

# Argumentation and Modeling: Integrating the Products and Practices of Science to Improve Science Education

**Abstract.** There is now growing consensus that K12 science education needs to focus on core epistemic and representational practices of scientific inquiry (Duschl, Schweingruber, & Shouse, 2007; Lehrer & Schauble, 2006). In this chapter, we focus on two such practices: argumentation and computational modeling. Novice science learners engaging in these activities often struggle without appropriate and extensive scaffolding (e.g., Klahr, Dunbar, & Fay, 1990; Schauble, Klopfer, & Raghavan, 1991; Sandoval & Millwood, 2005; Lizotte, Harris, McNeill, Marx, & Krajcik, 2003). This chapter proposes that (a) integrating argumentation and modeling can productively engage students in inquiry-based activities that support learning of complex scientific concepts as well as the core argumentation and modeling practices at the heart of scientific inquiry, and (b) each of these activities can productively scaffold the other. This in turn can lead to higher academic achievement in schools, increased self-efficacy in science, and an overall increased interest in science that is absent in most traditional classrooms. This chapter provides a theoretical framework for engaging students in argumentation and a particular genre of computer modeling (i.e., agent-based modeling), illustrates the framework with examples of the authors' own research and development, and introduces readers to freely available technologies and resources to adopt in classrooms to engage students in the practices discussed in the chapter.

**Audience.** Science Teachers as primary audience with Policy Makers and Researchers as secondary audiences.

**Keywords.** Argumentation, Modeling, Inquiry, Critique, Explanation.

## Introduction

Science education has historically attempted “to cultivate students’ scientific habits of mind, develop their capability to engage in scientific inquiry, and teach them how to reason in a scientific context” (NRC, 2011). These three foci have often been treated separately in traditional approaches to science education, however, with the result that science is often treated as isolated rote facts or artificial and arbitrary five-step methods (Driver, Leach, Miller, & Scott, 1996; Lemke, 1990). There is now growing agreement that students need to understand science and the processes of science as functions of argumentation and modeling (Duschl, 2008; Kelly, 2005; Lehrer & Schauble, 2006). The framework for the new science standards in the United States therefore “stresses the importance of developing students’ knowledge of how science and engineering achieve their ends while also strengthening their competency with related practices” (NRC, 2011, p. 3.1). The new standards use the term “practices” rather than “skills” to “stress that engaging in scientific inquiry requires coordination both of knowledge and skill simultaneously” (NRC, 2011, p. 3.1). This chapter discusses the practices of argumentation and modeling in terms of their roles in the scientific disciplines and in terms of practices appropriate for students in the classroom.

## What are Argumentation and Modeling?

True scientific literacy involves understanding how knowledge is generated, analyzed, justified, and evaluated by scientists and how to use such knowledge to engage in inquiry in ways that reflect the practices of the scientific community (Driver Newton, & Osborne, 2000; Duschl & Osborne, 2002). Scientific inquiry is often described as a knowledge building process in which explanations are developed to make sense of data and then presented to a community of peers so they can be critiqued, debated, and revised (Driver et al., 2000; Duschl, 2000; Sandoval & Reiser, 2004; Vellom & Anderson, 1999).

Argumentation and modeling are at the heart of the scientific enterprise. As Lehrer & Scahuable (in press) point out, in the world of science, inquiry may take on various forms. Inquiry may be observational, theoretical or computational. Inquiry may be carried out on a theorist's desk, in a physics lab, or a biological field station. However, despite these variations, all scientists engage in constructing, revising, applying, and defending models of the natural world (Giere, 1999; Hesse, 1966). Modeling has been described as the signature of research in the sciences (Nersessian, 2009), and argumentation is the process through which communities of scientists test, refine, and tentatively accept or reject models as a community. The ability to engage in scientific argumentation (i.e., the ability to examine and then either accept or reject the relationships or connections between and among the evidence and the theoretical ideas invoked in an explanation or the ability to make connections between and among evidence and theory in an argument) is, therefore, viewed by many as an important aspect of scientific literacy (Driver et al., 2000; Duschl & Osborne, 2002; Kuhn, 1993; Siegel, 1989). Thus scientific theories, modeling, and argumentation are not separate decontextualized entities. Scientific theories, modeling, and argumentation are dynamically interwoven and interdependent.

Learning to engage in scientific modeling and argumentation is challenging for students. Furthermore, opportunities for students to learn how to engage in scientific argumentation in a productive manner as part of the teaching and learning of science are rare (Newton, Driver, & Osborne, 1999; Simon, Erduran, & Osborne, 2006) as are opportunities to engage in authentic modeling. Traditional science curricula portray scientific theories as fixed and immutable facts to be memorized and accepted. Argumentation, when included at all, tends to either be a decontextualized game of creating rebuttals or an unreflective statement of "evidence" for theories that are treated as foregone conclusions. Similarly, models and modeling tend not to be integrated in school science in authentic forms. To the extent that they do appear in school, models usually play an illustrative, rather than scientific theory building role (Windschitl & Thompson, 2006).

