TEs co-developed and integrated five discourse lessons and related discussions in the Classroom Learning Environments (CLE) course and methods for teaching mathematics course during the Fall 2019 semester. A series of assignments supported PSTs in preparing to facilitate small group mathematical discussions with elementary students.

Our poster will provide an overview of how teacher educators learned to support PSTs' development of pedagogies for elementary students' mathematical argumentation within the Quality Talk small group discussion approach and offer an illustrative discourse analysis of a discussion with second grade students that was facilitated by one PST, named Laura. In this discussion, Laura demonstrates command of discourse features she learned in her CLE course and operationalized her belief that students, positioned with interpretive authority concerning the task, the mathematical concepts, and one another's ideas, can productively learn together. Within the discussion, the students solve a novel mathematics problem by discursively modeling a problem context in which the cost of green beans is a rate per unit length. They question their own problem representations when one student proposes subtraction as a way to solve the problem. The case illustrates productive connections between learning about discussion-based pedagogy in preservice teacher education and novice teachers' preparation to support critical-analytic discourse in an elementary mathematics task.

From social and embodied modeling to computational modeling in the "Computational Modeling in Science" (CMS) project

Chani Fridman, Sharona T. Levy, & Hagit Hel-Or

The CMS approach to scientific modeling in schools expands the scope of computational modeling to include embodied & social modeling. Embodied & social role-playing activities have the students represent entities in a system by physically moving about the classroom and interacting with other students and objects. This expansion of computational modeling is based on a number of principles: (1) role-playing simulations, which are familiar to teachers', provide a natural bridge into computational modeling (McSharry & Jones, 2000); (2) enabling students to ground scientific and computational abstractions in their bodies and movement, as described by embodied learning theory (Lindgren & Johnson-Glenberg, 2013); (3) having students communicate their ideas in social co-dependent participatory simulations can be a highly effective form of learning (Levy, 2017); (4) providing students with multiple access points into scientific modeling making modeling more inclusive.

The research was structured as a quasi-experimental pretest-intervention-posttest design with a comparison group. The topic of the learning unit included Kinetic Molecular Theory (KMT) and Gas Laws, along with several other related phenomena. First, teacher-led embodied-social modeling occurred with students enacting the rules of particles in a system. Next, similar student-led modeling had students suggesting questions, creating and exploring their embodied model. Finally, students engaged in computational modeling with the Much.Matter.in.Motion (MMM) platform (Levy, Saba & Hel-Or, 2020), which enables modeling many physics- and chemistry-based phenomena. The rules underlying particle behaviors, such as “change direction when you collide”, are elicited in these simulations and are later presented as computational blocks in the model coding environment.

In terms of overall learning, there was no difference between the experimental and control groups, both showing increased knowledge on the topics; however, concepts related to the micro-level were learned better by the experimental group. Students' confidence in their answers increased in the experimental group, while they did not do so for the students in the comparison group. An analysis of the students’ pictures of perfume spreading in the air showed three types of depictions, successively increasing in sophistication; the analysis showed that the experimental group, but not the comparison group, advanced from pretest to posttest in the sophistication of their understanding of gas behavior. Analysis of the classroom embodied simulations and computational models showed two themes: (1) a close relationship between ideas expressed at the beginning of the learning and the embodied social simulations, and (2) confusions between micro-and macro-levels were gradually resolved along the learning unit. We summarize that the approach we have developed does not show a significant advantage over normative learning when looking at the students’ overall conceptual understanding scores. However, when detailed concepts were considered, it was found that the micro-level concepts relating to KMT were learned significantly better with the CMS activities. The students also grew more confident in their answers through the activities, an important feature that may contribute to students’ perceived self-efficacy. We conjecture that the embodied social simulation provides a window into students’ thinking as they enact their ideas dynamically with their bodies, and also provides the feedback necessary for helping them revise non-scientific concepts.

Flares in the soup game: Improvisational collective choreography and computational expressivity

Lauren Vogelstein, Corey Brady, Rebecca Steinberg, & Curtis Thomas

We share our design and analysis of an activity called “The Soup Game” for a middle school camp integrating computation, mathematics, and art (“Action Camp”). The activity leveraged embodied sensemaking to provide entry points for conceptualizing agent-based programming as a creative performance space. By iteratively proposing and enacting choreographic elements together, student participants constructed, interpreted, and executed sequences of movement they later expressed computationally in NetLogo (Wilensky, 1999), eventually orchestrating hybrid human-computer performances. To study students’ embodied ideation processes, we look specifically at *flares*, movements that spread through regions of the group as they developed and enacted choreographic rules. We argue that flares offer one form of evidence of creative group-level thinking.

