

Article

Toward University Modeling Instruction—Biology: Adapting Curricular Frameworks from Physics to Biology

Seth Manthey* and Eric Brewe*[†]

*Department of Teaching and Learning and [†]Department of Physics, Florida International University, Miami, FL 33199

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University Modeling Instruction (UMI) is an approach to curriculum and pedagogy that focuses instruction on engaging students in building, validating, and deploying scientific models. Modeling Instruction has been successfully implemented in both high school and university physics courses. Studies within the physics education research (PER) community have identified UMI's positive impacts on learning gains, equity, attitudinal shifts, and self-efficacy. While the success of this pedagogical approach has been recognized within the physics community, the use of models and modeling practices is still being developed for biology. Drawing from the existing research on UMI in physics, we describe the theoretical foundations of UMI and how UMI can be adapted to include an emphasis on models and modeling for undergraduate introductory biology courses. In particular, we discuss our ongoing work to develop a framework for the first semester of a two-semester introductory biology course sequence by identifying the essential basic models for an introductory biology course sequence.

INTRODUCTION

The American Association for the Advancement of Science (AAAS) has issued a call for the reform of undergraduate biology and has identified six student competencies as essential to this reform (AAAS, 2011). One of these competencies is for students to gain skills at developing, implementing, and evaluating scientific models, because “modeling is a standard tool for biologists” (AAAS, 2011).

Not only has the AAAS made an explicit call for the inclusion of modeling abilities and skills as one of the core competencies, but the National Academy of Sciences (NAS) has made it one of the scientific practices that comprise *A Framework for K–12 Science Education* (National Research Council

[NRC], 2012). The framework even goes as far as to say “curricula will need to stress the role of models explicitly and provide students with modeling tools ... so that students come to value this core practice and develop a level of facility in constructing and applying appropriate models” (p. 59).

Even before AAAS and the NAS made model development and use a core competency and practice for biology students, there was considerable research by biology educators on models and modeling (Stewart *et al.*, 2005; Lehrer and Schauble, 2006; Windschitl *et al.*, 2008; Odenbaugh, 2009; Passmore *et al.*, 2009; Schwarz *et al.*, 2009; Svoboda, 2010; Svoboda and Passmore, 2011). However, there is no consensus on what models are, what constitutes the practice of modeling, and how to develop modeling skill while also delivering content.

Students' development and use of models has been well-researched in other fields of science, particularly within physics (Hestenes, 1987; Schauble *et al.*, 1991; Wells *et al.*, 1995; Desbien, 2002; Halloun, 2006; Brewe, 2008). It is from this work that we shape our argument for the adaptation of a pedagogical and curricular framework known as UMI to biology.

The aim of this paper is to discuss how models and modeling have been described within the different scientific disciplines, introduce the components of UMI, and provide

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Address correspondence to: Seth Manthey (smanthey@fiu.edu).

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examples of a basic model from the UMI viewpoint. We will then provide a framework to structure the curriculum around the essential basic biological models for the application of UMI to first-semester introductory biology.

BACKGROUND ON MODELS AND MODELING WITHIN BIOLOGY EDUCATION

Biology education research has investigated the use of models and the process of modeling in biology. However, this work tends to lack explanation of how to implement the pedagogical technique and descriptions of the organizing biological models needed for introductory university courses.

Arguing for the Use of Models

Researchers have called for models to be used in science courses, because this more closely aligns with authentic scientific practice. Windschitl *et al.* (2008) argue for the use of what they call “model-based inquiry” (p. 2) to become the new focus of science courses, as opposed to the traditional scientific method. Using the biology classroom as the context for their argument, they state that the traditional scientific method “emphasizes the testing of predictions rather than ideas, focuses learners on material activity at the expense of deep subject matter understanding, and lacks epistemic framing relevant to the discipline” (p. 1). Windschitl and colleagues contend that “model-based inquiry” is superior to the traditional scientific method, because it allows students to engage in an authentic practice of scientists, which is the “development of coherent and comprehensive explanations through the testing of models” (p. 5). Passmore *et al.* (2009) argue that models should be used in science courses, because models are the central practice of all scientific disciplines: “The development, use, assessment, and revision of models and related explanations play a central role in scientific inquiry and should be a prominent feature of students’ science education” (p. 395).

Functional Role of Models

Models are a prominent component of all scientific disciplines, although their roles vary across disciplines and within the discipline of biology. Passmore *et al.* (2009) state that a model gathers “theoretical objects and the processes they undergo and thus serves as a mechanism that can be used to explain why something in the natural world works the way it does” (p. 395). That is to say, models explain scientific theories.

