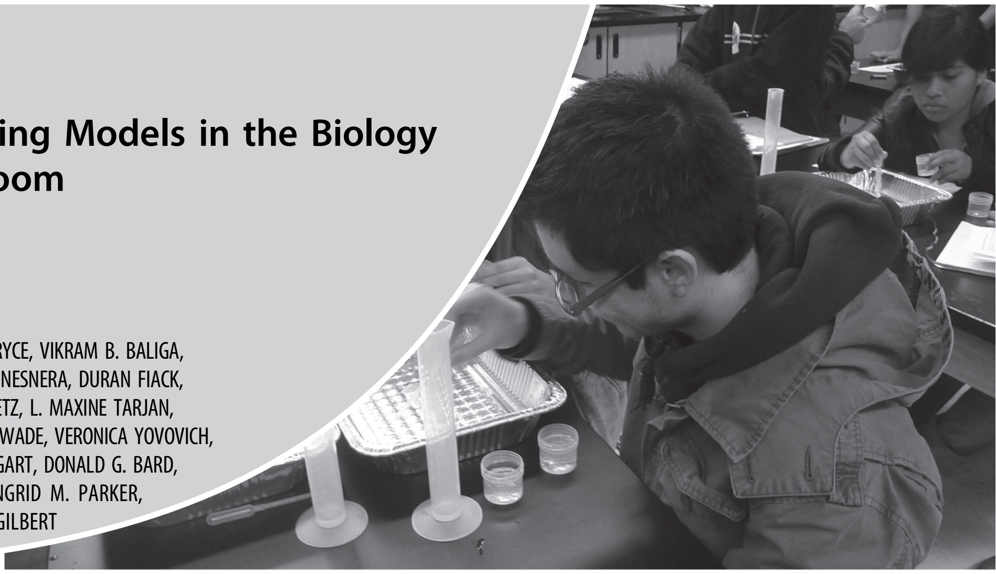
FEATURE ARTICLE

Exploring Models in the Biology Classroom



CALEB M. BRYCE, VIKRAM B. BALIGA, KRISTIN L. DE NESNERA, DURAN FIACK, KIMBERLY GOETZ, L. MAXINE TARJAN, CATHERINE E. WADE, VERONICA YOVOVICH, SARAH BAUMGART, DONALD G. BARD, DORIS ASH, INGRID M. PARKER, GREGORY S. GILBERT

Abstract

Models are simplified representations of more complex systems that help scientists structure the knowledge they acquire. As such, they are ubiquitous and invaluable in scientific research and communication. Because science education strives to make classroom activities more closely reflect science in practice, models have become integral teaching and learning tools woven throughout the Next Generation Science Standards *(NGSS). Although model-based learning and curriculum are not novel in educational theory, only recently has modeling taken center stage in K–12 national standards for science, technology, engineering, and mathematics (STEM) classes. We present a variety of examples to outline the importance of various types of models and the practice of modeling in biological research, as well as the emphasis of NGSS on their use in both classroom learning and assessment. We then suggest best practices for creating and modifying models in the context of student-driven inquiry and demonstrate that even subtle incorporation of modeling into existing science curricula can help achieve student learning outcomes, particularly for English-language learners. In closing, we express the value of models and modeling in life beyond the classroom and research laboratory, and highlight the critical importance of "model literacy" for the next generation of scientists, engineers, and problem-solvers.*

Key Words: Next Generation Science Standards; *model-based learning; inquiry-based science; scientific practice; student learning; inquiry-based learning.*

○ Introduction

The *Next Generation Science Standards* (NGSS) aim to make the teaching of science more closely aligned with the practice of science. The NGSS highlight models, which are simplified representations of more complex phenomena, as central to all aspects of learning in science, technology, engineering, and mathematics (STEM; NGSS Lead States, 2013a). Mirroring the process of scientific research, the NGSS are structured in three primary sections: *Disciplinary Core Ideas* (the knowledge base that scientists need to do their work), *Practices* (what scientists actually do), and *Crosscutting Concepts* (frameworks scientists use to connect core ideas). *Performance Expectations* (learning and skills assessment) within the NGSS are combinations of these *Crosscutting Concepts*, *Practices*, and *Disciplinary Core Ideas*. "Developing and using models" is one of seven NGSS *Practices*, and "Systems and system models" is one of eight *Crosscutting Concepts* within the NGSS (National Research Council, 2012a). Because NGSS *Performance Expectations* emphasize student engagement in using models to explicitly demonstrate knowledge of *Disciplinary Core Ideas* (e.g., HS-LS1-5: Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy), it is critical that teachers regularly and clearly incorporate scientific models in science lessons.

Models are key elements in daily practice for biologists, and model-based learning has a rich history in educational theory.

Models are key elements in daily practice for biologists, and model-based learning has a rich history in educational theory (Louca & Zacharia, 2012). Nevertheless, many biology teachers are not well versed in the broad range of models used by scientists and therefore find it difficult to envision how to incorporate them into classroom instruction (Hoskinson et al., 2014). This may be because instructors fail to realize that models extend far beyond the familiar 3D physical models of cell structure or the digestive system. In fact, teachers and scientists alike use a variety of model types in their instruction and research without labeling them as such.

