This is the accepted manuscript version of the chapter: Gravel, B. E. & Wilkerson, M. H. (In Press). Integrating computational artifacts into the multi-representational toolkit of physics education. To appear in R. Duit, D. Treagust, & H. Fischer (Eds.), *Multiple Representations in Physics Education.* The Netherlands: Springer.

Integrating Computational Artifacts into the Multi-Representational Toolkit of Physics Education

Brian E. Gravel[1] & Michelle H. Wilkerson[2]
Department of Education, Tufts University, Medford, MA, USA
Graduate School of Education, University of California, Berkeley, USA

Abstract [200 words]. Computational artifacts can serve as important components of the multi-representational toolkit of physics. But like any representation, the meanings of computational models are far from transparent: they are embedded within social, symbolic, and material contexts. In this chapter, we present case studies of two different learning communities that each worked to adopt a participant-generated computational artifact as a shared representational tool that they used to communicate and reason about physical systems. In one, collaborating physicists and mathematicians used a Mathematica notebook to explore the behavior of liquid crystals. In the other, a fifth grade science class used a student-generated computer simulation to reason about the processes of evaporation and condensation. We show how both groups: (1) developed a shared understanding of the computational artifact as a representational tool, (2) leveraged the artifact to focus their attention on their respective goals, and (3) discussed the strengths and limitations of the architecture of the computational environment relative to those goals. We highlight similarities and differences in how professionals and students took up these computational artifacts as shared representations, and discuss instructional implications given the increasingly computational and multi-representational focus of K-12 science education.

Keywords: Computational model; computational representation; scientific modeling; computer simulation; shared representations; classroom discourse

Computational artifacts such as simulations and visualizations are important representational tools in physics and physics education. But as with any representation, the meaning of a given computational artifact is not immediately transparent, and we cannot expect each individual to interpret it the same way. Instead, computational artifacts are constructed, used, and adapted over time by particular learning communities for particular purposes. Community members must negotiate how such artifacts should be understood as representations that can describe and uncover particular aspects of scientific phenomena. It is this process we are interested in: how *computational artifacts* (e.g., simulations, visualizations, scripts[1]) become meaningful *representations* or *models* of scientific systems as a community works to make sense of those systems. Exploring and supporting the processes by which such shared understandings develop is critical at a time when science educators are expected to engage learners in increasingly collaborative, computational, professionally authentic forms of science.

[1] Text computer code intended to be executed in a given computational environment is often referred to as a *script*.

In this chapter, we address the question: How does a learning community integrate a particular computational artifact into the shared multi-representational toolkit they use for communicating and reasoning about scientific phenomena? We explore this question using two case studies. In one, professional scientists and mathematicians take steps toward developing a new computational "solver" that allows them to create models of the dynamics of liquid crystals. In the other, a fifth grade classroom discusses a student-generated simulation of the formation of clouds. In both cases, development of a shared understanding of the computational artifact involved (1) Working to articulate the representational meaning(s) of the artifact and its connection to other more familiar representations; (2) Using shared language about the artifact to focus attention on the causal mechanisms describing the phenomenon of interest; and (3) Noting limitations of the representational artifact and its computational architecture. These similarities emerged even though the epistemic goals of the two groups were different: the scientists sought to efficiently predict liquid crystal dynamics in multiple dimensions, the students to visually reproduce weather patterns.

This process of integrating a computational artifact into a toolkit of disciplinary representations holds implications for educational theory and practice. In terms of theory, we argue that not enough attention has been granted in the literature to how *communities* of learners make sense of computational representations as tools for communication and reasoning. Our findings suggest this process is nontrivial, and critical for computational models to be deeply and meaningfully integrated into classroom-level scientific activity. In terms of practice, these preliminary findings point toward patterns of interaction that educators should attend to and encourage when integrating computational artifacts into their classrooms.

Background

There is a major effort to shift science education from an emphasis on facts and memorization toward an emphasis on construction of knowledge using the tools and practices of science (e.g. National Research Council, 2011). Scientific argumentation and modeling have become a major part of what advocates suggest should be practiced in the science classroom (Kuhn, 1993; Lehrer & Schauble, 2000; Windschitl, Thompson & Braaten, 2008). But while building and using computational representations (e.g., Mathematica notebooks) is a a critical part of professional practice in the sciences, still little is known about how learners develop the shared understandings needed to use them to argue and co-construct knowledge together in the classroom. This is important so that learners understand the epistemic and communicative power of a given computational representation, and its relationship to other representations used in science. Because these understandings take effort and negotiation, it is important that their development be systematically supported in classrooms.

Computational Representations in Scientific Practice

In scientific practice, argumentation and modeling go far beyond the spoken word. They fundamentally involve and are influenced by multiple forms of representation: from informal gestures that highlight structures or interactions, to the use of mathematical languages such as calculus, and diagrammatic conventions that specify or reveal patterns (Kozma, Chin, Russell & Marx, 2000; Ochs, Gonzales, & Jacoby, 1996). From this perspective, these practices are understood to include the discourses between individuals and between the individual and “the material, symbolic, and technological resources in their environment” (Kozma, 2003, p. 206). Representational tools, thus, play a central role in the how knowledge is generated, expressed, and shared to construct the “language of communication” for the ideas relevant to that community. (Noss, Bakker, Hoyles & Kent, 2007, p. 381). The situation is no less true in science classrooms, where the growing use of multiple representations can fundamentally shape how learners interact with one another and co-construct knowledge (Jewitt, Kress, Ogborn, & Tsatsarelis, 2001; Prain & Waldrip, 2010). All of this activity requires an understanding of how learners interpret, construct, and negotiate meaning across these various representational resources (Jewitt, 2008).

Some of the most powerful and ubiquitous modes of representation in physics are computational (Thijssen, 1999). These allow the behaviors, relationships, and/or data associated with a given system to be expressed or manipulated using a symbolic language that can be executed on a computer. When executed, these rules simulate the system of interest, allow users to explore how changes in some parameters of the system affect others, and perform computational manipulations and approximations. These representations offer practitioners opportunities to quickly prototype and evaluate conjectures. And, like equations or other forms of formal representation, computational representations are highly specific, sharable, and revisable by others (diSessa, 1995; Wilensky & Rand, 2007).

Despite their popularity, exactly *how* computational artifacts are meant to serve as representations in science practice is unclear, and varies from community to community (Grüne-Yanoff & Weirich, 2010). Scientists and philosophers of science are still working to understand how computational models might (or might not) be used to productively represent real-world systems, or to represent theory about those systems and their inner workings (Grimm et al., 2005; Peck, 2012). Thus, establishing the scientific utility of these computational artifacts is both a matter of personal judgment (Winsberg, 1999) and collaborative meaning making among colleagues (Chandrasekharan & Nersessian, 2014).