This lack of integration in traditional curriculum between the products and processes of science is evidenced by research on students engaging in inquiry. Research suggests, for example, that students often do not seek out or generate data that can be used to help test their ideas or discriminate between competing hypotheses (e.g., Klahr, Dunbar, & Fay, 1990; Schauble, Klopfer, & Raghavan, 1991). In addition, students often rely on their personal views rather than use the data at hand to generate and verify hypotheses (Hogan & Maglienti, 2001). In other situations, students may use inappropriate data from an investigation to draw conclusions, or they may fail to attend to important patterns in the data (McNeill & Krajcik, 2007; Sandoval & Millwood, 2005; Kuhn, 1993; Schauble, Glaser, Duschl, Schulze, & John, 1995; Chinn & Brewer, 1993; Driver et al., 1994). When reasoning about scientific phenomena which involve multiple "levels" (e.g., both macroscopic and microscopic), students often tend to confuse the attributes and behaviors present in one level with that of the other (Sengupta & Wilensky, 2009; 2010; Wilensky & Resnick, 1999; Resnick, 1994). Students also have difficulty generating explanations that are scientifically rigorous (Carey, Evans, Honda, Jay, & Unger, 1989; Lawson, 2003; Sandoval & Reiser, 2004). They may face similar challenges justifying and warranting their explanations (Clark & Sampson 2008; Sandoval & Millwood, 2005; Sadler, 2004; McNeill & Krajcik, 2007; Kuhn, 1991; Brem & Rips, 2000; Kuhn & Reiser, 2005; Bell & Linn, 2000; Jimenez-Aleixandre et al., 2000; Lizotte, McNeill, & Krajcik, 2004; Aikenhead, 2004; Linn, Eylon, & Davis, 2004), and establishing and evaluating their validity or acceptability in the context of a given phenomenon during scientific argumentation (Hogan & Maglienti, 2001; Linn & Eylon, 2006; Kuhn & Reiser, 2005; Zeidler, 1997; Clark & Sampson, 2006a; Kuhn, 1989). Finally, novice learners often underestimate the time and effort that will be required to learn successfully – their self-judgment abilities are not well developed, and they may not be motivated enough to learn with understanding (Schunk & Zimmerman, 1998).

## **What Should Students Understand?**

So what should students understand? First, modeling is the central enterprise, purpose, and goal of science. Second, argumentation is the practice that allows scientists to determine the fit of their models with the world. Third, communities of scientists evaluate models, methods, and evidence through argumentation using shared criteria and analytical approaches developed and agreed upon by the community.

**Modeling is the central enterprise, purpose, and goal of science.** Students should understand modeling as the *language* of science. As Rapp & Sengupta (2012) pointed out, models are physical, computational, or mental representations that are intended to stand in for some other thing, set of things, or phenomena. Scientific models are tools for expressing scientific explanations or theories in a form that can be directly manipulated, allowing for description, prediction, and explanation. As Lehrer, Schauble, & Lucas (2008) pointed out, the “big ideas” in science derive their power from the models that instantiate them, so to fulfill the promise of the “big ideas” outlined in national science standards, students must realize these ideas as models.

Modeling is the core epistemic action through which scientists generate new knowledge, and modeling is inherently tied to constructivism (Hestenes, 1993). From the constructivist perspective, meaning is constructed and matched with experience in a manner that makes that experience meaningful and the meaning experiential. Similarly, modeling, which is the process of development and refinement of a model, is a dialectical process between model construction and model matching. Therefore, as students engage in modeling-based curricula over an extended period of time, students should understand that modeling, by its nature, involves repeated cycles of developing, representing, and testing knowledge (Rapp & Sengupta, 2012; Duschl et al., 2008; Lehrer, Schauble, & Lucas, 2008).

**Argumentation is the practice that allows scientists to determine the fit of their models with the world.** As Lehrer, Schuable & Lucas (2008) discuss, scientific models are also forms of argument. In the scientific world, models are regularly mobilized to support socially grounded claims and counterclaims about the nature of physical reality (Bazerman, 1988; Latour, 1999; Lynch & Woolgar, 1990; Watson & Crick, 1953). Students should understand that argumentation is a central foundation upon which scientists make decisions. This decisions include what data to collect, how to collect it, which data to select, how to represent that data, and how to determine the implications of that data as they test and refine their models in terms of the fit of those models with the data and phenomena they are modeling in the world. Students need to understand that argumentation can act as the framework that can guide their exploration of causal mechanisms of a phenomenon using a model and their exploration of the fit of a model with the world. This parallels the ideas of “getting nature to speak” (i.e., the methods and tools used to collect and select data) and “portraying nature’s voice” (the interpretation and representation of the implications of that data) as outlined by Ford and Forman (2006). Thus a focus on argumentation can guide evaluations of the appropriateness of scientific methods, data selection, data representation, data interpretation, warrants, and claims and the fit and implications of models in terms of the underlying causal mechanisms in the phenomena being modeled. In order to engage in authentic argumentation, students need to understand the role of claims, data, and warrants in scientific disciplines. They also need to understand that acceptable and appropriate criteria, methods, and representational forms are to some degree specific to individual scientific disciplines depending on the nature of the phenomena investigated by that discipline.

**Communities of scientists evaluate models, methods, and evidence through argumentation using shared criteria.** Students should also understand that argumentation is the mechanism through which communities of scientists evaluate the models proposed by members of those communities in terms of the claims, evidence, and warrants involved in a proposed model as well as in the methods used to generate the evidence itself. As discussed above, scientific disciplines come to agree on a shared interpretation of acceptable and appropriate questions, methods, criteria, and representational forms for investigating the phenomena of interest to those disciplines. Dialogic argumentation amongst scientific community

members is the primary process through which this shared interpretation evolves. Dialogic argumentation focuses on the interaction of individuals or groups attempting to convince one another of the acceptability and validity of alternative ideas. Thus students should also come to understand that the shared interpretations of the community are not fixed or preordained in terms of acceptable and appropriate questions, methods, criteria, and representational forms. Instead, the shared interpretation of appropriate questions, methods, criteria, and representational forms continues to evolve through argumentation as the community advances in its understanding of the phenomena under investigation and as the tools and methods available to the community themselves evolve, often directly as a result of community's own explorations. In addition to the epistemological value of helping students understand the processes through which scientific communities' understandings of the world evolve, engaging students in dialogic argumentation is considered a powerful mechanism for increasing students' understanding of challenging concepts (e.g., Andriessen, Baker, & Suthers, 2003; Hogan, Nastasi & Pressley, 2000; Leitão, 2000) as well as for increasing students' ability to engage in productive argumentation and reasoning practices (e.g., Baker, 2003; Bell, 2004; Kuhn, Shaw, Felton, 1997).