We identified connections across our diverse research and teaching experiences, in themes of exploring the expressive potential of groups (Vogelstein, 2020) and engaging young learners to position themselves as *creators* of valued works, whether in the domain of dance, mathematics, or computational thinking. We came to see many similarities between creating movement scores for people to perform and writing code for agents (“turtles”) to perform. Steinberg & Thomas brought the seed of The Soup Game from activities they had used to give dance students opportunities (a) to experience how simple rules can generate complex choreographies, and

(b) to practice using their voice as leaders in creative collaboration. In the game, groups devised and named movement rules (e.g., "craziness" meant "spread out while always moving") that would later be called out to form performance scores. Bridging to computation, we leveraged parallels between movement rules and computational procedures; and we connected the *leader* calling out named rules to NetLogo's *observer* communicating commands to turtles. Our design also built on research showing the power of *syntonic learning* (e.g., "playing turtle," (Papert, 1980)), and group role play (e.g. participatory simulations, (Brady et al, 2016)).

We focus on the spread of movement ideas when campers jointly created movement rules and worked out how to enact them. Video recordings from multiple camera angles captured different perspectives on the activity (Hall, 2000). We augmented Interaction Analysis (Hall & Stevens, 2015) with newer, embodied forms of reenactment and analysis (Vogelstein et al., 2019), which we also extended. We found that participants often interpreted others' movements as invitations to move, themselves—as *proposals* to respond to (cf., Vogelstein, 2020). Movements spread as flares within regions of the participant group when generating rules. Flares served to clarify and extend emerging choreographic elements in *shape*, *space*, and *time*—physically performing ideas, and observing others, afforded new noticings (Kirsh, 2010). Flares also revealed compositionally rich possibilities that *stretched the meanings* of rules. We show how flares provide evidence of collective sensemaking: physical proposals and responses allowed the group to explore its expressive potential and the enacted meanings of commands they generated.

References

Ackermann, E. (1996). Perspective-taking and object construction: Two keys to learning. *Constructionism in practice: designing, thinking, and learning in a digital world, Lawrence Erlbaum, Mahwah, NJ*, 25-35.

Aikenhead, G., & Michell, H. (2011). Bridging cultures: Indigenous and scientific ways of knowing nature. Don Mills, Ontario, Canada: Pearson Education.

Bang, M. (2020). Learning on the Move Toward Just, Sustainable, and Culturally Thriving Futures. *Cognition and Instruction*, *38*(3), 434-444.

Blackledge, A., & Creese, A. (2017). Translanguaging and the body. *International Journal of Multilingualism*, *14*(3), 250–268.

Brady, C., Weintrop, D., Anton, G., & Wilensky, U. (2016). Constructionist learning at the group level with programmable badges. In *Proceedings of Constructionism* (pp. 61-68).

Boal, A. (1985). *Theatre of the Oppressed*. *Theatre Communications Group*.

Bruner, J. (2010). Narrative, culture, and mind. *Telling stories: Language, narrative, and social life*, *46*, 49.

Danish, J. A. (2014). Applying an activity theory lens to designing instruction for learning about the structure, behavior, and function of a honeybee system. *Journal of the Learning Sciences*, *23*(2), 100–148.

Danish, J. A., Enyedy, N., Saleh, A., & Humburg, M. (2020). Learning in embodied activity framework: a sociocultural framework for embodied cognition. *International Journal of Computer-Supported Collaborative Learning, 15*(1), 49-87. doi:10.1007/s11412-020-09317-3

DeLiema, D. & Steen, F. F. (2014). Thinking with the body: conceptual integration through gesture in multiviewpoint model construction. In M. Borkent, B. Dancygier, Hinnell, J. (Ed.) *Language and the Creative Mind* (pp. 275-294). Stanford, CA: CSLI Publications.

Dickes, A. C., & Sengupta, P. (2013). Learning Natural Selection in 4th Grade with Multi-Agent-Based Computational Models. *Research in Science Education*, *43*(3), 921–953.

Dickes, A. C., Sengupta, P., Farris, A. V., & Basu, S. (2016). Development of Mechanistic Reasoning and Multilevel Explanations of Ecology in Third Grade Using Agent-Based Models. *Science Education*, *100*(4), 734–776.

Forrester, J. W. (1961). Industrial Dynamics. MIT Press.

García, O., & Kleyn, T. (2016). Translanguaging with multilingual students: Learning from classroom moments. New York, NY: Routledge.

Goodwin, C. (2018). *Co-operative action*. New York, NY: Cambridge University Press.

Greeno, J. G., & Van De Sande, C. (2007). Perspectival understanding of conceptions and conceptual growth in interaction. *Educational Psychologist*, *42*(1), 9–23. https://doi.org/10.1080/00461520709336915

Hall, R. (2000). Video recording as theory. In D. Lesh & A. Kelley (Eds.) Handbook of Research Design in Mathematics and Science Education (pp. 647-664). Mahweh, NJ: Lawrence Erlbaum

Hall, R., & Stevens, R. (2015). Interaction analysis approaches to knowledge in use. In *Knowledge and Interaction* (pp. 88-124). Routledge.