Odenbaugh (2005), while agreeing with Passmore and colleagues, believes that models serve to do much more. He argues that they allow the biological community to explore possibilities, investigate more complex systems, provide conceptual frameworks, create accurate predictions, and generate explanations (Odenbaugh, 2005). Odenbaugh says the models allow scientists to explain and reason within specifics that may have previously been unknown, and Svoboda and Passmore (2011) add that models “facilitate the communication of ideas” (p. 2). Thus, scientists use models to discuss, modify, manipulate, and expand their understanding.

Odenbaugh’s argument that models allow scientists to investigate more complex systems is one that we view as fundamental. Biological systems range from internal cellular systems to whole ecological systems. These systems comprise many intertwined components. To develop models of these complex systems, scientists must identify simplifying assumptions, while attending to the relevant components. This process reduces the scale students and scientists must use in order to effectively reason about these complex systems.

To demonstrate the functional role of models within biology, we now present a contextualized argument using *Listeria monocytogenes* as a multipurpose specific model. *L. monocytogenes*, the Gram-positive bacterium responsible for diseases such as meningitis, septicemia, and gastroenteritis, has been used as a model organism—a specific model—for cellular biologists to describe many complex phenomena. One of the complex phenomena that *L. monocytogenes* has been used to model is that of the invasion of macrophages. Through the development of this *L. monocytogenes*-specific model of macrophage invasion, researchers have been able to generalize to a basic pathogenic bacteria model for these complex phenomena (Hamon *et al.*, 2006).

The use of a *L. monocytogenes*-specific model has allowed researchers to “suggest the need for [further] empirical studies” (Svoboda and Passmore, 2011, p. 2). For example, while modeling the phenomenon of the listeriolysin O pore-forming mechanism, researchers found that this toxin exhibits optimal activity at a lower pH than other pore-forming toxins, which suggests a direction for future studies (Hamon *et al.*, 2006).

Thus, modeling is a beneficial practice for students, because it is an authentic practice of biology. Several questions remain concerning the use of modeling in the classroom: What are the basic models in an introductory biology class? How do we systematically engage students in the construction, validation, deployment, and modification of these models? It is our aim to provide answers to these questions.

Models and Modeling in the Classroom

Moving from the field and into the classroom, Lehrer and Schauble (2006) describe the act of modeling in the classroom, saying, “one cannot engage in the activity of modeling without modeling *something*, and the something (the content and domain) is critical with respect to the questions raised, the inquiry pursued, and the conclusions reached. At the same time, modeling is a practice, not a predigested heap of facts” (Lehrer and Schauble, 2006, p. 383). The specific model of *L. monocytogenes* discussed above demonstrates the value of modeling *something*. If the researchers had explored the macrophagic invasion mechanisms or pore-forming toxins phenomena without using *L. monocytogenes* as the specific model, the information they learned would simply have become a generic list of facts, rather than a contextualized, validated, and applied model separate from the phenomenon.

While we agree with Lehrer and Schauble (2006) regarding the importance of modeling *something*, they also argue that models function as analogies (p. 372). These analogies allow students to have a representation of phenomena, such as the solar system, that are otherwise too large to easily understand. We argue that, for Lehrer and Schauble, models

function as a way for students to interact with learned content and not as a way for students to both learn and engage with the content. However, we believe their perspective needs to be expanded to include having students use and develop models. By using and developing models, students are not only exploring content but also developing a deeper and richer understanding of the phenomena. We think that students also learn through modeling the foundational knowledge elements and their structure, as valued within a discipline.

These arguments on the function and benefit of models and modeling in biology show the importance of identifying the models within introductory biology. The identification of these models would allow the full development of a two-semester introductory biology sequence. The difficulties of developing model-based courses can be alleviated by drawing upon research from the physics education community on their use of models in physics classrooms.