## **Integrating Argumentation and Models**

How might teachers integrate argumentation and modeling in the classroom in support of these goals? This first section discusses an excellent approach for engaging students in argumentation around pre-existing models developed by Sampson and colleagues (Sampson & Gleim, 2009; Sampson, Grooms, & Walker, 2009).

Many websites provide free access to fantastic pre-existing models that students can use to explore a wide range of scientific phenomena. Netlogo (<http://ccl.northwestern.edu/netlogo/>), PhET (<http://phet.colorado.edu/>), and Concord (<http://www.concord.org>), for example, have created large libraries of models that are freely available for teachers and students. Simply providing students with computational models, however, has not proven very effective, just as generic, traditional approaches to hands-on labs have not proven very effective according to the National Research Council's "America's Lab Report" on the efficacy of traditional approaches to science labs in schools (NRC, 2005). The National Research Council suggests that effective hands-on lab activities and computational model lab activities (1) focus on true inquiry to help students develop skills for grappling with the ambiguity and complexity of scientific investigations, (2) engage students in reading, writing, and critical discussions about the process and ideas, and (3) engage students in constructing and critiquing arguments about the phenomena and evidence associated with the explanations that they develop.

Sampson and colleagues (Sampson & Gleim, 2009; Sampson, Grooms, & Walker, 2009; 2011) have developed the Argument-Driven Inquiry (ADI) approach to help science teachers transform traditional laboratory activities and computational models into short, integrated instructional units that incorporate all of the features outlined by the National Research Council. The ADI approach provides "opportunities for students to design their own investigations, gather and analyze data, communicate their ideas with others during structured and interactive argumentation sessions, write investigation reports to share and document their work, and engage in peer review during a laboratory investigation" (Sampson, Grooms, & Walker, 2009). As outlined by Sampson and colleagues, the full version of the ADI instructional model consists of eight steps, which we outline in more detail in the following paragraphs.

**Identification of a Task.** In this stage, the students and the teacher first consider the phenomena to be investigated in light of previous experiences and other materials. The students then develop or select a question to explore.

**Generation and Analysis of Data.** This stage is a hands-on or virtual model-based investigation of the students' questions. While most ADI units focus on hands-on labs, several have been developed for use

with computational models, such as a NetLogo model that allows students to explore the impact of camouflage on the survival of butterflies. The students design controlled comparisons with the model to collect data for their question.

**Production of a Tentative Argument.** In this stage, students construct an argument that includes an explanation, evidence, and their reasoning in a format that can be shared with other students. Sampson and colleagues recommend whiteboards for this purpose. The explanation is essentially an answer to the research question and may articulate a qualitative relationship or causal mechanism. The evidence includes measurements or observations to support the explanation in terms of traditional numerical data or observations. Sampson and colleagues specify that, “in order for this information to be considered evidence, it should show (a) a trend over time (b) a difference between groups, or (c) a relationship between variables” (Sampson & Gleim, 2009, p. 467). The reasoning clarifies how the evidence supports the claim and why the evidence is justifiable and appropriate for the claim.

**Argumentation Session.** The students then share their arguments with one another and critique and refine one another’s explanations and the connections of the data to those explanations, in small groups or as a whole class. This step serves multiple purposes: it exposes students to the ideas of other students, allows students to respond to the questions and challenges of students who have created different explanations, and engages students in the knowledge-building processes core to the scientific disciplines. The argumentation sessions also allow teachers to assess students’ progress and thinking as well as to encourage students to think about overlooked issues or data. Through this process, students are exposed to the theory-laden nature of science and have the opportunity to come as a group to develop and share criteria for judging the plausibility of explanations, warrants, and reasoning.

**Investigation Report.** The students then write up an investigation report that explains the goals of the work, the methods employed, and their refined arguments about their findings.

**Double-Blind Peer Review.** The students next review reports from other students in a double-blind format. The class works together to develop criteria, which may be supplemented by the teacher in the form of guide sheets or critique sheets. The goal is to generate high-quality feedback and to help students understand how the process works in the disciplines.

**Revision of the Report.** Following the peer review, students have the opportunity to revise and refine their reports.

**Explicit and Reflective Discussion.** The class then engages in an explicit and reflective discussion about the inquiry process and the causal mechanisms underlying the phenomena under investigation.

Sampson and colleagues have developed several tools that can be used to help scaffold students as they work through each step of the ADI approach. For example, they have developed an "investigation proposal" that teachers can use to help students design better investigations during the process. Similarly, they have developed multiple peer review guides with varying degrees of scaffolding that teachers can provide for students to use during the peer-review process depending on the needs of their students. Sampson and colleagues have also developed some simpler approaches that have components of ADI but are not a full ADI, to provide a progression that can ultimately support students engaging in the full ADI process. For example, if teachers do not want to have students design an investigation and collect data but still want to do the argumentation sessions, Sampson and colleagues have an approach called "generate-an-argument" (Sampson & Grooms, 2010; Sampson & Gerbino, 2010). Similarly, if teachers want students to collect data and to do the whiteboards, but do not want students to write reports or go through the peer-review process, they can do the "evaluate-alternatives" approach (Sampson & Gerbino, 2010; Sampson & Grooms, 2009).