Here, we (1) highlight the diversity of ways in which models are used to conduct and teach science and (2) provide a framework for intentional use of models in biology classroom activities as emphasized by the NGSS. As practicing scientists and educators working together to infuse inquiry-based science curricula in local middle and high school classrooms through a National Science Foundation GK–12 program (http://scwibles.ucsc.edu), we offer a perspective on the use of models in the biology classroom that comes from both

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biological research and educational theory. We describe a range of ways in which models can be used in the classroom, and how the NGSS emphasize modeling as a central practice. We outline a "modeling continuum," analogous to Herron's (1971) inquiry continuum, and make suggestions for how teachers can acknowledge and enhance their use of models in the classroom in either subtle or substantial ways to more effectively mirror the essential scientific practice of modeling.

○ Models in Biology Research

Scientists primarily use models in two ways. First and foremost, models are used to increase our understanding about the world through evidence-based testing. To evaluate the merits and limitations of a model, it must be challenged with empirical data. Models that are inconsistent with empirical evidence must be either revised or discarded. In this way, modeling is a metacognitive tool used in the hypothesis-testing approach of the scientific method (Platt, 1964). Second, scientists use models to communicate and explain their findings to others. This allows the broader scientific community to further challenge and revise the model. Furthermore, this dynamic quality of scientific models allows researchers to test, retest, and ultimately gain new understanding and insight.

Biologists use models in nearly every facet of scientific inquiry, research, and communication. Models are helpful tools for representing ideas and explanations and are used widely by scientists to help describe, understand, and predict processes occurring in the natural world. All models highlight certain salient features of a system while minimizing the roles of others (Starfield et al., 1990; Hoskinson et al., 2014). By nature of their utility, models can take many forms based on how they are created, used, or communicated. After reflecting on the types of models we use in our daily work as biological researchers, we have identified three main categories of models used regularly in scientific practice: concrete, conceptual, and mathematical (Figure 1).

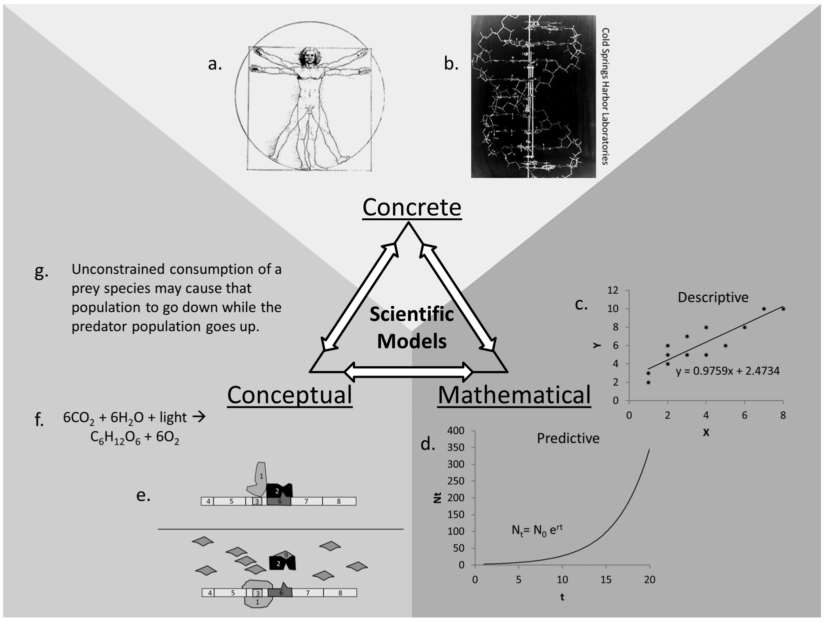


Figure 1. Scientific models may be concrete (physical representations in 2D or 3D), mathematical (expressed symbolically or graphically), or conceptual (communicated verbally, symbolically, or visually). Concrete models can be simplified representations of a system (**a**) or working-scale prototypes (**b**). Mathematical models can be descriptive or predictive, and empirical or mechanistic. A descriptive model, such as a regression line, depicts a pattern of association that is derived from empirical data (**c**), whereas a predictive model uses equations to represent a mechanistic understanding of a process (**d**); each can be expressed both symbolically and visually. Conceptual models focus on an understanding of how a process works and can be expressed as visual (**e**) or symbolic (**f**) representations as well as through verbal descriptions or analogies (**g**).

Development of scientific models of one type can prompt and inform models of other types. For example, Watson and Crick developed a physical model of DNA to help determine how different nucleotide bases can pair to produce a double-helix structure (Figure 1b), which in turn suggested a conceptual model for DNA replication (Watson & Crick, 1953). Jacques Monod's observation of a "double growth curve" of bacteria that deviated from the expected exponential growth model led to the development of a new, more accurate model of cellular regulation of gene expression (Figure 1e; Jacob & Monod, 1961). Ecologists James Estes and John Palmisano developed conceptual models of population growth and decline among marine predator–prey species (Figure 1g) on the way to creating mathematical models of sea otter, sea urchin, and kelp dynamics along the Alaskan coast (Estes & Palmisano, 1974).

○ Models in Learning & Teaching

"Model-based learning" refers explicitly to the understanding gained while creating or refining scientific models (Louca & Zacharia, 2012), but mental models are central to learning theory more broadly and provide the foundation for all other types of models (Johnson-Laird, 1983). Mental models often preexist instruction and are limited to conceptual or mathematical forms. A person's conceptual understanding of a process or relationship (i.e., mental model) directly informs his or her creation of a model, whether that model is concrete, conceptual, or mathematical. Through testing and experience, these models can be updated to reflect reality more accurately. As students iteratively draft scientific models, they inevitably modify their underlying mental models through analysis. In a classroom context, students refine their own mental models as they observe, analyze, and discuss the modeling work of others.