Computational Representations in Science Education

Given their centrality in contemporary scientific practice, many researchers have started to explore how computational representations might be used in science education. Most such work has focused on the construction and use of simulations to promote learning in particular domains such as ecosystem dynamics or Newtonian physics (Clark et al., 2009; Hilton & Honey, 2011; Perkins et al., 2006). Here, we limit our focus to studies that have explored the construction and/or use of computational representations primarily as a way to engage learners in the practices of scientific argumentation and modeling.

One approach to using computational representations in classrooms involves developing software tools and curricular sequences that engage individuals or small groups of students in building their own computational models to generate and test explanations and arguments. Stratford, Krajcik, and Soloway (1998) documented what they called “Cognitive Strategies for Modeling”--analysis, relational reasoning, synthesis, testing and debugging, and making explanations--that they argue students engage in while building dynamic computational models. Others describe similar phases of construction, analysis/exploration, and evaluation as critical for engaging in argumentation through computational construction (Clark & Sengupta, 2013; Ergazaki, Zogza & Komis, 2007). Xiang and Passmore (2014) documented how learners reasoned about a phenomenon, articulated understandings of that phenomenon using program code, and evaluated the resulting artifact in a cyclic and interwoven fashion as they constructed and revised simulations of natural selection. However, less work examines how such artifacts might afterward be used at the classroom level to support collective argumentation and knowledge construction .

A second line of work engaged large groups or whole classrooms in argumentation using data and evidence from scientific simulations. Much of this work focuses broadly on pedagogical and discursive patterns in the classroom (Smetana & Bell, 2014; Hennessey, Deaney, & Ruthven, 2006), rather than the specific roles simulations are expected to play in learning and knowledge construction (Greca, Seoane, & Arriassecq, 2014). However, there is some evidence that working to understand the meaning of a given computational representation is nontrivial. Berland and Reiser (2011) found that some middle school students blurred the distinction between inferences and evidence when engaged in scientific argumentation using a computer simulation of ecosystem dynamics. They believed that differences in graphs within the simulation reflected fundamentally different computational rules rather than randomly-generated variation. Those students who *did* attend to the distinctions between inference and evidence tended to construct more persuasive arguments for their peers. Hmelo-Silver and colleagues (2015) described how two teachers engaged their students differently in simulation-mediated inquiry. They found that one teacher, Mr. Fine, encouraged students to explicitly reason through what particular features of the simulation were meant to represent. The authors noted that this approach was likely to help students use the technology for reasoning and knowledge construction, rather than only for content acquisition.

Computational Representations as Distributed

In this chapter we bring together the two lines of work described in the previous section. We are interested in studying communities in which members construct their own computational artifacts, and in the ways those artifacts then become understood, shared, and integrated into the representational toolkit of the community as a whole.

To better understand this point of intersection, we draw on Osbeck and Nersessian’s (2006) notion of “distributed representations”. Distributed representations are “...created and used in the cooperative practices of persons as they engage with natural objects, manufactured devices, and traditions, as they seek to understand and solve new problems" (p. 144). They interpreted the distribution and use of representations as involving two notions they termed *cognitive partnering* and *representational coupling*. Cognitive partnering involves forming links across people and artifacts in order to allow or sustain sense-making practice. For example, researchers may note that they are building on colleagues' prior ideas or work. Or, they may grant agency to particular artifacts - for example, by suggesting components of a physical model *want* to behave a particular way - as they come to view those artifacts as partners in thinking. Representational coupling involves articulating relations across multiple representational resources, so that those resources form systems that can be used as models for reasoning.

Osbeck and Nersessian's work was conducted in the context of biomedical engineering laboratories involving, primarily, physical representations. However, their account offers insight into our own question about computational representation in knowledge communities. In many research collaborations, such as the one we describe below, a subset of members of a team create a computational artifact. The artifact is to be used meaningfully by the wider team, with the intention of moving forward the collective work. And in classroom communities, there is increasing interest in developing shared epistemic and representational practices to move forward students' work (Enyedy, 2005; Greeno & Hall, 1997). These processes of partnering and coupling with computational artifacts are critical in order for those artifacts to become "distributed representations" that allow the community to move forward.

Research Design

This study was conducted as part of the NSF-funded project entitled SiMSAM: Bridging Student, Scientific, and Mathematical Models with Expressive Technologies (henceforth "the SiMSAM Project"; IIS-12172100). One goal for the project is to better understand what authentic computational modeling practice might look like in middle school science. We did this by developing and researching how students use a simulation construction toolkit (henceforth "SiMSAM" for *Si*mulation, *M*easurement, and *S*top-*A*ction *M*oviemaking; Wilkerson-Jerde, Gravel, & Macrander, 2013), and by consulting with, and studying the behavior of, professional scientists who use computational modeling in their own work.

Our research design is most closely aligned with an interpretivist paradigm that seeks to acknowledge and work from the "localized meanings of human experience" (Treagust, Won, Duit, 2014, p. 7). Building from a design-based research perspective (Brown, 1992; Collins, 1992), we seek to develop theory about modeling with representational toolkits by designing a tool (i.e., SiMSAM) that allows us to iteratively examine that theory over cycles of engagement. We do not attend explicitly to "culture" in ways others within this paradigm have done, but we carefully consider contexts – e.g., a research group, a particular classroom – as places with specific conditions, from which we hope to develop descriptions of theory that explain the dynamics we observe. Further, the standards for quality research within interpretivist paradigms overlap with those of DBR in valuing sustained and prolonged interactions in the field, careful, repeated sifting through data, reflective analysis of data, and clear and rich reporting (p. 9).

Study Context

The question we put forth in the introduction to this chapter was: *How does a learning community integrate a particular computational artifact into the shared multi-representational toolkit they use for communicating and reasoning about scientific phenomena?* We pursue this question through a comparative case study of two learning communities with different goals - one more professional, and one more pedagogical. For each, computational models served a central role in mediating how participants communicated and reasoned with one another about physical phenomena. We conduct a descriptive multiple case analysis with these two complementary cases for the purpose of theory-building.

Professional Scientists: The LCD Research Group

The LCD Research Group was a collaboration of theoretical physicists, computational mathematicians, and mechanical engineers. The group sought to model the behavior of liquid crystal structures, which could in turn inform the development of faster and more energy-efficient liquid crystal displays. Their work involved extending established 1-dimensional and 2-dimensional models of liquid crystal behavior to more complex, multi-dimensional cases. Such extensions had been previously difficult. The governing mathematical descriptions of the phenomena (based on the Ericksen-Leslie equations, Lin & Liu, 2000) were often too complex to solve analytically and most computational algorithms were inefficient and expensive to operate. The group sought to leverage recent advances in the algorithmic design of computer-based mathematics "solvers" to develop more efficient models.