Thus, the ADI approach to lab instruction “fosters scientific literacy and allows students to develop scientific habits of mind, provide evidence for explanations, and think critically about suggested alternatives” (Sampson, Grooms, & Walker, 2009). Teachers can use the ADI instructional approach as a way to transform traditional computational models and hands-on experiences (where students typically follow a set procedure and answer relatively rote “analysis” questions) into powerful inquiry activities integrating inquiry with models and argumentation in a manner paralleling the actual inquiry processes within the scientific disciplines themselves. As Sampson and colleagues explain, this approach thus has “great potential and should enable more students to develop a sophisticated understanding of both the concepts under study and the process through which scientific knowledge is developed, evaluated, and refined” (Sampson & Gleim, 2009).

## **Integrating Argumentation and Modeling**

The previous section outlines an excellent approach for authentically incorporating argumentation and inquiry with hands-on labs, which in turn can be easily extended to the use of pre-built computational models. In what follows, we present an approach for moving beyond pre-existing models to instead engage students in argumentation and inquiry that focuses on modeling itself. More specifically, how might we structure and scaffold students’ modeling activities in terms of argumentation in a manner that parallels the authentic practices of the scientific disciplines? As discussed in the overview of this chapter, argumentation and modeling are the core practices at the heart of the scientific enterprise. Developing an approach for meaningfully integrating them would represent an authentic experience for students integrating the processes and products of science.

Hestenes (1993) argued that there are three kinds of epistemic modeling *games*<sup>1</sup> in which scientists usually engage: model building, model ramification and model deployment. In the first type, “modeling building,” the objective is to build a model to meet given specifications. These specifications are often derived from empirical data of observations. The second type, “ramification,” involves analyzing the properties (that is, the ramifications) of complex systems, i.e., systems that involve interactions between multiple factors or variables. The third type, “deployment,” involves the matching of models to empirical phenomena and data. In what follows, we present a general outline of how argumentation can be integrated to support such modeling in the context of computational models. Specifically, we outline an approach for the productive integration of argumentation and modeling through which students can engage in all three epistemic types of modeling.

Many model-based or modeling-based curricula typically engage in only one of these types of modeling. For example, a common use of computer models in science curricula occurs in the form of using pre-built simulations as demonstrative lecture aids that allow students to interact with simulations, primarily through controlled experimentation (variable manipulation) that helps them understand relevant aspects of the lecture. Another common form of classroom use involves students conducting guided inquiry using prebuilt models through cycles of predict-observe-explain (Sengupta & Wilensky, 2009). In these learning activities, students primarily engage in model-deployment. In other words, students are provided with the model with mathematical relationships specified by the designer, and students discover these relationships through conducting experimentation activities based on the control of variables.

Curricula that involve students developing their own computational models are significantly more challenging to implement, and often require extensive modeling expertise on the part of the teacher, as well as extensive one-on-one scaffolding that is often beyond the scope of usual K-12 classroom

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<sup>1</sup> We will interchangeably use the terms *activity* and *game* in this chapter.

instruction. For example, Harel & Papert (1991) reported a study in which students constructed Logo models of fractions over an extended period of five months, during which they received support from experienced peers such as MIT graduate students. Sherin and colleagues (1992) reported a study in which students engaged in learning Newtonian mechanics by constructing Logo programs in the Boxer programming environment (diSessa & Abelson, 1986), but that course involved 5 weeks of programming instruction followed by 10 weeks of physics instruction. This second course was taught by expert programmers and teachers with extensive experience using and teaching with Logo. In such curricula, students do indeed engage in model construction and model deployment, and possibly even model ramification, but such curricula are challenging to implement in K-12 settings. This is due to the demands on teacher preparation (i.e., teachers need to be domain experts as well as programming experts), and due to the challenges of integrating programming with science content, which in turn has implications for class time (length of the course).

From the perspective of designing a learning environment, our approach to integrating modeling and argumentation has the following three objectives. First, the integration of argumentation into modeling should evolve as progressions in terms of both modeling and argumentation spread across multiple investigations in the curriculum. Second, aligning with constructivist perspectives, these investigations should build on one another. Third, integrated learning environments should support key practices of argumentation (e.g., critique, evaluation, explanations) as well as all three epistemic forms of modeling outlined by Hestenes in terms of building, ramification, and deployment (1993).

Based on our review of the literature, we believe that such integration requires the development of a new kind of modeling platform that enables students to construct models without requiring programming experience, and provides software-embedded scaffolds that use argumentation as a focal activity during the process of modeling. Over the past year, we have been developing a software-based learning environment that is freely available to teachers that supports both modeling and argumentation in the context of learning science in K-12 classrooms. We describe below the key design principles guiding the design of the learning environment.