MODELING WITHIN THE PHYSICS CLASSROOM CONTEXT

There is much overlap between scientific disciplines on the practice of using models. However, there are differences between the disciplines in employing models as the curricular focus. Hestenes (1987, 1992) describes models as being one of the integral parts of scientific knowledge. He defines a scientific model as “a surrogate object, a conceptual representation of a real thing” (Hestenes, 1987, p. 4) and a physics model as a mathematical model. This is one of the major differences between biology and physics models. We reject these strict definitions of scientific and physics models and expand these definitions of models, particularly scientific models, to better function for biology. Halloun (2006) defines a scientific model as “a conceptual system mapped, within the context of a scientific theory, onto a specific pattern in the structure and/or behavior of a set of physical systems as to reliably represent the pattern in question and serve specific functions in its regard” (p. 24). While this definition of a scientific model is more in line with modeling in biological systems, it is insufficient to shape how models can be used in a classroom. With this in mind, we define a scientific conceptual model as a coordinated set of representations (e.g., graphs, equations, diagrams, and/or written descriptions) of a particular class of phenomena that exist in the shared domain of discourse. In addition, we contend that students should first model specific situations by constructing *specific* models and then abstract out to *basic* models (Nersessian, 1995, 2002). Basic models are models that cover all fundamental conceptions, but that are not tied to specific phenomena or systems. In the example of *L. monocytogenes*, a specific model of how *L. monocytogenes* invades cells was first constructed. This was later generalized to a more basic model of pathogenic bacteria. Basic models are both descriptive and explanatory, while being general enough to apply to multiple similar phenomena (Halloun, 2006). The procedural knowledge that Hestenes refers to as the scientific method can be incorporated into the biology classroom through the process of developing specific models that are then abstracted out to more basic models (Hestenes, 1987).

Windschitl *et al.* (2008) also aver that modeling and model-based reasoning can, and in fact should, serve as the new

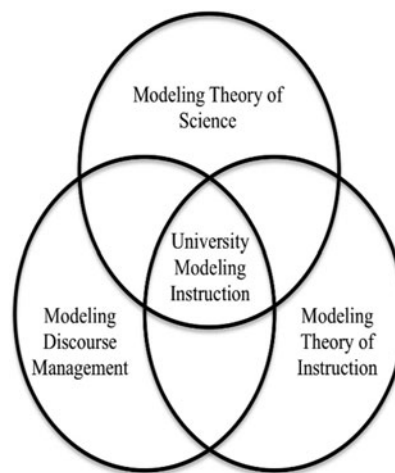


Figure 1. UMI is considered the nexus of modeling theory of science, modeling theory of instruction, and modeling discourse management.

norm within science classrooms. UMI is a curricular framework that establishes modeling as the science classroom norm. UMI is composed of three aspects: modeling theory of science (Hestenes, 1987; Wells *et al.*, 1995; Halloun, 2006), modeling theory of instruction (Hestenes, 1987; Wells *et al.*, 1995; Brewé, 2008), and modeling discourse management (Desbien, 2002; Durden *et al.*, 2011). We draw on University Modeling Instruction—Physics (UMI-Physics) to scaffold the development of UMI in biology, and we provide an overview of these theoretical foundations in the following section.

UNIVERSITY MODELING INSTRUCTION

UMI represents the juncture of the modeling theory of science, the modeling theory of instruction, and modeling discourse management, as seen in Figure 1. We will now describe each of these three components in further detail.

Modeling Theory of Science

The modeling theory of science is the basic premise that scientific paradigms, such as biology, progress through an ongoing process of model construction, validation, deployment, and revision (Halloun, 2006). This basic premise also states that disciplinary knowledge is generated through this same ongoing process. Thus, UMI rests on the epistemological foundation established by the modeling theory of science. In the modeling theory of science, a scientific theory is a set or family of models and a “set of particular rules and theoretical statements that govern model construction and deployment and that relate models to one another” (Halloun, 2006, p. 17). This perspective places models in the middle of a hierarchical structure, below laws and theories but above concepts, and argues that models are the way in which scientists understand and conceptualize science (Hestenes, 1987). This middle level between theories and concepts allows models to serve a critical function within science; they act as the bricks and mortar of a theory and are the basis for how scientists argue.

Therefore, they serve as the ideal level for the development of student of understanding of both concept and theory.

Modeling Theory of Instruction

The modeling theory of instruction serves as a framework for the application of the modeling theory of science to the classroom. The modeling theory of instruction asserts that building, validating, deploying, and revising models is the central activity of scientists, and students therefore should be engaged in a similar pursuit. Models should be the focus of the content and modeling should be the primary activity in which students are engaged throughout a science course. The modeling theory of instruction suggests a pedagogy that is student-centered, and it intentionally creates a community of learning through student-to-student communications. This pedagogy also explicitly asks students to create, validate, deploy, and revise these scientific models. The process of creating and developing models “focuses on qualitative and quantitative model development and testing” (Brewer, 2008, p. 1155) and follows a specific path called the modeling cycle that Brewer describes as “introduction and representation, coordination of representations, application, abstraction and generalization, and refinement” (Brewer, 2008, p. 1156).