Two principal investigators in this collaboration were disciplinary consultants for the SiMSAM Project. We asked to video record a research group meeting to gain insight into how computational models are discussed and used as a part of professional scientific work. We collected data during a meeting early in the collaboration. Four people were physically present at the meeting, and one attended via Skype projected on a laptop. Brian (author) attended the meeting. He used one video camera on a tripod to capture the whole group's conversation and interaction, and a second hand-held camera to capture the gestures and sketches participants made over the course of the meeting. He also interviewed Ian, the theoretical physicist, after analyzing the video episodes to gain further insight into the goals, purposes, and activities of the meeting.

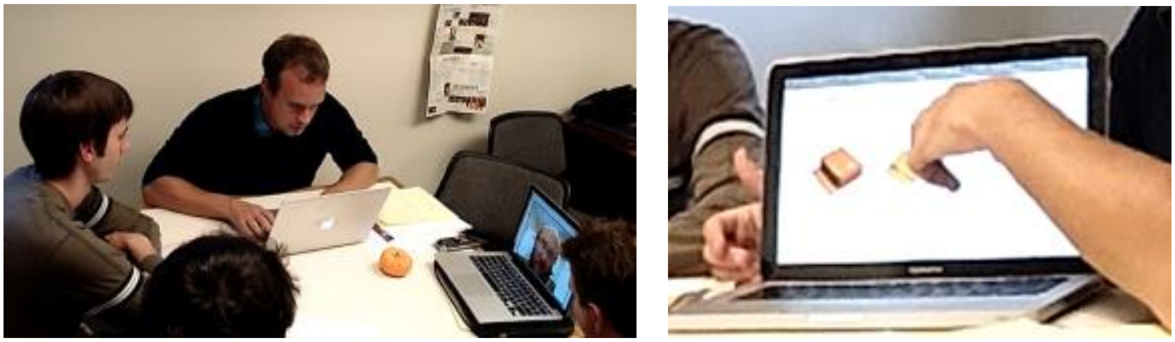

Figure 1. Cameras were positioned to capture the LCD Group's face-to-face and Skype interactions. One camera was directed to capture gestures and written artifacts in detail.

5th Grade Science Class: The Evaporation and Condensation Lesson

The SiMSAM research group partners with classroom teachers to enact scientific modeling activities. During the activities, middle school students use computer-based animation and simulation tools to construct models of "experiential unseens" (p. 165; Gravel, Scheuer, & Brizuela, 2013), such as smell diffusion or air pressure. In this chapter, we report on data collected from one such enactment with a fifth-grade class in an urban public K-8 school in the northeastern United States. The class was socioeconomically, racially, and linguistically diverse, and students in the class were accustomed to puzzling about science questions, volunteering theories, and challenging one another's ideas.

The two–week activity was designed to focus on evaporation and condensation as related to the particulate nature of matter. For the first week, students addressed the question "When you take a cold bottle of soda out of the fridge, why does it get wet after some time?" and for the second, "What happens to puddles on a hot day?". During both weeks, students were first invited to discuss their theories as a class and to create drawn models. Next, they worked in groups of 2-3 with SiMSAM and a desk-mounted camera to create stop-motion animations using common craft materials. Students could then crop images from their animations, which became programmable entities. Finally, they used these entities to create computational simulations representing the processes of condensation or evaporation. Periodically throughout the sequence, students reviewed one another's animations and simulations in small groups and as a whole classroom, usually lead by their teacher Mr. Arbor. We video-recorded all classroom-level and group-level interactions, as well as on-screen and on-board activity.

Analysis

We approached the data presented in this chapter as a descriptive multiple-case study with theory-building as a goal. Our guiding "quintain" (shared phenomenon of interest across instances; Stake, 2006, p.4) was the uptake of a particular computational artifact as a shared representational tool. We sought evidence of this phenomenon by investigating episodes within each case where we knew computational artifacts were likely to be used as representational tools. We bounded video segments by identifying instances from that data during which computational artifacts were explicitly taken up, interpreted, used, and critiqued by each group as representations of the phenomena under study.

Next, we analyzed the video segments as holistic single cases (Yin, 2009), working to understand each independently. We did this through a process of iterative, collaborative viewing (Jordan & Henderson, 1995) during which we took notes and divided episodes into descriptive segments based on major themes. As we elaborated these themes, we identified markers in talk and interaction that we used as evidence that participants had taken up computational artifacts as representational tools. We will describe these themes and markers in further detail below. After working to understand each case independently, we began to draw comparisons and contrasts across the two cases. We complemented these comparisons with additional close viewing. In our presentation of data in the next section, we similarly present each case separately at first and only subsequently identify similarities and differences across them.

For the purposes of this chapter, we present transcript excerpts, images, and analysis as evidence of the patterns we observed. In the transcripts, we identify the classroom teacher (Mr. Arbor) and researchers with asterisks to distinguish them from our focal participants, the professional scientists and students. Additionally, we bold-faced sections of transcripts that are quoted and discussed in the analysis narrative.

Case 1: Modeling Liquid Crystal Displays

We take this case from a research group meeting during which Ian, the theoretical physicist lead on the project, presented a model he generated for group discussion. Ian's role in the collaboration, with his colleague Matthew's help, was to contribute multidimensional systems of equations to describe crystal behavior. Peter, Justin, and John were mathematicians responsible for designing a "solver" for this system of equations based on their own computational algorithms. A mechanical engineer, not present at this meeting, would go on to collect empirical evidence to support their work. The goal of the meeting we focus on here was for all members of the group to understand the basic behavior of liquid crystals, and how those behaviors were typically modeled.

Episode 1 - "It's just gonna lie down?"

This episode began with Ian showing the group a multi-representational description of liquid crystal behavior in 1-dimension. He generated two 3D plots using Mathematica that showed changes in crystal orientation and fluid velocities (how the liquid crystals move in localized contexts) against time (Figure 2, R1). These plots, generated by the script written in Mathematica, serve as the central computational artifact for the discussion.

In the plots, liquid crystals were assumed to start in what he called a "distorted state," or "partially switched upward", and moving to a position of rest over time. In a subsequent interview about this episode, Ian likened the crystals to small sticks that either laid flat on a table, or with one end lifted at some angle relative to the surface of the table. He called attention to the first plot on the screen (R2), and used a gesture with his finger to point upwards (R3), illustrating the orientation of the crystal.