Learning theorists from the cognitivist school typically sought ways to translate mental operations into visible forms called "representations," such as diagrams or flowcharts. The internal representations that comprise mental models are tightly linked to reasoning associated with learning (Bauer & Johnson-Laird, 1993; Johnson-Laird, 2010). To this end, the emphasis of NGSS on modeling in the science classroom may present unique learning opportunities for students who are English-language learners. Developing and

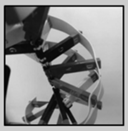
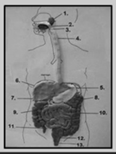
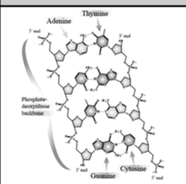
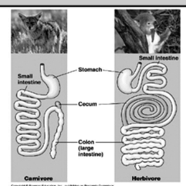
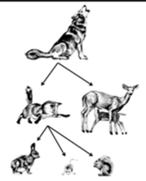
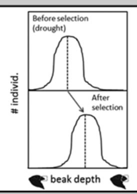
Mode	DNA	Digestive System	Food Web	Evolution
Concrete (material) models are typically made of solid material	DNA physical model (e.g., constructed from plastic molecular model kit) 	Clay model of digestive system 	Terrarium (or aquarium) 	Galapagos finch beaks 
Verbal models include descriptions, metaphors, analogies, and mnemonics to explain phenomenon (can be spoken or written)	"The DNA molecule is structured like a twisted ladder with sugar-phosphate molecules as the side rails and base pairs as the rungs."	"The gastrointestinal tract is like a long, continuous tube of varying diameters (depending on the organ)."	"Species exist in a complex web of what-eats-what within an ecological community."	"Finch beaks are specialized for feeding like different types utensils. Forks, knives, spoons, and chop sticks are each more suited for certain food items than others."
Symbolic models include chemical formulas, equations, and mathematical expressions	Knowing A-T and G-C, calculate A from G. If G = 20%, then what % A? (100-(2*20))/2) = 30% A	Simple enzyme-catalyzed reaction kinetics: $E + S \underset{k2}{\overset{k1}{\rightleftharpoons}} ES \xrightarrow{k3} E + P$	Assuming 10% of net energy production is transferred up to the next trophic level, how much energy is available to 2° consumers if producers generate 10,000 kcal? About 100 kcal	Lg beak size = A (dominant) Sm beak size = a (recessive) 100 finches have the following genotypes: 50AA, 15Aa, & 35Aa. Calculate allelic frequencies for A & a pre & post selection when 100 sampled finches have genotypes: 75AA, 5Aa, and 20aa.
Visual models include graphs, diagrams, and animations				
Gestural models refer to the use of body parts as a mode of explanation	Instructor demonstrates unzipping and pairing motion with hands and interlocking fingers	Sequential, repeated gripping motion with hands to demonstrate peristalsis	Students stand in 3 or 4 rows (trophic levels), then pass a ball of yarn to demonstrate appropriate trophic linkages in an ecosystem	Using different types of utensils, students pick up different types of materials of seeds of varying size and shape

Figure 2. Examples of biological concepts taught in the high school biology curriculum, represented by each of Gilbert's (2004) five modes of modeling at different scales.

using models provides these students with nonverbal ways to express understanding initially, and their consistent use in the classroom gives these students practice and confidence in speaking about how models explain observations (Quinn et al., 2011). The interplay between representations (i.e., models) of a system and the language used to describe them builds students' conceptual understanding of the system in question while refining their science literacy (Quinn et al., 2011; Stoddart et al., 2011).

Model-based learning has seen numerous interpretations in theory and practice (Gobert & Buckley, 2000; Buckley et al., 2004; Clement & Rea-Ramirez, 2008; Louca & Zacharia, 2012; Windschitl, 2013). Here, we adopt Gilbert's (2004) taxonomy of five modes of modeling: concrete, verbal, symbolic, visual, and gestural (Figure 2). These closely overlap our categorization of models in biological research (Figure 1), with the addition of gestural models, which scientists use regularly to complement their verbal communications. A key distinction is that the five modes of modeling (Figure 2) offer a framework for how models are used in teaching, while our three categories of models (Figure 1) provide a structure for categorizing models used routinely in science. This three-part taxonomy of model types is useful for identifying things that are unknown (new hypotheses, unexplored relationships among variables), whereas modeling used in teaching often illustrates known concepts to help students make sense of what scientists accept as supported by evidence.

Model-based learning typically consists of five steps: (1) observation and data collection, (2) construction of a preliminary model, (3) application, (4) evaluation, and (5) revision of the preliminary model (Fretz et al., 2002). In practice, model-based learning and model-based inquiry are reflections and extensions of the scientific method (Windschitl et al., 2008) and have been applied across a variety of disciplines in both computer-based learning environments and classroom settings (Fretz et al., 2002; Clement & Rea-Ramirez, 2008).