## **Design Guidelines for Integrating Modeling and Argumentation in Agent-Based Computational Environments**

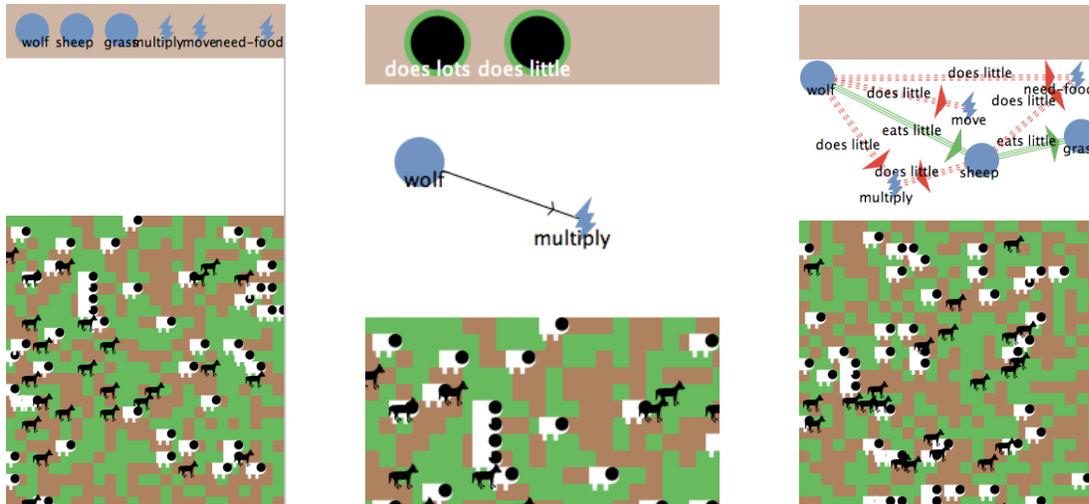
Our work is grounded in a constructivist paradigm of learning (Smith, diSessa & Roschelle, 1994). In this paradigm, new knowledge is constructed actively by the learners by bootstrapping, rather than discarding, their prior knowledge. This idea guided our focus on agent-based modeling. The term “agent” in the context of an agent-based model (or ABM) denotes individual computational objects or actors (e.g., cars), which are controlled by simple rules assigned by the user. ABMs are particularly suited for representing and understanding complex aggregate behaviors. It is the interactions between agents (based on these rules) that give rise to emergent aggregate-level behaviors of the model (e.g., formation of a traffic jam as an emergent aggregate outcome). A traffic jam can be thought of as a result of an aggregation of interactions between many individual “agents” or cars. At the individual level, the operating “rules” for each car are simple: each car accelerates if there is no car right ahead, and it slows down if it sees another car close ahead (Wilensky and Resnick 1999). The pattern that emerges as an aggregation of many such interactions between individual cars is the traffic jam. Emergent phenomena are often counter-intuitive to understand; for example, while individual cars move forward, the overall jam propagates in the backward direction (Resnick, 1994).

When students work with ABMs, they use their intuitive knowledge at the agent level as they are asked to manipulate and reason about the behaviors of individual agents. Then, by visualizing and analyzing the aggregate-level behaviors that are dynamically displayed in ABM simulations that involve interactions

between multiple agents, students can develop multi-level explanations by connecting their relevant agent-level intuitions with the emergent phenomena (Resnick, 1994; Wilensky & Resnick, 1999; Klopfer, Yoon, & Um, 2005; Sengupta & Wilensky, 2011; Blikstein & Wilensky, 2009). The scholars cited above have argued that in most science classrooms, aggregate-level formalisms are typically used to teach scientific concepts and phenomena, such as using the Lotka-Volterra differential equation to explain how populations of different species in a predator-prey ecosystem change over time (Wilensky & Reisman, 2006). While mathematically correct, these formalisms do not immediately make explicit the underlying agent-level attributes and interactions of the system, and, as such, remain inaccessible for most students. In contrast, agent-based reasoning (i.e., reasoning about the attributes and behaviors of the individual agents) has been claimed to be more accessible and to provide a bridge to aggregate reasoning (Levy & Wilensky, 2008). These claims are substantiated by experiments showing that when complex phenomena traditionally taught in high school (e.g., microscopic processes of electrical conduction) are represented in the form of multi-agent based models, much younger students (e.g., 4th and 5th graders) can access and understand those phenomena (Sengupta & Wilensky, 2011; Dicks & Sengupta, 2011).

**Designing modeling primitives and other scaffolds to support model development.** Our goal is to engage students in learning through developing a computational model. This necessitates some form of programming (i.e., students specifying computational variables and their relationships). However, rather than introducing students to domain-general concepts in programming, our goal is to introduce them to domain-specific computational primitives for modeling particular phenomena. Over the past year, we have been developing ViMAP-Arg, an agent-based computational modeling environment to support the integration of computational modeling and argumentation, based on the ViMAP architecture (Sengupta, 2011; Sengupta & Wright, 2010). The ontology of primitives we have chosen in ViMAP-Arg is based on node-link representations. Nodes and links indicate domain-specific conceptual entities, and students design a model by selecting nodes and relevant links between them (see Figure 1). For example, the upper portion of Figure 1a shows a list of the nodes through which students can control the behavior of an ABM simulation of a wolf-sheep predation ecosystem (bottom portion of Figure 1a). These nodes represent the different types of agents in the system (e.g., wolf, sheep, and grass) and the actions pertaining to each type of agents (e.g., move, multiply, need-food). The key interactions between agents (e.g., eating) are specified through links that appear as options only when a student clicks on relevant nodes (e.g., wolf, sheep, or grass). Once the student selects two nodes, (e.g., wolf and multiply), the students can also specify the quantitative level of the interaction by choosing between options (e.g., “eats a lot” versus “eats a little”) (Figure 1b). Figure 1c shows a screenshot of a sample model developed by selecting nodes and links that specify all the relevant actions and interactions between the different types of agents in the simulation.