Ian So this a first - this is example one.
[Ian points to R1 displayed on his laptop]
Its easy to set up all sorts of examples, but this is example one where you start from initially a **distorted state**, its admittedly not a very distorted state, but initially quite a distorted state, and then, so here you're looking at theta.
[Ian points to R2]
So this is - what this would be, is the cell[2] is sort of **partially switched upwards**
[Ian gestures with his finger pointing up, R3]
and then um, we just allow it to relax for a minute.

Peter So **as you go up in Z I'm going**?
[Peter gestures upward with his finger, going from a horizontal position to a vertical position, R4]

Ian Yeah exactly so so, yeah... good job Matthew.
[Ian thanks Matthew and takes pen/paper from him]
So basically here, like that.
[Ian produces a drawing of theta as it changes across the liquid crystal cell, R5]

John Okay alright.

Ian Yea so here - because its not getting all the way up pi over two
[Ian points to peak of 3D plot, R2]
it's only up to a certain point, but you know, **it's at some sort of theta max**. Um and so that's what that graph initially means.
[Ian draws a Cartesian plot showing the front view of 3D plot, where cross sections at different times, t, are sketched on the same plane, R6]
And so the point is that **its gonna then relax over time**, and you can see indeed it does.

Peter And **it's just gonna lie down**?

Ian Yeah it just lies down.

[2] The "cell" referred to by the physicists is a unit of analysis for examining liquid crystals between two boundaries, like in an LCD display. These "cells" have boundaries in one direction, and operate as infinite spaces on the other direction for the purposes of analyzing their dynamics.

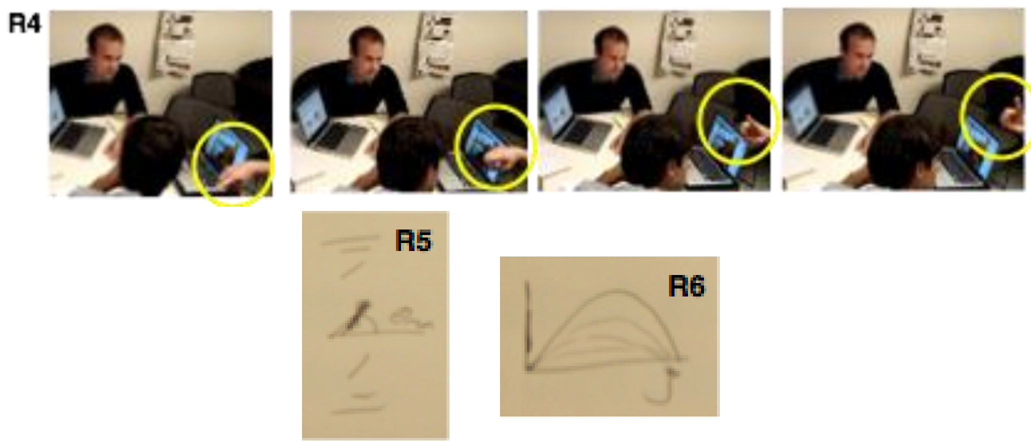

Figure 2. Representational elements from Case 1, Episode 1. R1 shows the example that Ian first presents containing the particular parameters modeled and the 3D plots produced by the computational scripts in Mathematica. This is the central computational artifact for this Episodes 1 and 2 of Case 1.

Following Ian's initial description of "Example 1," Peter re-articulates what he understood the plot to represent. He used a similar gesture to Ian's (R4): a pointed finger moving upward from a horizontal position. Ian confirmed Peter's interpretation, and switched from gesture to paper to further clarify what the plot showed in terms of the z-axis, or time. He explained that the highest peak on the plot was some "theta max," which he labeled on the drawing as the point where the crystal was pointed upward at some maximum angle (R5). He drew line segments at decreasing angles to the horizontal, to show the shift in orientation, and drew cross sections of the 3D plot in a graph to show how "it relaxes over time." Peter confirmed his understanding of the change in orientation over time with a colloquial description, "It's just gonna lie down" as the orientation of the crystal goes from more vertical to more horizontal.

Throughout this episode, Ian connected the computational model he was introducing to a large collection of representational forms - including gesture, sketches, and 2D plots. As Peter worked to understand the 3D plots generated by the model, he appropriated and repeated the representations Ian employed and also offered new, colloquial descriptions. This back-and-forth allowed Ian and Peter to negotiate a shared understanding of the first plot, and to develop a shared language for describing features of the plots and the phenomenon more generally. We view this as an instance of the types of "representational coupling" described by Osbeck and Nersessian (2006) - both across members of the collaboration, and across representational tools.

Episode 2 - "There's kind of a funny bump"

In our final episode, Ian presents a second example to the group that includes a new plot derived from the mathematical model and corresponding Mathematica script. The plot demonstrates what happens when a cell is turned "on," that is, when the liquid crystals are activated or distorted electrically (moving them to the corresponding condition to switching the cell "off" in Episodes 1).

Justin *[Justin is on Skype, and has the Mathematica notebook running on his computer – Figure 3 - R1]* Could I ask a question Ian?

Ian Yes, of course!

Justin So when I look at the, the profile on the left (*R2*), theta as a function of zeta and t.

Ian Yep, yep

Justin If I sort of look at that head on so that the t-axis is going into the page. *[Ian manipulates the plot in the notebook to generate R3]* There's a kind of a **funny bump** around the boundary conditions I noticed…

Ian Yeah yeah yeah yeah yeah

Justin Is that **expected from the physics** or something that we might be guessing as being a **numerical problem**?

Ian I, I wouldn't be at all surprised if its a numerical problem um because um… um… yeah, simply because um I don't think its expected from the physics. Um, that's why I kind of hesitate to say this is sort of a robust test case…

Justin Fair enough, I'm just thinking that **if that's saying that theta is going from zero all the way up to Pi over two**, and then bouncing back right

Ian He's basically looking at this bump here. *[Ian points to the screen]*

Peter I kind of want to look at it now. *[Peter controls the mouse and manipulates the 3D plot - from the top image to the second image to see it "head on" - R3].*

Ian Can you see it? Okay can you look at it head on - yeah can you see that? [*Ian points out the "funny bump" on the plot - R4*]. I could actually try and plot it. I could do a cross-sectional plot I'm sure. Um

Justin If you did a plot of T = 1, you'd probably see it.