Modeling Discourse Management

While both the modeling theory of science and the modeling theory of instruction may together establish a classroom that engages students in authentic scientific practice, we believe that it is also important to structure the discourse to support the development of models and the process of modeling. Modeling discourse management shapes in-class discourse by providing instructors with a set of discourse management tools to guide students so that authentic science discourse occurs. These discourse management tools range from the intentional lack of closure, which can cause “students to wrestle with the issues outside class and return with new ideas to share” (Desbien, 2002, p. 84) to Socratic questioning. Other modeling discourse management tools are small-group work, whole-class discussions, and “seeding” (Desbien, 2002, p. 83). Seeding is the introduction of a new concept, idea, or question into an intentionally chosen small group that allows them to create their own interpretation of the concept, idea, or question (Durden *et al.*, 2011). The small group then presents the created interpretation to the whole class. Classroom discussion is generated, because students, rather than the instructor, present the idea, and this leads to a resolution.

Research on UMI-Physics

UMI has been developed and researched in the PER community, whose research has explored the effects of UMI on the gender and ethnicity gaps (Brewer *et al.* 2010), students’ attitudes about science (Brewer *et al.*, 2009), and students’ self-efficacy (Sawtelle *et al.*, 2010). These research results are one of the motivating factors in adapting UMI to biology.

Using the Force Concept Inventory (FCI; Hestenes and Wells, 1992), Brewer *et al.* (2010) explored the odds of success effects that UMI-Physics had on the ethnicity and gender gaps that exist within the physics discipline. They also investigated the performance differences between students

in traditional lecture courses versus those enrolled in UMI-Physics. The results were that students in UMI-Physics outperformed students on the postinstruction FCI (61.9% vs. 47.9%, respectively, $p < 0.001$). In addition, UMI-Physics students had higher (6.73-fold) odds of success (a grade of C– or higher) than those in traditional lecture. However, these positive results become mixed when broken down to examine gender and ethnicity. UMI-Physics did not widen the ethnicity gap in FCI scores, the ethnicity gap in odds of success, or the gender gap for odds of success, but it did widen the gender gap for FCI score (Brewer *et al.*, 2010).

UMI-Physics classes not only have predominantly positive results with regard to conceptual understanding of physics topics (Brewer *et al.*, 2010), but they also have the first published positive results for reformed introductory physics courses on the Colorado Learning Attitudes about Science Survey (CLASS-Phys; Brewer *et al.*, 2009). This survey targets students’ attitudinal beliefs and compares them with expert attitudinal beliefs, such as “viewing physics as a coherent, connected group of topics and seeing problem solving as a conceptually grounded search through the knowledge base, rather than as a hunt for equations” (Adams *et al.*, 2006; Brewer *et al.*, 2009, p. 013102-1). It was found that UMI-Physics had significant positive shifts overall and positive shifts in four of the subcategories that make up the CLASS-Phys (Brewer *et al.*, 2009).

Self-efficacy, one’s confidence in one’s ability to perform a task, is another area that has been explored within the context of UMI-Physics. Traditional lecture classrooms had negative impacts on the self-efficacy of all students, a result in contrast with that of UMI-Physics, which had neutral impacts when evaluating all students. However, when the results were broken down by gender, the study shows distinct differences between the components of self-efficacy interactions with gender (Sawtelle *et al.*, 2010).

Using the results of Brewer *et al.* (2009, 2010) and Sawtelle *et al.* (2010), we argue that the UMI framework of UMI-Physics should be used to adapt and reform undergraduate biology courses.

UNIVERSITY MODELING INSTRUCTION—BIOLOGY

Adapting University Modeling Instruction to Biology

One of the major challenges faced in adapting a UMI framework from physics to biology lies in the need to adapt model-centered epistemology to authentically represent the discipline of emphasis. This is due to the fact that physics is a discipline with clearly defined and distinguishable laws and theories, while biological theories and laws are difficult to distinguish.

To adapt the model-centered epistemology for biology, we are adapting the middle-out hierarchical structure described by Halloun (2006). This structure places models at the basic level—the middle—of the “conceptual hierarchy, between theory and concept” (p. 21). We propose adapting this hierarchy by replacing theory with what we will refer to as theoretical structure. This change allows us to account for the elements that comprise the ontological and epistemological assumptions—the things, relationships, and mechanisms

Table 1. Comparison of content in UMI-Bio and a more standard biology course^a

UMI	Standard course
Models are constructs that are built in accordance to theoretical structures, biological principles, and constraints	Biological principles are given as a set of facts and applied to gain understanding of phenomena.
Models are built by the application of representational tools and can then be used to solve problems.	—
Models are temporal and must be validated, refined, and applied.	Content is permanent; validation has already taken place.
Basic models are applied to specific biological phenomena.	Theoretical structures and biological principles apply to specific situations.
Modeling is a process that is learned through participation within a community of practice.	Understanding is a game that requires tricks and is learned by memorizing large numbers of definitions and facts.
Models are distinct from phenomena they represent and can include causal, descriptive, and predictive elements.	Content is not separate from the phenomena.