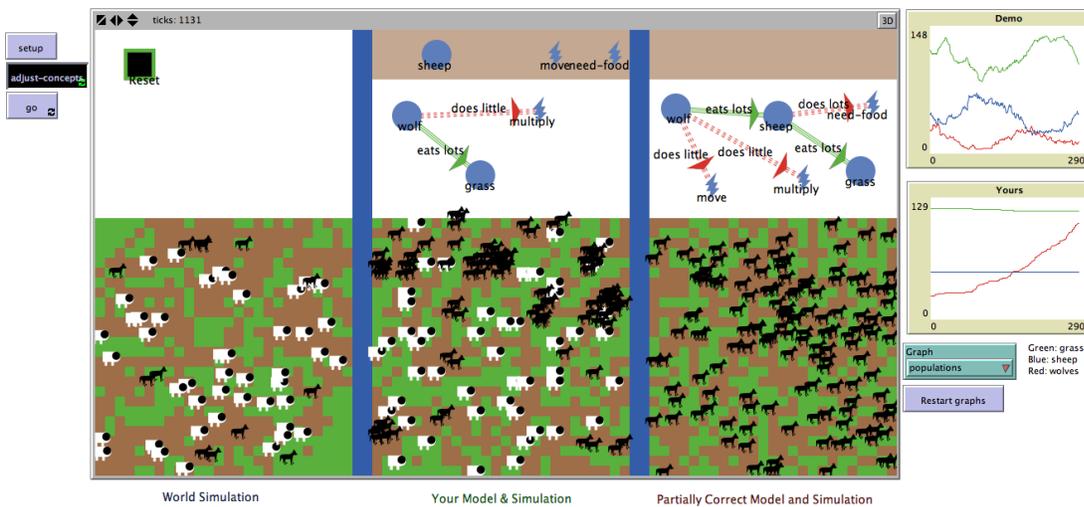
Because modeling is an iterative process, students can run the model during any stage of the model construction phase to test how components of their model affect the overall behavior of the simulation. Note that nodes and links represent agent-level behaviors and interactions between agents. Students can also visualize aggregate-level effects of these agent-level interactions in the form of graphs (e.g., graphs showing populations of different species over time).



Figures 1a-1c (L - R). Stages in creating a model using ViMAP-ARG.

**Designing software supports to leverage argumentation in order to support model development, ramification and deployment.**

In order to engage students in model ramification and deployment, students are also provided with multiple simulations displayed side-by-side in the learning environment (see Figure 2). The scaffolding here is provided in terms of the different levels of control that the student has over the models underlying each of these simulations. Besides the students’ own model which they construct from scratch, the other two models include a target “world”<sup>2</sup> simulation and a partially built faulty model. The target “world” simulation that the students are working to model provides target outcomes for the students’ own models. The faulty or partially-correct simulation is pre-built by the teacher or curriculum authors in order to create cognitive conflict in the students’ minds about important contextually relevant variables. The model (i.e., the node-link relationships) underlying the world simulation is completely hidden from the students, while the model underlying the faulty simulation can be modified by the students.



<sup>2</sup> Our use of the term “world” here is different than the usual use of the term in the literature on computational microworlds, where a microworld usually indicates a simulation (e.g., Resnick, 1994). Technically, ViMAP-Arg is a collection of three microworlds (or simulations). However, in our usage, “world” simulation indicates a target set of behaviors that are canonically correct and expert-like, and can act as a scaffold for modeling activities.

*Figure 2.* Screenshot of the user interface of ViMAP-ARG.

In terms of the models they develop, students begin with a template of a simple model in their modeling environment that is largely functional but has one or two nodes or parameters that need to be adjusted or changed to make the model reflect the target “world” data more closely. This might be framed for the students as a proposed model that needs to be critiqued and refined. As students progress in their modeling sophistication, the students can work to modify more sophisticated template models involving more parameters and nodes, and can also begin to develop new models using the same environment without the template of an initial model. Subsequent target data sets and representations involve increasing numbers of agents and explore elaborations on the preceding target models. The sequence of models therefore allows students to systematically explore the underlying science phenomena in a systematic sequence.

Providing students with multiple simulations can facilitate the data collection and analysis process by allowing students to simultaneously compare the target world data with output data from two versions of their own models. Students can then simultaneously compare the similarities and differences between the target world data in the world simulation and the two versions of the simulations over which they have control of the underlying models. In doing so, students engage in model deployment by scientifically assessing the aggregate-level effects of their model through conducting experiments. This comparison between the multiple simulations makes this a meaningful endeavor for the students. Students also engage in model ramification, as they explore how different assumptions and specification about the behavior of agents impact the overall aggregate-level outcomes.

A highly scaffolded version of this phase could then ask students to collect data in two variants of the constructed model and identify the salient data as evidence in a comparison about the validity of their claims. This would facilitate the students’ ability to connect differences in the data outputs with structural differences within their own models. This approach thus supports “debugging”, which is a core epistemic and presentational practice central to model development that involves identification of bugs (i.e., dissonances between the intended behavior of the model and the actual behavior of the model). However, in this context, the process of debugging indicates refining of models in a data and theory driven manner that supports practices central to argumentation, as opposed to a less productive process of model refinement through random trial and error.

Over the course of a given modeling project and also across the span of projects across the curriculum, the specific prompts for specific comparisons would fade or be reduced as students begin to understand the role and process of critique, allowing the students to take more responsibility for determining which aspects of the models are salient to compare, what data would support such a comparison, and what might constitute random sampling variation versus fundamental differences in both the target and student models.

## **A Closer Look at the Discursive Practices Related to Argumentation in the Integrated Modeling Environments**

In this section, we take a closer look at how discursive practices related to argumentation are supported in the integrated learning environment shown in Figure 2. We focus on three central practices: critique, explanation, and argumentation. We discuss how each of these practices can be supported in our learning environment, how these practices help develop students’ multi-level understandings of the target phenomena, and what a sample progression of the activities might look like.

**Critique.** In terms of argumentation, our proposed approach focuses on critique, explanation, and argumentation regarding the fit between the student’s model and the target “world” data in Figure 2, or similar comparisons using other modeling tools. Each cycle of modeling begins with the student critiquing the fit between the current version of the student model and the target world data in terms of both aggregate behaviors and agent level behaviors.