Ian Would that be useful? I'm not sure - it may, let's see

Justin I'm perfectly content with your answer, I just wanted to ask if

Ian No no no, I agree with you Justin and I suspect that - that's actually why - I'm glad you raised it because it was actually something I was a little sort of - yeah - it was something I looked at and was like, "I don't know about that." But given that this is obviously a sort of **very generic and nasty solver**. And then the other problem right, there's another problem so, that I'm a little sensitive to, is that, is that there's two pieces in the Mathematica notebook. There's a solver part and that may, may -that may, even if that gives the correct solution, um this then there's then a plotting part, you know. So then its making this fancy 3D plot. **We don't actually know whether that's sort of doing a good job**. So it could either be an artifact of the numerics or of the plotting potentially um. And I agree with you for raising it, because its **definitely not physical**, so, yup. Yup. And its why we shouldn't take this to-- I said this notebook is not intended to be sort of the be-all and end-all um, but it is intended to be a sort of place to start and something of value to everybody to kind of understand at least what's going on.

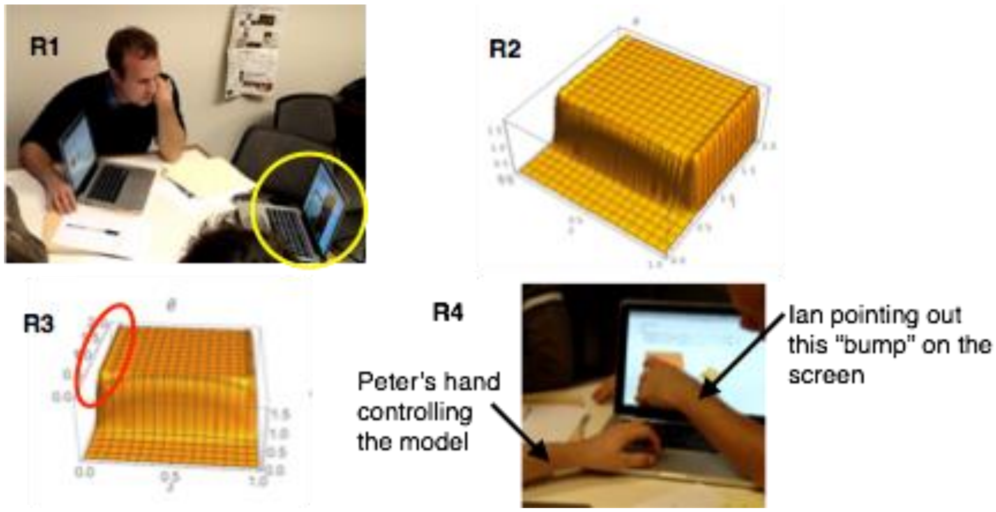

Figure 3. Representational elements from Case 1, Episode 3.

In this episode, Justin asks whether a “funny bump” on the 3D plot (Figure 3, R2) was “expected from the physics” or whether it was a “numerical problem,” resulting from the generic functions within Mathematica that generated the plot. The question leads Peter and others to investigate further by rotating the plot within the computational environment (R3), while Justin suggests generating a new plot at t=1. Ian explains that the “bump” most likely arises as a feature of the “very generic and nasty solver” that Mathematica used to generate the plots, which reflects the basic difficulties in modeling LCD systems that motivated the collaboration in the first place.

The team’s rapid navigation and critique of this new plot reflects their increasing comfort with the computationally-generated plots as representations of the behavior of liquid crystals. Their shared understanding is evident in the effortful work they put into distinguishing whether the anomaly Justin noticed was an intentional and predictive element of the representation, or an artifact of the computational tool itself. When Ian notes the plot is indeed a bad prediction of the physics of liquid crystals, the importance of the computational architecture - the Mathematica solver and plotter - in influencing whether and in what ways the plots may (or may not) be used as tools that represent particular aspects of the intended phenomena is accentuated.

Case 2: Modeling Condensation and Cloud Formation

Our second case study is drawn from the ninth day of the modeling activities done in one of Mr. Arbor’s 5th grade classrooms. This episode begins toward the end of the second week, after students had just finished constructing simulations of an evaporation scenario: *What happens to puddles on a hot day?*

In the excerpt below, the students had gathered together as a classroom. A simulation constructed by Sergio, Luis and Ryan was projected on a screen at the front of the room. The simulation featured puddles located at the bottom of the screen, small blue objects the group identified as “water droplets” positioned immediately above those puddles, and clouds at the top of the screen (Figure 4a). The students programmed the simulation so that when run, the water particles moved upward in a somewhat random path toward the clouds. When each particle touched a cloud object, the particle would disappear and a new, smaller cloud would appear on the screen near the point where the particle and cloud intersected (Figure 4b).

Figure 4. The student generated simulation projected on the Smartboard. In the simulation, “water droplet” objects positioned near puddle objects (a, left) move toward cloud objects. When a droplet intersects a cloud, it disappears and a new cloud appears near the site of intersection (b, right).

Episode 1: “What do we think about this representation?”

Students observed the simulation running in SiMSAM, and Mr. Arbor asked the class to comment on what it represented in terms of evaporation and condensation. A discussion with six students follows.

Mr. Arbor*	What do we think guys? What do we think about this, **this simulation, this representation of it**? Sheree?
Sheree	**I think it represents** when the sun evaporates the water, um the clouds they start to make new ones because of the **water vapor**.
Edgar	**I think it represents** because the **water droplets are going up**, and then the clouds are getting bigger and bigger because all the water's up, then when it gets full it [gestures down].
Mr. Arbor*	Ok, and that's the next step, if this simulation were to keep going it would probably show that.
Miles	I think it's just like the **water droplets are going up, and then it's just gonna get bigger and bigger** and then it's gonna like start getting ready to...
Alan	**I think they're trying to represent** that the **water vapor forms new clouds**, like more clouds.
Mr. Arbor*	I'm even seeing something, I'm trying to remember if this came up in this class or the other class, like, when there's evaporation, and it goes into the air, **does it form its own new clouds, or does it add on to the clouds that are already here**? So it seems, from what we see here it seems to be adding on to clouds that are already there. That idea was kind of floating around in this room too.

Kenny First of all I want to say props to you guys -- that was really good. And I noticed, and um, I think **the blue little puff balls, they were representing evaporation going up** into the air and every time it hit the cloud it like, it duplicated because each every time the little puff balls, **I guess it'd be the evaporation or the water vapor**, it make like a, it added onto the cloud that was already there.

Madison I think it was really cool that they made that the, **when the water vapor hit the clouds that it cloned itself.**

In this short exchange, students begin to make connections between the computational artifact - the SiMSAM simulation and its constituent symbols, behaviors, and interactions - and the phenomenon it is meant to represent. Sheree and Edgar establish the meaning of the blue puff-balls as symbols for water vapor/water droplets. Edgar and Miles offer descriptions of how the upward motion of the water droplet objects and duplication of the cloud objects are meant to represent evaporation and condensation. Alan touches on a specific mechanism that underlies the water cycle: He notes that the water droplets cause the duplication of clouds when they collide with them, which may represent how clouds are "formed."