○ A Modeling Continuum within the Framework of NGSS

The *Framework for K–12 Science Education* (National Research Council, 2012a) offers an outline for teachers to provide gradual exposure to model development to students at each grade level. The use of models for K–12 students progresses from simple (e.g., model duplication) to complex applications (e.g., tests of model reliability and predictive power) as classroom activities transition from demonstrations by the instructor toward student-directed inquiry (Figure 3). In earlier grades (K–2), students largely focus on recognizing models as tools that can be used to explain familiar structures (e.g., a plastic skeleton or diagram of a plant) or scientific practices (e.g., measuring quantities, comparing relationships). Students are presented with

Model Development (Simple to Complex)	Scaffolding Questions for Students
Identification	• What object or process does the model represent?
Features & Assumptions	• What are the salient features that you decided to include and why are they important? • Compare your original object or process with your model. What features did you need to leave out of the model to make it clear? Are those features important? • Are some features more biologically accurate than others? Does it matter whether they are biologically accurate?
Usage	• What is the domain over which your model is applicable? • What scientific questions can you answer using the model?
Evaluation	• How can you test how well this model represents the object or process you were trying to represent? • How can you make this model more realistic? • Create a quiz for your classmates where they are only allowed to use information from your model to answer.
Revision	• Based on your quiz results, would you make any additions or clarifications to your model? • What would happen if you removed one feature of your model? Would the model still represent your original object or process? What is the smallest number of features you could use in your model (the simplest model you can make) and still represent your original object or process?
Synthesis	• What other kinds of models could you have made to represent your original object or process? What would be the advantages & disadvantages of the different model types? For instance, how could you create a complement to the clay cell model to illustrate more processes?

Figure 3. Asking students questions about their model can help them make subtle shifts toward more complex engagement with models; students shift from simply identifying models, to using them, to constructing their own models. This progression of how students engage with models parallels that which is established across grade levels (NGSS Lead States, 2013a).

model-building activities that are designed to unveil common characteristics of models and how they are used in STEM fields.

During the next stage of educational development (grades 3–5), students start to build and revise simple models to design solutions to problems or represent phenomena (e.g., 3-LS1-1: Develop models to describe that organisms have unique and diverse life cycles, but all have in common birth, growth, reproduction, and death; NGSS Lead States, 2013b). Students begin to develop and apply models to describe processes, explain relationships, and make predictions.

As students advance to middle school (grades 6–8), the use of models expands to predicting and testing more abstract phenomena (e.g., MS-LS1-7: Develop a model to describe how food is rearranged through chemical reactions, forming new molecules that support growth and/or release energy as this matter moves through an organism; NGSS Lead States, 2013b). At this stage, students undertake increasingly open-ended investigations of model structure. Such investigations include variable modification to validate observed changes in a system, integration of uncertain and unobservable factors and/or variables, and the generation of data to test hypotheses explicitly. Finally, in high school (grades 9–12), students construct and use models for more advanced prediction and to represent interactions between variables within a system (e.g., HS-LS2-5: Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere; NGSS Lead States, 2013b). Inquiry at this stage is largely focused on the critical evaluation and comparison of different models to improve predictions and explanatory power.

This learning progression for "Developing and using models" (NGSS Lead States, 2013a) offers a continuum of exposure to modeling through inquiry. Students are initially taught how to recognize the use of models in STEM fields before advancing to more complex activities in which they revise, compare, and evaluate models on the basis of predictive and explanatory power. In this framework, models are constructs that are useful to ask or answer a question, rather than just to describe an object (e.g., a mathematical equation versus a physical model of a cell). Models are abstract descriptions that can be refined through evidence-based testing by examining the assumptions, domain, parameters, and structure of the model (see Figure 4).

○ Inquiry & Learning to Create & Modify Models: Classroom Best Practices

Inquiry encompasses more than just asking questions: it involves expanding one's depth of knowledge (Webb, 1997) through systematic exploration of a subject from various perspectives. A scientist or student engaged in inquiry begins by distinguishing what is known from what is unknown in the context of a specific learning outcome.