Aggregate behaviors involve the overall populations of each agent in the models as recorded in graphs created when running the student model or as provided in the target world data sets and representations. Examples in an ecology model would include the average population levels of each agent, patterns of change of the populations compared to one another (e.g., the squirrel population starts lower than the rabbit population but ends up higher), and the overall shapes of each population graph (e.g., discussing the amplitude and frequency of the population sine curves in a predator-prey interaction). Critique of aggregate behaviors involves comparing the graphs created when running the student model and the target world data and critiquing how closely the two sets of graphs match one another. Because agent-based models inherently incorporate variability from run to run, this activity includes a high level of authenticity because students need to run each model multiple times to determine which differences are likely due to sampling variation, and which differences might represent fundamental differences in the structures of the underlying models. It is also authentic in terms of students needing to determine which differences might be more or less salient for the phenomena under investigation.

Agent level behaviors involve the characteristics and behaviors of individual agent types in the model. Examples in an ecology model might include how fast an agent of a given type moves, what it eats, whether it reproduces, how much energy it needs, and whether and how it changes its behavior depending on the proximity of other agents. In some ways, one might think about the difference between aggregate behaviors and agent level behaviors as paralleling the ideas of “intrinsic” and “extrinsic” properties from chemistry, with aggregate behaviors being extrinsic in the sense that they are a population function of how many agents are involved at any given moment and the properties emerging from groups of agents, while agent level behaviors are “intrinsic” in the sense that they are the behaviors of individual agents. Comparing agent behaviors could involve tracking and watching individual agents in each model and comparing how they act and interact with the other agents in the model. Comparing agent behaviors might also involve tracking graphical output of mean behaviors or histograms of behaviors for individual agent behaviors (e.g., the speed of an agent type or the rate of reproduction for an agent type in an ecology model). As with the critique of aggregate behaviors, this involves a high degree of authenticity in the sense that students need to account for sampling variation as well as make decisions about what types of agent behaviors would be salient to track in terms of the phenomena under investigation. Thus, this is not a cookie-cutter activity, but one in which students need to think deeply about their goals, the processes of measurement and sampling, and the underlying phenomena.

While all modeling activities implicitly involve critique, traditional modeling activities often do not explicitly articulate this critique process or provide explicit scaffolds to support students engaging in the critique. Our approach proposes that students should have an explicit critique phase prior to each successive iteration in their model construction and revision. In terms of progressions across the curriculum and within a modeling project, students should initially be provided with specific prompts for the aspects of aggregate and agent level outputs they should compare, and directions as to how they should do so. Students should be prompted to explicitly address each of these comparisons through written description or other interfaces. Simply including fields in an electronic word processing document or paper handout can be sufficient. More sophisticated computer-based interfaces integrated into a modeling environment, however, could provide more flexible approaches. In an integrated computer-based modeling environment, for example, this could involve specifying the degree of matching point-by-point. A computer-based integrated environment could provide feedback regarding the critique point-by-point and support students in adjusting their critique in terms of any of those points.

**Explanation.** If discontinuities between the target world data and the student's model are identified through the critique phase, the student should then be scaffolded in creating an explanation/claim about the source/mechanism in the constructed model that leads to the discontinuity. This is essentially the creation of a claim about the underlying causal mechanism that simultaneously identifies and proposes corrective action. As with critique, traditional modeling activities implicitly include explanation of the sources of difference between the target world data and the student's model, but students in traditional modeling activities are also free to attempt random trial and error in revising the underlying structure of their model rather than investigating reasoned explanations for observed differences. Students should also be scaffolded in thinking about the implications of their proposed structural explanation in terms of whether the proposed changes fit all aspects of the world data and how the proposed change in the model might change what we think about the phenomena under investigation. For example, a student might conceivably improve fit between world data population graphs and the student's model by allowing deer to "fly" in the model, but that student should be encouraged to consider whether or not that fits with what else is known about deer. Thus students should be encouraged to consider explanations in terms of causal mechanisms that increase model fit with all aspects of the world data, rather than treating the modeling process solely as a programming challenge.

**Argumentation.** After creating an explanation about the source of differences between the agent and aggregate level outputs in terms of changes that need to be made to the student's model, the student should then be scaffolded in identifying and collecting further evidence for and against the proposed causal mechanism. This can include evidence collected during the Critique phase or during subsequent experimentation. Of specific importance, the teacher and the scaffolding should help students search for evidence that might contradict their claims, as well as evidence that might supports their claims, because research has shown that students initially tend to focus only on evidence that supports their claims and ignore evidence that contradicts their claims in a manner very similar to the ways in which scientists have historically dealt with anomalous data (Chinn & Brewer, 1993).

As with the Critique and Explanation phases, this scaffolding might simply comprise explicit prompts in a paper hand-out or electronic word processing document that provide instructions and fields for students to complete at the beginning of each successive iteration of their models, or these scaffolds might be integrated into the modeling environments themselves. Electronic word processing documents can be superior to paper handouts because they can allow students to "copy" aggregate and agent level output graphs and then "paste" them into the document. Students can then mark and annotate the graphs in their document to illustrate the specific comparisons or data points of interest. Paper hand-outs rely on students to draw and describe their data, which can focus students more explicitly on salient points, but can also become cumbersome. Ultimately, however, either approach can prove productive.

In modeling environments developed specifically to support this process, more flexible approaches for students to identify data might include the ability for students to "click" on specific points in the target world data and the data from their own models. A sophisticated environment might then provide feedback about how well the highlighted data supports the claim that has been made and prompt further reflection. Similarly, a sophisticated environment might allow students to create playable "movie" clips tracking the behaviors of individual agents in the model world to support claims about the agent characteristics in the model in comparison to the target world data (which might also include feedback from the environment about the fit between the data and claims).

A very important component of this phase involves engaging the student not only in identifying evidence that supports and conflicts with a claim but also in providing reasoning for why that data represents valid evidence regarding that claim.