Alan's suggestion makes space for Mr. Arbor to focus students' attention on a key question about the phenomenon: do water droplets form new clouds or add to the clouds that are there? Kenny's response is a deliberate attempt to link the objects in the simulation with the ideas currently under negotiation: "the blue little puff-balls, they were representing evaporation going up." He re-articulates language used in the opening conversation when he says, "I guess it'd be the evaporation or the water vapor." Then, he extends this language to the specific simulated interaction under question, noting that when cloud objects are "duplicated" this suggests clouds are "added onto the cloud that was already there". In his comment, Kenny links "blue little puff-balls" with "water vapor" and "evaporation," establishing an explicit connection between the language, objects/symbols, and the ideas represented in the computational artifact. Madison sustains this focus by revoicing Kenny's interpretation using the term "cloned", referencing the SiMSAM clone function used to create the simulation.

Episode 2 - "Maybe you could have a color option"

A bit later in the conversation, Michelle (author) redirected the conversation to see if there were other representational elements students wanted, but were unable to add to their simulations.

Kenny I know this might not be possible, but maybe, make the color change? I don't know if that's gonna be useful or not, but I'm just saying.

Teacher What piece would you have change color?

Kenny The clouds.

Teacher And talk to me about why.

Kenny	Because when um, when it evaporates, **sometimes a cloud gets too heavy then it starts raining, and maybe the clouds get like darker** or
Teacher	I remember that from your animation, you guys changed the color of the clouds.
Kenny	So yea, maybe let the color, maybe you could have a color option.
Brian*	So if you were to have a rule, what would the rule be?
Kenny	Like um maybe for the clouds, if I'm alone, **maybe say there's like a color change there's like a color scroll thing there, and you can change the color**.
Brian*	So would it just get darker? Or would it get darker if there was... what would make it get darker?
Kenny	Say um like, maybe it could be like um, the blue little, **the blue puff-balls like every maybe you could set it so like how many puff-balls make it change color?**
Madison	Or like **if I bump, then it will like change color.** Like I if you press, or I want the little puff ball, and then it should be another menu saying I can change this color.

In this episode, Kenny proposed a new feature for the SiMSAM environment. Rather than producing a second cloud when a water droplet collides with the existing cloud, Kenny wanted to make clouds become darker in color. We can interpret Kenny's suggestion in more than one way. It could be that Kenny wants better visual fidelity between the simulation and what he has observed in the world. When it begins to rain clouds often look "darker" rather than larger. Or, Kenny's proposal to link clouds getting darker to raining (a behavior that had not yet been added to the simulation) could be a way to chain events together to prompt a re-initiation of the water cycle, an idea the class had discussed in the first excerpt.

Kenny continued with his line of reasoning to propose two additional functions for the simulation "environment." One was a "scroll thing" to change the color. The other was to have the simulations record the number of puff-ball-to-cloud interactions and to control the color based on this quantity. Madison adds that we could do this functionally using the "bump" paradigm already present in the architecture of the tool - "bump" standing for interaction between objects. The suggestions not only demonstrate a rich intellectual engagement with the notion of artifact as tool. They also illustrate a firm understanding that the engine underlying the simulation - the architecture of the computational tool itself - can be revised to improve the overall quality of the representation of the model.

Discussion

The LCD Research Group and 5th Grade Science Classroom we report on in this chapter are quite different learning communities. However, we argue that both successfully adopted a computational artifact as a representational tool. In this section, we draw comparisons between the processes and practices we found in the two cases. Both groups: (1) developed a shared understanding of the computational artifact as a representational tool; (2) leveraged the artifact to focus attention on their respective goals; and (3) discussed strengths and limitations of the computational environment relative to those goals. In this section, we draw comparisons across the two cases, and identify specific discursive moves that marked ways in which members of each community begin to treat their respective computational artifacts as representational tools in service of their different epistemic goals. We then explore what these comparisons and discursive moves suggest for educators and designers interested in integrating computational representations into physics education.

From Making Sense to Making Use of Computational Artifacts as Representations

The research question driving our work was: How does a learning community integrate a particular computational artifact into the shared multi-representational toolkit they use for communicating and reasoning about scientific phenomena? These two case studies suggest that this process is effortful and explicit. In both cases we examined, we identified three relatively distinct phases of this process of integration.

In the first phase, members of each community worked deliberately and explicitly to develop a shared understanding of the artifact. With the professionals, this unfolded mainly through Ian's articulation of connections between the computational 3D plots and gestures, two-dimensional graphs, and sketches that illustrated the behavior of the crystals modeled. His collaborators indicated understanding by taking up and repeating certain gestures and phrases Ian used, and by testing their own colloquial descriptions of the phenomena. With the students, this process began with Mr. Arbor encouraging his students to explain what they understood the simulation to represent. They first described the visible objects on the screen (like puff-balls), and then with Mr. Arbor's support described what they believed behaviors and rules (such as cloning) expressed within the simulation to reflect phenomenally.

In the second phase, both the professionals and students used the shared language and understandings they had developed to question what each computational artifact implied for events and parts of the system *not* directly represented. The professionals discussed how fluid velocity extended beyond the single crystal represented in the plots. The students suggested specific ways to incorporate other information about the water cycle into the simulation, such as rain or that water sources reduce in size as they evaporate. Finally, in the third phase, both groups began to identify constraints within the computational architectures used to produce each representation that limited what could be appropriately represented. For the physicists, these limitations became apparent through the appearance of anomalous bumps in plots that did not correspond to expected physical behavior. The students noted that they wished to be able to change the color of objects in their simulation, as a way of increasing either the visual or phenomenal fidelity of their representation.

Upon further analysis, we found these different phases involved three types of discursive moves practiced by both the professionals and the students. These are described in Table 1.

Discursive Moves	**Description**	**Case 1 Expert Examples**	**Case 2 Classroom Examples**
Meta-Representational Talk	Explicit conversation about what symbols, materials, behaviors in the computational artifact mean in terms of the phenomenon under study; and critique of the representational adequacy of the artifacts relative to the phenomena under exploration and the collective knowledge of the learning community.	"So as you **go up in Z** I'm going (Peter gestures upward with his finger, going **from a horizontal position to a vertical position**)?" "There's a kind of **a funny bump around the boundary conditions** I noticed…"	"...every time the little puff balls, **I guess it'd be the evaporation or the water vapor**" **"I think they're trying to represent** that the **water vapor forms new clouds**, like more clouds."
Articulation of Mechanism	Establishing links between elements of the artifact and causal mechanisms describing the phenomenon.	**"It's just gonna lie down"**	**"...when the water vapor hit the clouds that it cloned itself.**"
Extension of Computational Architecture	Acknowledging/proposing features of computational architecture supportive or limiting of tool's sufficiency in modeling the phenomenon.	"So then its making this fancy 3D plot. **We don't actually know whether that's sort of doing a good job.** So it could either be an artifact of the numerics or of the plotting potentially."	"Like if you press, or I want the little puff ball, and then it should **be another menu saying I can change this color**."