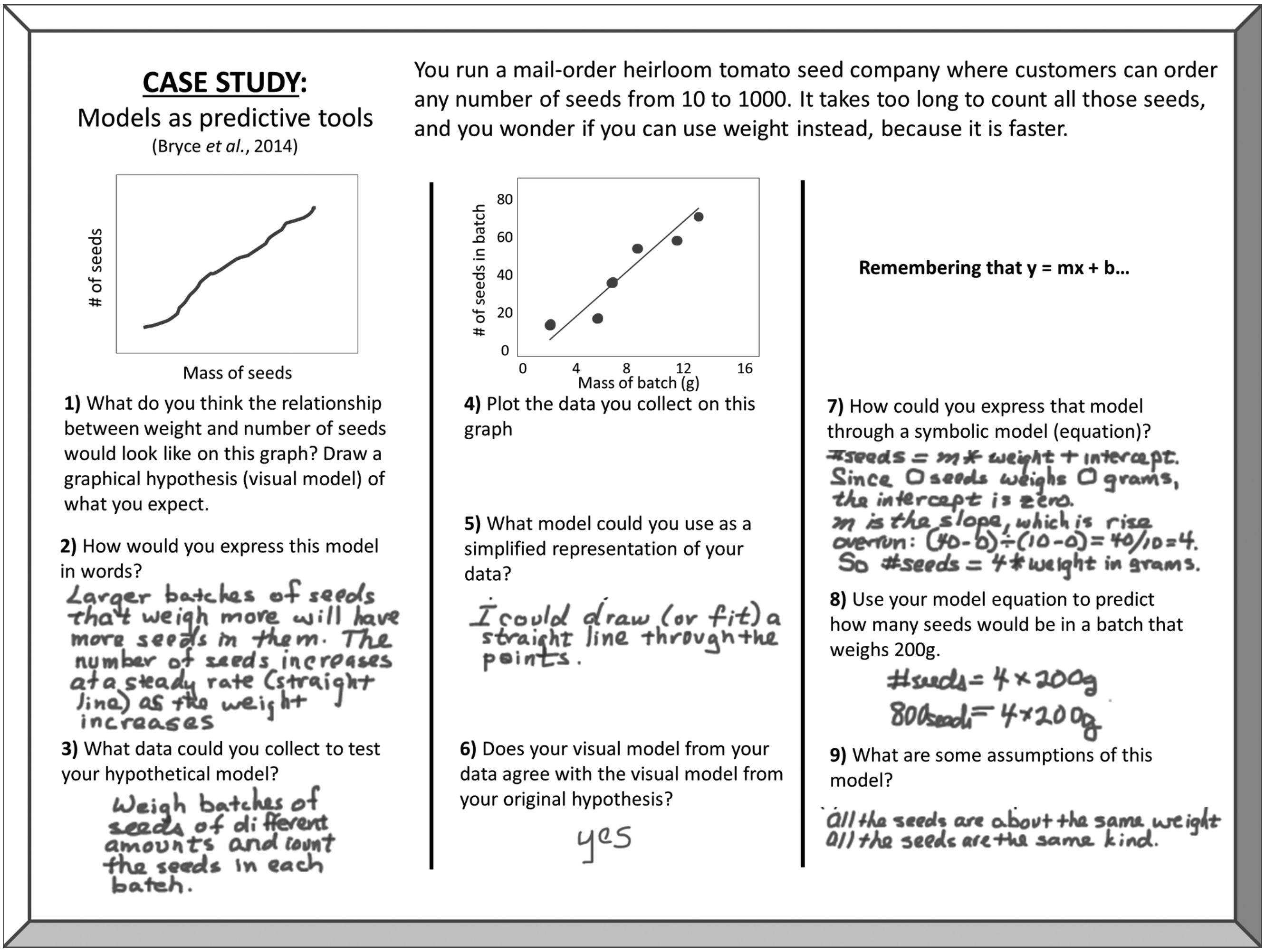


Figure 4. Case study (Algebra I and Algebra II students): Models as predictive tools (Bryce et al., 2014).

Creating models helps identify the most important features of complex processes and is a productive exercise for inquiry-based activities. Breaking down a complex process into its constituent parts helps students derive the process itself rather than memorize a series of facts about a process. Next, the student creates a model to represent and simplify a phenomenon and/or relationship in order to develop questions and hypotheses, which are subsequently tested through data collection. Data are used to reevaluate the initial model and develop arguments based on evidence. Additionally, revising models provides students with metacognitive opportunities – they better understand their own thinking through evaluation. Initial models evolve to reflect the learning that ultimately results from curiosity-driven investigations to understand how a system operates (NGSS Lead States, 2013a).

Perhaps the most effective use of models and modeling in the classroom is to have students create a model upon exposure to a new idea, and then revisit and revise that model over an extended period (Windschitl, 2013). Students return to their models multiple times over the course of a unit to incorporate ideas learned from subsequent readings, activities, tests, and discussions. In this way, students revise and develop more nuanced models while using critical-thinking skills to expand their depth of knowledge. For example, after being introduced to the term *biodiversity*, high school students devised their own conceptual and mathematical models to assess biodiversity. Over the course of the school year, they tested and refined these models by quantifying plant and insect diversity before and after planting a native plant garden on the school's campus (Yost et al., 2012).

This prolonged time frame may prove challenging for instructors who are just beginning to use model-based inquiry in their classrooms. However, it deepens students' understanding of the scientific process and, from our experience, becomes easier to implement with practice. When considering this approach to models and modeling, certain forms of models are better suited for use in science classrooms than others. Models are most effective in science education when they offer clear visual representation of processes or phenomena, incorporate both observable and unobservable features, are context-rich, and can easily be revised (Windschitl, 2013). Unobservable features are not detectable by human senses or technology. Events or processes may be unobservable because of their spatial scale (e.g., atoms, the universe) or temporal scale (e.g., evolution, continental drift) or because they are not accessible physically (e.g., Earth's core) or temporally (e.g., geologic time; Ambitious Science Teaching, 2015). Unobservable features also include inferred relationships, such as

Table 1. Student model-assessment criteria.

Criterion	Description	Example
Composition	Does the model include all the major components of the process it describes?	Does a food web include all key species and connections?
Accuracy	Does the model accurately describe the underlying process that generated your data?	Are cause-and-effect relationships appropriately represented by the model?
Prediction	Can you make predictions with your model?	Does your regression of number of seeds on mass of seeds accurately predict the number of seeds in a new batch of seeds? (See Figure 4, question 8)
Comprehension	Does the student understand the assumptions of the model?	Can a student use his or her model to describe the process it represents?

the slope of a regression line, which is not itself measured empirically but, rather, relies on inference from data.