Kirsh, D. (2010). Thinking with the body.

Lehrer, R. (2009). Designing to develop disciplinary dispositions: Modeling natural systems. *American Psychologist*, *64*(8), 759.

Lehrer, R., & Schauble, L. (2010). What kind of explanation is a model? In *Instructional explanations in the disciplines* (pp. 9-22). Springer, Boston, MA.
Levy, S. T., & Wilensky, U. (2008). Inventing a "mid level" to make ends meet: Reasoning between the levels of complexity. Cognition and Instruction, 26(1), 1–47.
Levy, S.T. (2017). Learning about Complex Systems from the Bottom Up: Role-playing Together in a Participatory Simulation. I. Levin & D. Tsybulsky (Eds.), *Digital Tools and Solutions for Inquiry- Based STEM Learning*. A volume in the Advances in Educational Technologies and Instructional Design (AETID) Book Series. Hershey, Pennsylvania: IGI Global.
Lowan-Trudeau, G. (2012). Methodological Métissage: An interpretive Indigenous approach to environmental education research. *Canadian Journal of Environmental Education (CJEE)*, *17*, 113-130.
Li Wei. (2018). Translanguaging as a practical theory of language. *Applied Linguistics*, *39*(1), 9–30.
Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational Researcher*, 42(8), 445-452.
Levinson, S. C. (1996). Frames of reference and Molyneux's question: Crosslinguistic evidence. In P. Bloom, M. A. Peterson, L. Nadel, & M. F. Garrett (Eds.), *Language and space* (pp. 109-170). Cambridge, MA: MIT Press
Manz, E., Gibbons, L, Okun, A, Chalmers-Curren, J., & O'Connor, C. (2020). Exploring elementary teachers' classroom discussion puzzles: A cross-disciplinary analysis. In Gresalfi, M. and Horn, I. S. (Eds.). (2020). *The Interdisciplinarity of the Learning Sciences, 14th International Conference of the Learning Sciences (ICLS) 2020, Volume 4.* Nashville, Tennessee: International Society of the Learning Sciences.
McSharry, G., & Jones, S. (2000). Role-Play in Science Teaching and Learning. S*chool Science Review*, 82(298), 73-82.
Murphy, P. K., & Firetto, C. M. (2017). Quality talk: A blueprint for productive talk. In P. K. Murphy (Ed.), *Classroom discussions in education* (pp. 101–133). New York: Routledge.
Nemirovsky, R., & Monk, S. (2000). "If you look at it the other way…": An exploration into the nature of symbolizing (pp. 177-221). In P. Cobb et al. (Eds.), *Symbolizing and communicating in mathematics classrooms: Perspectives on Discourse, Tools, and Instrumental Design* (pp. 177-224). New Jersey: Erlbaum.
Ochs, E., & Capps, L. (1996). Narrating the self. *Annual review of anthropology*, 19-43.
Ochs, E., Taylor, C., Rudolph, D., & Smith, R. (1992). Storytelling as a theory-building activity. *Discourse processes*, *15*(1), 37-72.
Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. Basic Books, Inc..
Saba, J., Hel-Or, H., & Levy, S. T. (2020, June). "When is the pressure zero inside a container? Mission impossible" 7th grade students learn science by constructing computational models using the Much. Matter. in. Motion platform. In *Proceedings of the Interaction Design and Children Conference* (pp. 293-298).
Sengupta, P., Kinnebrew, J. S., Basu, S., Biswas, G., & Clark, D. (2013). Integrating computational thinking with K-12 science education using agent-based computation: A theoretical framework. *Education and Information Technologies*, *18*(2), 351–380.
Stec, K. (2012). Meaningful shifts: A review of viewpoint markers in co-speech gesture and sign language. *Gesture, 12*(3), 327-360.
Vogelstein, L. (2020). Physical Research: Professional Dancers Exploring Collective Possibilities in a Solidifying Substrate. In *14th International Conference of the Learning Sciences, Nashville, TN.*
Vogelstein, L., Brady, C., & Hall, R. (2019). Reenacting mathematical concepts found in large-scale dance performance can provide both material and method for ensemble learning. *ZDM*, *51*(2), 331-346.
Wilensky, U. (1999). NetLogo. Evanston, IL: Center for Connected Learning (CCL), Northwestern University.
Wilensky, U., & Reisman, K. (2006). Thinking Like a Wolf, a Sheep, or a Firefly: Learning Biology Through Constructing and Testing Computational Theories—An Embodied Modeling Approach. *Cognition and Instruction*, *24*(2), 171–209. http://doi.org/10.1207/s1532690xci2402_1
Wilensky, U., & Rand, W. (2015). *An introduction to agent-based modeling: modeling natural, social, and engineered complex systems with NetLogo*. MIT Press.
Quale, A. (2002). The role of metaphor in scientific epistemology: A constructivist perspective and consequences for science education. *Science & Education*, *11*(5), 443-457.