**Progressions.** Many aspects of suggested progressions are discussed in the critique, explanation, and argumentation sections above in terms of progressions within a given modeling project as well as over time in successive modeling projects within the curriculum. Essentially, students will initially require a great deal of explicit scaffolding and support for each of the three phases. Furthermore, projects early in the curriculum might only include the critique phase, then gradually add the explanation and argumentation phases in later projects in the curriculum. Each phase should include explicit and detailed scaffolding when first introduced to make the underlying processes, goals, and criteria explicit. Discussions between the students and teacher should also make these processes, goals, and criteria explicit.

Scaffolding should subsequently be faded and reduced over time as students became more proficient. This reduction and fading is critical. The purpose of these scaffolds is not simply to help students explore the underlying science phenomena through inquiry-based modeling but also to support students in developing proficiency and habits of mind for engaging in authentic inquiry. As outlined earlier in this chapter, students should engage in inquiry that integrates products and processes of science. The explicitness and specificity of the scaffolding should be reduced in terms of the prompts and directions provided to the students. The goal in instruction involves fading aspects of the direct scaffolding/prompting within phases and actually gradually removing the phases themselves.

In terms of larger progressions within modeling projects, the arguments developed in the argumentation phase might then be plugged into the argumentation sessions and potentially even the blind peer review components of the ADI model. This would allow students to understand the role of argumentation within the scientific community as well as provide excellent feedback and practice highlighting the core ideas of modeling and argumentation, including the opportunity to develop shared understanding and criteria as a community for engaging in inquiry.

## Summary & Discussion

Science educators and historians of science have shown that scientific practices like argumentation and modeling develop only over the long term, both historically within the sciences and individually within the lifetime of individuals (Lehrer & Schauble, 2010). Early in this chapter, we claimed that students should understand three core ideas. First, modeling is the central enterprise, purpose, and goal of science. Second, argumentation is the practice that allows scientists to determine the fit of their models with the world. Third, communities of scientists evaluate models, methods, and evidence through argumentation using shared criteria and analytical approaches developed and agreed upon by the community. To address these goals, this chapter has outlined both the ADI approach developed by Sampson and colleagues for integrating argumentation with pre-built models (Sampson & Gleim, 2009; Sampson, Grooms, & Walker, 2009) and our proposed approach for integrating argumentation with modeling in agent-based computational environments.

From the perspective of the first goal of helping students develop a modeling-based epistemology of science, we argued that it is important that students should understand that modeling is the central enterprise, purpose, and goal of science, while they are engaged in longer term, authentic scientific inquiry. Based on Hestenes' (1993) categorization, our pedagogical approach involves fostering such an epistemology by engaging students in three kinds of modeling activities, including model development, model ramification, and model deployment in a computational learning environment that integrates modeling and argumentation. We have proposed design guidelines, as well as presented ViMAP-Arg, a freely available learning environment designed specifically to support both argumentation and modeling in the context of learning about population dynamics in a predator-prey ecosystem. The interested reader can go to this website and use an alpha-version of our online system:

<http://www.vanderbilt.edu/m3lab/arg2.html>

In terms of the second goal of helping students understand that argumentation is the practice that allows scientists to determine the fit of their models with the world, we have presented the ADI approach, based on which teachers can design instruction that will enable students to develop argumentation practices using pre-designed models. In addition, we have also outlined our own approach for integration with modeling in terms of how key discursive practices central to argumentation (such as critique and explanation) can be integrated with modeling. We propose that a productive integration of argumentation and modeling can result in a curriculum in which students can engage in all of the three kinds of modeling discussed by Hestenes (1993) in terms of development, ramification, and deployment. This stands in contrast to many typical modeling curricula in which students engage in one of these kinds of modeling. A key feature of our designed learning environment, ViMAP-Arg, is that students are provided with multiple simulations of the same phenomena that are displayed side-by-side. These simulations vary in terms of degree of accuracy, as well as in terms of the degree of students' access to and control over the underlying mathematical relationships that govern each simulation. It is through scaffolded learning activities that involve critique and explanation, based on comparison between the mathematical behavior of these simulations, that students engage in all the three kinds of modeling activities. Although we have contextualized much of our discussion in the particular context of ViMAP-Arg, we believe that the key design features we discussed here are generalizable, in that they can guide the design and development of computational learning environments to support the integration of modeling and argumentation in the context of learning other scientific domains (such as physics and chemistry).

In terms of the third overarching pedagogical goal, our proposed approach can be integrated into an overarching ADI framework to more closely integrate modeling and argumentation in service of engaging students as communities of scientists. In such activities, guided by the ADI approach, students' models developed in ViMAP-Arg can be used so that they can engage in evaluating models, methods, and evidence through argumentation using shared criteria and analytical approaches developed and agreed upon by the community.

While science education has historically attempted “to cultivate students’ scientific habits of mind, develop their capability to engage in scientific inquiry, and teach them how to reason in a scientific context” (NRC, 2011), these three foci have traditionally often been treated separately (Driver, Leach, Miller, & Scott, 1996; Lemke, 1990). There is now growing agreement that students need to understand science and the processes of science as functions of argumentation and modeling (Duschl, 2008; Kelly, 2008; Lehrer & Schauble, 2006). The framework for the new science standards in the United States therefore “stresses the importance of developing students’ knowledge of how science and engineering achieve their ends while also strengthening their competency with related practices” (NRC, 2011, p. 3.1). Toward this end, this chapter has outlined how approaches for integrating argumentation and modeling can productively engage students in inquiry-based activities that support learning of complex scientific concepts as well as the core argumentation and modeling practices that are at the heart of scientific inquiry.

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