In the classroom, instructors generally rely on formative assessment to evaluate student learning and performance. In the context of model-based learning, assessment should evaluate the development of student knowledge and the application of that knowledge toward a deeper understanding of scientific practices (National Research Council, 2012a). We offer four assessment criteria that can be used to evaluate the composition, accuracy, predictive power, and comprehension of models to determine the depth of student knowledge and application of models in the classroom (Table 1).

We emphasize here that, while modeling is an essential scientific and classroom practice for enhancing learning, it complements rather than precludes the use of other demonstrated teaching tools. Teachers should choose the correct teaching tool for their learning objective. Therefore, their goals will determine how much time they spend on modeling in the classroom. In other words, modeling is the most appropriate learning tool in many, but not all, situations. For example, if you want students to learn how to pipette, they probably do not need to draw a conceptual model about pipetting. However, drawing arrows to illustrate the interactions between organisms can help tremendously in understanding food webs.

○ Subtle Shifts in the Classroom

It would be ideal to incorporate many full-scale, inquiry-based modeling activities into science classes to encourage students to explore and explain the natural world. However, limited time and resources in existing science curricula mean that this is not always practical. Fortunately, teachers can shift their lesson plans in subtle ways to incorporate modeling exercises on a smaller scale while still enhancing student learning. Even at small scales, the repetitive, contextualized practice of model-building helps students acquire knowledge, generate predictions and explanations, analyze and interpret data, develop communication skills, and make evidence-based arguments through active participation (Schwarz et al., 2009). Many types of activities currently used in the classroom can be easily adapted in small, manageable ways to teach students about models by using "subtle shifts" (Figure 3). Here, we explore how to enhance lab and classroom activities by engaging students with scientific modeling in small but meaningful ways.

Figure 5. Clay cell models with organelles are ubiquitous in biology classrooms, but inquiry can be infused to illustrate the process of modeling beyond simple physical representations.

We often ask students to create simplified physical replicas of objects, which supports active learning (i.e., "learning by doing"; DuFour et al., 2006). In STEM courses, active learning with physical objects increases student performance, particularly in historically underrepresented populations (Eddy & Hogan, 2014; Freeman et al., 2014), through engaging the tactile senses (Nersessian, 1991; Begel et al., 2004). Active, hands-on learning also helps students analyze the organization and orientation of component parts (Haury & Rillero, 1994).

Revisiting an example mentioned earlier, a common classroom-learning activity is to have students construct a clay model of a cell (Figure 5). Through some simple, scaffolded inquiry, this basic physical representation can be a vehicle to a deeper understanding of modeling as a *process*. Asking questions about the physical models they have made can help students understand the context and justification for their model, as well as think critically about what their model truly represents. What cell features did they include in the clay cell model, and what features did they omit – and why? What does this model demonstrate about a cell? Which aspects of a cell are hard or impossible to represent with a clay model? Further, teachers may try shifting the objective of building physical models from serving as simple representations to addressing scientific questions. For instance, instead of building a model that reproduces the features of plankton, have students construct models of plankton to test the effect of structure on plankton sinking rates (Smith et al., 2007). By generating hypotheses about the traits that affect buoyancy, creating a series of models of different shapes, and then timing their sinking rates through a viscous liquid (e.g., corn syrup), students can use models to learn why high surface-area-to-volume ratio is a common adaptation that reduces sinking rates of oceanic plankton.

Biology students often learn about complex processes, such as nutrient cycling or DNA transcription and translation, through system models. System models are organized groups of related objects or components that form a whole (National Research Council, 1996, 2012b). An example of a simple system model is the "Vitruvian Man" figure used in some anatomy courses (Figure 1a). The Vitruvian Man is an illustration created by Leonardo da Vinci that depicts a male figure in two superimposed positions, simultaneously inscribed in both a circle and a square. This image of the human figure is a model that represents ideal human proportions as described by the ancient Roman architect Vitruvius. On this illustration, da Vinci's notes describe 15 ideal human proportions, the most famous of which is that the height of a person equals the length of his or her outspread arms. Da Vinci's visual model remains one of the most referenced and reproduced images in the world, appearing in books and films and even on coins, and presents an excellent opportunity for classroom inquiry.

Beyond engaging the iconic Vitruvian Man image in a historical and cultural context, students can explore it as a model by questioning its assumptions and testing its accuracy (Baliga & Baumgart, 2014). This activity gives students the opportunity to use a general model to form a specific hypothesis, analyze data, and, ultimately, argue whether the evidence they gathered supports their hypothesis. Students can explore patterns in human anatomical scaling by taking linear measurements of various body parts across many individuals (i.e., fellow classmates). Using measured body dimensions to generate scatterplots and linear regressions, students can examine the relationships between the measurements. This provides students with a visual representation of how variable their data are and allows them to see whether ratios between body-part lengths are consistent across individuals. Then they can assess whether people exhibit Vitruvian proportions by comparing their data with predictions outlined by da Vinci on the Vitruvian Man. This activity also gives students the freedom to ask and answer other questions that arise and test their own hypotheses, such as whether proportions between body parts are consistent across individuals, or whether the proportions differ across age groups or between males and females. This subtle shift toward an intentional use of models in the classroom allows students not only to learn what a model represents, but to develop the ability to critically examine a model's assumptions and limitations and even design new models of their own.