Table 1. Discursive moves practiced as professionals and students worked to make sense and make use of computational artifacts as representations of physical phenomena.

Meta-representational talk refers to instances where participants established explicit links between elements of the computational artifacts and aspects of the phenomenon that they are working to understand. This action includes explicitly linking the artifact to other, already-understood representations, or describing what elements of the artifact represent in the phenomenon itself. We see this metarepresentational talk as the means by which each group constructed a shared understanding of the artifact. It was also the means by which they developed a shared language around that artifact, such that it could then become a tool for thinking and an object of critique. We view critique as a metarepresentational tool (diSessa & Sherin, 2000) used to position the artifacts as a useful contribution, but also incomplete, malleable, and fallible. Justin's attention to the "funny bump" and Alan's questioning whether water vapor forms new clouds or builds on existing clouds are examples of critique.

Building on these publicly-established and shared understandings and language, participants then focused their attention on more specific causal mechanisms related to the phenomenon under study. They began to **articulate the mechanisms** that linked cause and effect, and questioned how these mechanisms were represented within and extended beyond the artifact itself. Peter spoke about liquid crystals just "lying down" and "kicking the water," and

Madison proposed that water vapor joins clouds to "clone" new clouds. This serves as evidence that participants used the representational elements and rules to envision new situations.

Finally, both communities began to develop some understanding of the underlying computational architecture that was employed to generate each artifact (Mathematica and SiMSAM). As they developed this understanding, they made suggestions for how to **extend** the architecture to accommodate their epistemic goals. The professionals recognized the need to extend or redevelop the numerical solvers needed to model liquid crystals, indeed one of the major goals of their collaboration. The students proposed a new feature for SiMSAM, the ability to change the color of objects, which would allow them to better approximate the visual features of the water cycle and, perhaps, better computationally illustrate its perpetual nature. This understanding of the architecture underlying the artifact adopted by the community is particularly interesting because it also provides a basis for the community to evaluate and integrate future artifacts into their practice.

Understanding the Representational Toolkit of Physics and Physics Education

Computational tools are an integral part of the toolkit of physics and researchers are calling for increased integration of computational tools in physics education. People have cited a number of functional and epistemic reasons to support this integration. However, increased attention must be paid to these computational environments as representational tools, and how their features can be understood relative to other existing representations, and what specific purposes they are meant to serve.

With both learning communities, the integration of these computational environments into the toolkit of physics is deliberate, explicit, and effortful. At the heart of these integrative processes are learning communities that negotiate shared meaning of an artifact relative to each community's epistemic goals. Variations in process and goals across communities complicate how we think the negotiations of meaning. To understand these dynamics of negotiation and use, it is important to understand and articulate what it is professionals and students are trying to do with these tools in the first place. In our study, we argue there is a difference in the implicit understandings of the goals of these objects for each community. The professionals recognize their model as a knowledge-generating tool; the students focus on accuracy and completeness of their model in representing their understandings of the phenomena. While moments occurred when reviewing their simulations prompted new questions about the phenomena, the students overwhelmingly focused on the adequacy of their representations.

For physics education, these differences highlight the importance of designers and educators being explicit about how computational environments, specifically simulations, shoudl be used in the curriculum. There are many possible ways these environments can be used: as demonstrations or virtual experiments that students can manipulate, as a medium for communicating one's own understanding of a system, or as a tool to yield new insights into the system under study. All of these goals involve treating a computational artifact as a representational tool that supports thinking and communicating. The processes by which this treatment unfolds--negotiation, critique, revision--take time and require deliberate attention to how they are situated within epistemic actions and goals of the learning community.

Conclusion

One of the most important parts of learning a discipline is learning how to use the tools and language of that discipline required for participation. We argue that computational artifacts are becoming a fundamental component of these tools and languages, and should be treated as such in educational contexts. However, integrating computational artifacts in a way that respects their representational status alongside established forms such as diagrams or equations requires attention and support.

Our findings in this chapter describe the deliberate ways in which two learning communities negotiated a shared meaning for particular computational artifacts. Specifically, we identified three phases and three discursive moves that emerged across cases. Using the notion of "distributed representations" (Osbeck & Nersessian, 2006), we contribute more precise descriptions of how computational artifacts become representational tools taking into account the particular commitments of different learning communities. In so doing, we make available these findings for guiding how teachers notice and support the integration of computational artifacts as representational tools in their classrooms. By supporting attempts to integrate these tools, we can tune teachers' attention to the purpose and use of computational representations within the larger multi-representational toolkit of physics and physics education.

References

Berland, L. K., & Reiser, B. J. (2011). Classroom communities' adaptations of the practice of scientific argumentation. *Science Education*, *95*(2), 191-216. doi: 10.1002/sce.20420

Brown, A. L. (1992). Design experiments: Theoretical and methodological challenges in creating complex interventions in classroom settings. *The Journal of the Learning Sciences*, *2*(2), 141-178.

diSessa, A. A. (1995). Designing Newton's laws: Patterns of social and representational feedback in a learning task. In R.-J. Beun, M. Baker, & M. Reiner (Eds.), *Dialogue and Interaction: Modeling Interaction in Intelligent Tutoring Systems*. Berlin: Springer-Verlag, 105-122.

diSessa & Sherin (2000) Meta-representation: An introduction. *The Journal of Mathematical Behavior*, *19*(4), 385-398.

Chandrasekharan, S., & Nersessian, N. J. (2014). Building cognition: The construction of computational representations for scientific discovery. *Cognitive Science*. Advance online publication. doi: 10.1111/cogs.12203

Clark, D. & Sengupta, P. (2013). Argumentation and modeling: Integrating the products and practices of science to improve science education. In M. S. Khine & I. M. Saleh (Eds.), *Approaches and strategies in next generation science learning*. pp. 85-105. Hershey, PA: IGI Global. doi: 10.4018/978-1-4666-2809-0.ch005

Clark D., Nelson B., Sengupta P., & D'Angelo C. (2009). Rethinking science learning through digital games and simulations: Genres, examples, and evidence. Washington DC: National Research Council.

Collins, A. (1992) Toward a design science of education. In E. Scanlon & T. O'Shea (Eds.), *New directions in educational technology*. Berlin: Springer-Verlag.

