Models and Modeling in Science Learning

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Definition and Theoretical Background

Models are physical, computational, or mental representations that are intended to stand in for some other thing, set of things, or phenomena. *Scientific models* in particular are tools for expressing scientific theories in a form that can be directly manipulated, allowing for description, prediction, and explanation. For example, a biology teacher might show students a plastic replica of a human heart, identifying the ventricles and their relative locations. The replica is not an actual heart, but rather a sculpted reproduction that is intended as an educational tool. This type of model can be handled by students, perhaps taken apart and reassembled, as a means for becoming familiar with the structural features of the heart. The types of educational supports and activities used in everyday science classrooms often rely on such *physical models* (e.g., ball-and-stick chemical molecules; a globe of the Earth; mechanical models of engines built with Lego bricks and gears). There are, though, other types of models that have proven valuable as educational tools. *Virtual models* are computer reproductions of actual objects (e.g., a 3-dimensional image of a brain; a program that can explode the Earth to display the interior structure) or interactions between those objects and phenomena (e.g., PHET simulations of the behavior of electrical circuits) that are manipulated through a software interface. Notably, virtual models are useful for exploring concepts or processes, but do not necessarily allow a learner to modify or iterate the underlying computer program or architecture. In contrast, *computational models* are glass-box simulations of scientific phenomena which can be modified, extended, and rebuilt by learners through direct manipulation of their underlying programs. Computational models have been designed for research domains including physics (e.g., electrical conduction), biology (e.g., natural selection), chemistry (e.g., gas laws), and materials science (e.g., crystallization) (as examples, developed in the NetLogo modeling platform). These models allow individuals to design and test aspects of their simulated objects and processes, and have been used successfully as learning environments in K-16 settings. We also note that these various models are also employed by scientists in actual research laboratories, and thus are not restricted in terms of who might benefit from their usage.

The externalized physical, virtual, and computational models that are employed in science classrooms and laboratories are intended as supports for helping individuals to build internalized *mental models* for scientific concepts. Mental models are mental representations for objects and concepts we learn and know about. For example, an experienced Earth Scientist likely has an elaborate understanding of the causes and consequences of earthquakes, such that predictions could be made about the likelihood of tectonic events under various geological circumstances. When we run mental simulations in our minds for how and why things might happen, we are employing mental models. Mental models, then, are crucial memory representations that can exemplify adequate comprehension. They are the mental products that hopefully result from the use of scientific models.

In the context of science education, modeling refers to the process of constructing, extending, verifying, or testing scientific models. As Schwarz and White (2005) clarify, the term *scientific modeling* identifies the process used in much of modern science that involves (a) embodying key aspects of theory and data into a model—frequently a computer model, (b) evaluating that model using criteria such as accuracy and consistency, and (c) revising that model to accommodate new theoretical ideas or empirical findings as necessary. Consider that one of the central pedagogical goals of modeling is to scaffold students' development of mechanistic explanations of scientific phenomena. In pursuit of this goal, scientific modeling requires that individuals define and identify important variables and their characteristics as pertaining to the object, system, or phenomenon being modeled. Based on these definitions, individuals can think about how the identified variables interact, and as such, how measurement of those variables and the overall model might be constructed. And the success or failures of the resulting models as adequate tools for generating hypotheses and testing data-driven outcomes can be utilized in an iterative way to consider their effective redesign. Scientific modeling, then, is an iterative design process that encourages conceptual understanding and careful testing of model-relevant topics. It is worth noting that the activities described here are directly in line with the activities associated with the scientific method in general; as such, it might be argued that models are themselves the actual language of science (e.g., Giere, 1988).

But beyond theoretical considerations, there is considerable evidence that scientific models and the process of scientific modeling are effective tools for learning. For example, researchers have contended that engaging in the modeling process can help individuals develop sophisticated mental models of scientific phenomenon as well as deep domain knowledge. For example, students who utilized lab-based simulations of ground-water flow demonstrated better understanding of underlying scientific principles (e.g., Darcy's law) as compared to students who were provided with informationally equivalent readings (Renshaw, Taylor, & Reynolds, 1998). In another example, students who used computational models of electrical conduction demonstrated a much better understanding of key concepts in electricity, as compared to students who underwent traditional textbook based instruction (Sengupta & Wilensky, 2009).

Important Scientific Research and Open Questions

But what makes modeling so effective as an educational practice? Researchers have argued that computer modeling can make scientific material more accessible and interesting by bootstrapping students' personal and intuitive knowledge, as well as their naïve representational competencies. Beyond issues of motivation and engagement, researchers have also argued that models embed activities in contexts that are highly *authentic* - that is, the activities involved in scientific modeling closely align with researchers' actual practices of doing and thinking about science (Lehrer & Schauble, 2000). Thus, students who engage in modeling are involved in scientific activities that necessitate causal reasoning, hypothesis testing, the generation and evaluation of ideas, and the representation, recording, and analysis of data through scientific inscriptions. These activities encourage encoding into memory, deeper processing, and the types of cognitive experiences that foster learning and transfer (Rapp & Kurby, 2008).

Over the past decade or so, several new forms of modeling have emerged in science education; these models incorporate aspects of physical, virtual, and computational models in their design and usage. Some notable examples include emergent modeling, micro-behavior based modeling, tangible programming, and hybrid modeling. Emergent models are best suited for modeling complex systems, in which complex phenomena at one level (e.g., population dynamics in ecosystems; behavior of electrical circuits) emerge from simple interactions between thousands (or hundreds of thousands) of individual level actors or "agents" (e.g., predators and preys; electrons and ions), without a key leader or a centralized process. Micro-behavior based modeling is an even more recent invention - it provides students with a few prototypical "agents" and their "behaviors." Micro-behaviors themselves are bits of code that are carefully designed to be easily understood, composed, and parameterized. Students assemble and execute combinations of these micro-behaviors to generate a composite model. Tangible programming combines the power of traditional computational programming with the usability of simple physical manipulatives (e.g., wooden blocks). Tangible programming has been used successfully in informal settings (e.g., museums) for science education. Finally, hybrid or bi-focal modeling involves connecting real-world sensors and physical devices (e.g., motors) to computational models. Using such models, students can control, validate, and refine their computational models with real-world data. As these descriptions suggest, contemporary modeling trends are affording the opportunity to consider processes, phenomena, and objects that are multidimensional and complex, which without modeling would be difficult to observe and challenging to understand.

There are a variety of directions we envision for the future of scientific modeling, but here we constrain discussion to three important elements. First, there is still a need for data on the ways in which modeling practices influence learning. This could involve projects that range from, but are not limited to, ethnographic analyses of classrooms that utilize modeling as a primary or complementary instructional tool, randomized controlled trials of comparison classrooms utilizing different types of modeling scenarios and tasks, and mixed methods designs that seek to describe and explain any potential benefits (and limitations) of modeling activities. Second, future work should examine how to best prepare students for engaging in modeling practice. For example, researchers are now investigating various approaches through which students can be introduced to emergent modeling in specified STEM domains including physics, chemistry, biology, materials science, etc. Third, there is a genuine need for preparing teachers to employ modeling activities in their classrooms. This includes not just informing instructors about the available tools and models that they might use as part of their instructional activities. It involves investigation of the challenges that students and teachers face while engaged in modeling, as well as the design of useful instructional supports that promote effective student and teacher interactions with scientific modeling.

Cross-References

Mental models
Modeling & simulation
Problem-based learning
Simulation-based learning

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