○ Models & Modeling as an Essential Life Skill

These examples illustrate the functionality of models in scientific research for biologists and as effective learning tools for students, yet the utility of modeling reaches far beyond research labs and classrooms. Modeling forms an integral part of how we interpret and understand a complex world (Hoskinson et al., 2014). Maps are two-dimensional models that help us navigate three-dimensional cities. Instruction manuals provide visual models of steps to help us assemble furniture, install plumbing or light fixtures, or mount objects on the wall. We create mental models when planning parties to predict how much food to make, where guests will sit, and what activities they may enjoy. Past experiences with friends are the "data" we use to model and predict guest needs and behaviors. Models of many sorts help us organize the information we gather as we identify patterns and processes and, as a result, aid in refining our understanding over time.

The ability to create, manipulate, and communicate models not only enhances students' science learning, but also provides a foundational skill set that will be useful throughout life. "Model literacy" empowers students to think critically by providing them with a systematic way to explore "what if" and "how" questions about the apparent processes that govern a system. By elucidating processes and promoting dialogue, models can better inform decision making and improve communication. Hence, model literacy is a vital tool for answering many of the biggest questions that the next generation of scientists, engineers, and other problem-solvers will face.

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References

Ambitious Science Teaching (2015). Models and Modeling: an Introduction. Available online at http://ambitiousscienceteaching.org/wp-content/uploads/2014/09/Models-and-Modeling-An-Introduction1.pdf.

Baliga, V. & Baumgart, S. (2014). A matter of human proportions: are you Vitruvian? SCWIBLES Learning Modules. Available online at http://scwibles.ucsc.edu/2015/11/05/a-matter-of-human-proportions/

Bauer, M.I. & Johnson-Laird, P.N. (1993). How diagrams can improve reasoning. *Psychological Science, 4,* 372–378.

Begel, A., Garcia, D.D. & Wolfman, S.A. (2004). Kinesthetic learning in the classroom. In *Proceedings of the 35th SIGCSE Technical Symposium on Computer Science Education* (pp. 183–184). New York, NY: ACM.

Bryce, C., Goetz, K. & Barrick, P. (2014). Predict this! Using models to observe correlation and improve predictions. *SCWIBLES Learning Modules*. Available online at http://scwibles.ucsc.edu/2015/11/05/predict-this/

Buckley, B.C., Gobert, J.D., Kindfield, A.C.H., Horwitz, P., Tinker, R.F., Gerlits, B. et al. (2004). Model-based teaching and learning with BioLogica™: What do they learn? How do they learn? How do we know? *Journal of Science Education and Technology, 13,* 23–41.

Clement, J.J. & Rea-Ramirez, M.A. (Eds.). (2008). *Model Based Learning and Instruction in Science, vol. 2.* New York, NY: Springer.

DuFour, R., DuFour, R., Eaker, R. & Many, T. (2006). *Learning by Doing: A Handbook for Professional Learning Communities at Work.* Bloomington, IN: Solution Tree.

Eddy, S.L. & Hogan, K.A. (2014). Getting under the hood: how and for whom does increasing course structure work? *Cell Biology Education, 13,* 453–468.

Estes, J.A. & Palmisano, J.F. (1974). Sea otters: their role in structuring nearshore communities. *Science, 185,* 1058–1060.

Freeman, S., Eddy, S.L., McDonough, M., Smith, M.K., Okoroafor, N., Jordt, H. & Wenderoth, M.P. (2014). Active learning increases student performance in science, engineering, and mathematics. *Proceedings of the National Academy of Sciences USA, 111,* 8410–8415.

Fretz, E.B., Wu, H., Zhang, B., Davis, E.A., Krajcik, J.S. & Soloway, E. (2002). An investigation of software scaffolds supporting modeling practices. *Research in Science Education, 32,* 567–589.

Gilbert, J.K. (2004). Models and modelling: routes to more authentic science education. *International Journal of Science and Mathematics Education, 2,* 115–130.

Gobert, J.D. & Buckley, B.C. (2000). Introduction to model-based teaching and learning in science education. *International Journal of Science Education, 22,* 891–894.

Haury, D.L. & Rillero, P. (1994). *Perspectives of Hands-On Science Teaching*. Columbus, OH: ERIC Clearinghouse for Science, Mathematics and Environmental Education.

Herron, M.D. (1971). The nature of scientific enquiry. *School Review, 79,* 171–212.

Hoskinson, A.-M., Couch, B.A., Zwickl, B.M., Hinko, K.A. & Caballero, M.D. (2014). Bridging physics and biology teaching through modeling. *American Journal of Physics, 82,* 434–441.

Jacob, F. & Monod, J. (1961). Genetic regulatory mechanisms in the synthesis of proteins. *Journal of Molecular Biology, 3,* 318–356.

Johnson-Laird, P.N. (1983). *Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness.* Cambridge, MA: Harvard University Press.

Johnson-Laird, P.N. (2010). Mental models and human reasoning. *Proceedings of the National Academy of Sciences USA, 107,* 18243–18250.

Louca, L.T. & Zacharia, Z.C. (2012). Modeling-based learning in science education: cognitive, metacognitive, social, material and epistemological contributions. *Educational Review, 64,* 471–492.

National Research Council (1996). Science content standards. In *National Science Education Standards* (pp. 103–208). Washington, DC: National Academies Press.

National Research Council (2012a). *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, DC: National Academies Press.