Enyedy, N. (2005). Inventing mapping: Creating cultural forms to solve collective problems. *Cognition and Instruction*, *23*(4), 427-466.

Ergazaki, M., Zogza, V., & Komis, V. (2006). Analysing students' shared activity while modeling a biological process in a computer-supported educational environment. *Journal of Computer Assisted Learning, 23*(2), 158-168. doi: 10.1111/j.1365-2729.2006.00214.x

Gravel, B.E., Scheuer, N., & Brizuela, B.M. (2013). Using representations to reason about air and particles. In Brizuela, B.M. & Gravel, B.E. (Eds.). *Show me what you know: Exploring representations across STEM disciplines* (pp. 163-182). New York: Teachers College Press.

Greca, I. M., Seoane, E., & Arriassecq, I. (2014). Epistemological issues concerning computer simulations in science and their implications for science education. *Science & Education*, *23*(4), 897-921. doi: 10.1007/s11191-013-9673-7

Greeno, J. G., & Hall, R. P. (1997). Practicing representation: Learning with and about representational forms. *Phi Delta Kappan*, *78*(5), 361-367.

Grimm, V., Revilla, E., Berger, U., Jeltsch, F., Mooij, W. M., Railsback, S. F., Thulke, H-H., Weiner, J., Wiegand, T., & DeAngelis, D. L. (2005). Pattern-oriented modeling of agent-based complex systems: lessons from ecology. *Science*, *310*(5750), 987-991. doi: 10.1126/science.1116681

Grüne-Yanoff, T., & Weirich, P. (2010). The philosophy and epistemology of simulation: a review. *Simulation & Gaming*, *41*(1), 20-50. doi: 10.1177/1046878109353470

Hennessey, S., Deaney, r., & Ruthven, K. (2006). Situated experience in integrating use of multimedia simulation into secondary science teaching. *International Journal of Science Education*, *28*(7), 701-732. doi: 10.1080/09500690500404656

Hilton, M., & Honey, M. A. (Eds.). (2011). *Learning science through computer games and simulations*. Washington, DC: National Academies Press.

Hmelo-Silver, C. E., Liu, L., Grey, S., & Jordan, R. (2015). Using representational tools to learn about complex systems: A tale of two classrooms. *Journal of Research in Science Teaching, 52*(1), 6-35. doi: 10.1002/tea.21187

Jewitt, C. (2008). Multimodality and literacy in school classrooms. *Review of Research in Education*, *32*(1), 241-267.

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *Journal of the Learning Sciences*, *4*(1), 39–103.

Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *The Journal of the Learning Sciences*, *9*(2), 105-143. doi: 10.1207/s15327809jls0902_1

Jewitt, C., Kress, G., Ogborn, J., & Tsatsarelis, C. (2001). Exploring learning through visual, actional and linguistic communication: The multimodal environment of a science classroom. *Educational Review*, *53*(1), 5-18. doi: 10.1080/00131910123753

Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction*, *13*(2), 205-226.

Kuhn, D. (1993). Science as argument: Implications for teaching and learning scientific thinking. *Science Education*, *77*(3), 319-337. doi: 10.1002/sce.3730770306

Lehrer, R., & Schauble, L. (2000). Developing Model-Based Reasoning in Mathematics and Science. *Journal of Applied Developmental Psychology, 21*(1), 39-48.

Lin, F. H., & Liu, C. (2000). Existence of solutions for the Ericksen-Leslie system. *Archive for Rational Mechanics and Analysis, 154*(2), 135-156.

National Research Council. (2011). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*, Washington, DC: National Academies Press.

Noss, R., Bakker, A., Hoyles, C., & Kent, P. (2007). Situating graphs as workplace knowledge. *Educational Studies in Mathematics, 65*(3), 367-384.

Ochs, E., Gonzales, P., & Jacoby, S. (1996). " When I come down I'm in the domain state": grammar and graphic representation in the interpretive activity of physicists. *Studies in Interactional Sociolinguistics*, *13*, 328-369.

Osbeck, L. M. & Nersessian, N. J. (2006). The distribution of representation. *Journal for the Theory of Social Behavior, 36*(2), 141-160. doi: 10.1111/j.1468-5914.2006.00301.x

Peck, S. L. (2012). Agent-based Models as Fictive Instantiations of Ecological Processes. *Philosophy & Theory in Biology*, *4*. doi: 10.3998/ptb.6959004.0004.003

Perkins, K., Adams, W., Dubson, M., Finkelstein, N., Reid, S., Wieman, C., & LeMaster, R. (2006). PhET: Interactive simulations for teaching and learning physics. The Physics Teacher, 44, 18.

Prain, V. & Waldrop, B. (Eds.) (2010). Representing science literacies. [Special Issue]. *Research in Science Education, 40*(1).

Smetana, L. K. & Bell, R. L. (2014). Which setting to choose: Comparison of whole-class vs. small-group computer simulation use. *Journal of Science Education and Technology*, *23*(4), 481-495. doi: 10.1007/s10956-013-9479-z

Stake, R.E. (2006). Multiple case study analysis. New York: The Guilford Press.

Stratford, S. J., Krajcik, J., & Soloway, E. (1998). Secondary students' dynamic modeling processes: Analyzing, reasoning about, synthesizing, and testing models of stream ecosystems. *Journal of Science Education and Technology*, *7*(3), 215-234.

Thijssen, J. M. (1999). *Computational physics*. Cambridge, England: Cambridge University Press.

Treagust, D., Won, M., & Duit, R. (2015). Paradigms in science education research. In Lederman, N.G. & Abell, S.K. (Eds). *Handbook of Research on Science Education* (Vol. 2). Routledge.

Wilensky, U., & Rand, W. (2007). Making models match: Replicating agent-based models. *Journal of Artificial Societies and Social Simulation (JASSS)*, 10(4).

Wilkerson-Jerde, M., Gravel, B. & Macrander, C. (2013). SiMSAM: An integrated toolkit to bridge student, scientific, and mathematical ideas using computational media. In *Proceedings of the International Conference of Computer Supported Collaborative Learning (CSCL 2013)* (Vol. 2, pp. 379-381). Madison, WI, USA.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941-967.

Winsberg, E. (1999). Sanctioning models: The epistemology of simulation. *Science in context*, *12*(02), 275-292.

Xiang, L., & Passmore, C. (2014). A framework for model-based inquiry through agent-based programming. *Journal of Science Education and Technology*, *24*(2-3), 311-329. doi: 10.1007/s10956-014-9534-4

Yin, R.K. (2009). *Case study research: Design and methods*. Los Angeles: Sage.