National Research Council (2012b). Dimension 2: Crosscutting Concepts. In *A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (pp. 83–102). Washington, DC: National Academies Press.

Nersessian, N.J. (1991). Conceptual change in science and in science education. In M.R. Matthews (Ed.), *History, Philosophy, and Science Teaching* (pp. 133–148). Toronto, Canada: OISE Press.

NGSS Lead States (2013a). Appendix F – Science and Engineering Practices in the NGSS. In *Next Generation Science Standards: For States, By States.* Available online at http://www.nextgenscience.org/next-generation-science-standards.

NGSS Lead States (2013b). DCI Arrangements of the *Next Generation Science Standards.* In *Next Generation Science Standards: For States, By States*.

Platt, J.R. (1964). Strong inference. *Science, 146,* 347–353.

Quinn, H., Lee, O. & Valdés, G. (2011). Language demands and opportunities in relation to *Next Generation Science Standards* for English language learners: what teachers need to know. Understanding Language, Stanford University. Available online at http://ell.stanford.edu/publication/language-demands-and-opportunities-relation-next-generation-science-standards-ells.

Schwarz, C.V., Reiser, B.J., Davis, E.A., Kenyon, L., Achér, A., Fortus, D. et al. (2009). Developing a learning progression for scientific modeling: making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46,* 632–654.

Smith, S., Caceres, C., Culver, D. & Hairston, N., Jr. (2007). Exploring sinking rates of phytoplankton. GK–12 at Gobles Public Schools. Available online at http://www.kbs.msu.edu/index.php/component/content/article/65-k-12/230-gobles-public-schools.

Starfield, A.M., Smith, K.A. & Bleloch, A.L. (1990). *How to Model It: Problem Solving for the Computer Age.* New York, NY: McGraw-Hill.

Stoddart, T., Whitenack, D., Bravo, M., Mosqueda, E. & Solis, J. (2011). English language and literacy integration in subject areas. ELLISA Project. Available online at http://education.ucsc.edu/ellisa/.

Watson, J.D. & Crick, F.H.C. (1953). Molecular structure of nucleic acids: a structure for deoxyribose nucleic acid. *Nature, 171,* 737–738.

Webb, N.L. (1997). Criteria for alignment of expectations and assessments in mathematics and science education. *Research Monograph No. 8.* Washington, DC: Council of Chief State School Officers.

Windschitl, M. (2013). Models and modeling: An introduction. *Tools for Ambitious Science Teaching*. Available online at http://ambitiousscienceteaching.org/wp-content/uploads/2014/09/Models-and-Modeling-An-Introduction1.pdf.

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,* 941–967.

Yost, J., Fresquez, C. & Callahan, B. (2012). Native plant garden: assessing biodiverstiy using a school garden. SCWIBLES Learning Modules. Available online at http://scwibles.ucsc.edu/Products/Yost_Garden.html.

CALEB M. BRYCE is a PhD candidate in Ecology and Evolutionary Biology at the University of California, Santa Cruz, 100 Shaffer Rd., Santa Cruz, CA 95060; e-mail: cbryce@ucsc.edu. VIKRAM B. BALIGA is a PhD candidate in Ecology and Evolutionary Biology at the University of California, Santa Cruz, 100 Shaffer Rd., Santa Cruz, CA 95060; e-mail: vbaliga@ucsc.edu. KRISTIN L. DE NESNERA is a PhD candidate in Ecology and Evolutionary Biology at the University of California, Santa Cruz, 100 Shaffer Rd., Santa Cruz, CA 95060; e-mail: kdenesne@ucsc.edu. DURAN FIACK is a PhD candidate in Environmental Studies at the University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064; e-mail: dfiack@ucsc.edu. KIMBERLY GOETZ is a PhD candidate in Ecology and Evolutionary Biology at the University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95060; e-mail: kimtgoetz@gmail.com. L. MAXINE TARJAN is a PhD candidate in Ecology and Evolutionary Biology at the University of California, Santa Cruz, 100 Shaffer Rd., Santa Cruz, CA 95060; e-mail: ltarjan@ucsc.edu. CATHERINE E. WADE has a PhD in Environmental Studies from the University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064; e-mail: cwade@ucsc.edu. VERONICA YOVOVICH is a PhD candidate in Environmental Studies at the University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064; e-mail: vyovovic@ucsc.edu. SARAH BAUMGART is a science teacher at Watsonville High School, 250 E. Beach St., Watsonville, CA 95076; e-mail: Sarah_Baumgart@pvusd.net. DONALD G. BARD is an Adjunct Professor of Biology at Cabrillo College, Aptos CA and of Anatomy at Monterey Peninsula College, Monterey, CA, as well as a Program Coordinator for the SCWIBLES GK–12 program at the University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064; e-mail: dbard@ucsc.edu. DORIS ASH is an Associate Professor of Education at the University of California, Santa Cruz, 1156 High St., Santa Cruz, CA 95064; e-mail: dash5@ucsc.edu. INGRID M. PARKER is a Professor of Ecology and Evolutionary Biology at the University of California Santa Cruz, 1156 High St., Santa Cruz, CA 95064; e-mail: imparker@ucsc.edu. GREGORY S. GILBERT is a Professor of Environmental Studies at the University of California Santa Cruz, 1156 High St., Santa Cruz, CA 95064; e-mail: ggilbert@ucsc.edu