^aAdapted from Brewe (2008).

that make up the model of situation—across the disciplinary boundaries that are serving to shape the middle-out hierarchical structure of models and modeling.

Representations used in constructing the model must also be altered when adapting UMI from physics to biology. Representations play a vital role within the modeling process, as it is through the addition and refinement of these representations that a model's robustness is developed. In UMI, as in science, the representations used within the model must coordinate with one another, which is what allows models to explain phenomena.

In adapting UMI to biology, we have chosen to feature some of the cross-disciplinary representations from UMI-Physics in conjunction with biology-specific representations from both primary literature and representative textbooks. However, for the purposes of this paper, we will focus on these cross-cutting representations. These cross-cutting representations not only cross the boundaries for UMI, but also are those that allow us to define a common theme that ties together scientific disciplines.

An example of a UMI representation that can be used across disciplinary boundaries is the energy pie chart. Energy pie charts are representations used to describe the storage and transfer of energy within a given system, such as the system of a ball dropping to the ground or energy transfer from coral zooxanthellae to the coral polyps and continuing throughout the food web in a coral reef biome. The incorporation and use of the energy pie chart representational tool allows for students to describe the substance-like flow of energy within a specific ecosystem. For a further discussion on the use of energy pie charts, see Brewe (2011). This representational tool is able to cross-cut from the introductory physics models to the introductory biology models; featuring it in both types of courses shows energy to be a common thread in both disciplines.

Content Organization

Much like the organization of UMI-Physics as described by Brewe (2008), UMI-Biology (UMI-Bio) organizes its content for introductory biology around a small number of basic models. This is beneficial, because “the organization matches expert knowledge organization in which a few fundamental principles are viewed as requisite for a very broad understanding” (Brewe, 2008, p. 1156). Not only does this orga-

nization reflect expert knowledge organization, but it also allows students to see this small number of basic models as a manageable amount of knowledge to understand. This is unlike a traditional two-semester sequence of introductory biology that focuses on covering 20-plus chapters containing a large number of principles, concepts, and topics. Further differences between UMI-Bio and a traditional introductory biology course can be seen in Table 1, modified from Brewe (2008).

Short Theoretical Vignette of UMI-Bio

Another way to envision UMI-Bio is through a short description of an idealized class activity in which a plant cell model is discovered to be inadequate to explain phenomena and an animal cellular model is introduced. Prior to the class, students will have worked extensively with prokaryotic cells, plant cells, cell stains, and light microscopes, and should have an understanding of scale, structure and function, and energy pathways. Students will first be asked to create descriptive models of a new cell type presented to them on a prepared microscope slide. Students can use the basic prokaryotic or plant cellular models as a template, but will quickly find that neither of these models can be applied to the current phenomena, as the scale and many of the structural elements are different. Working in small groups, students would then collect observations to begin developing and refining their new descriptive cell model. While the students collect data, the instructor would ask one group why either of the basic models developed so far in the class (prokaryotic or plant cell model) do not apply to this current cell phenomenon. Students are likely to respond with “This is not a prokaryotic cell” or “It is not stained the same as a plant cell.” Once *the students* have introduced these ideas, the instructor would encourage them to pursue these ideas by asking what other organisms they believe this cell could be. This would lead to a discussion about organism types, with commonsense questions, such as, “What other organisms exist on this planet?” The need to consider other organisms would cause the instructor to introduce an animal cellular model. As a result of this interaction, the instructor will have seeded the group with the concept of an animal cell model. During the whole-class discussion, this group will be asked to introduce the general animal cell model to the whole class. This would allow for students as

Table 2. Essential model-centered hierarchies for the first semester of a two-semester general biology UMI-Bio sequence

General Biology I (semester 1)		
Theoretical structure (ontological assumption)	Basic model(s)	Specific model example(s)
Cellular biology		
Structure and function	Prokaryotic cell	<i>E. coli</i> and <i>Staphylococcus aureus</i>
Pathways of energy and matter	Plant cell	Elodea cell
	Animal cell	Human cheek cell
Genetics		
Evolution	Meiosis and mitosis	Ascaris mitosis and lily meiosis
Information flow, exchange, and storage mutation	Transcription and translation	AIDS virus
Reproduction and replication	Evolution	Rock pocket mouse

a whole class to build a more robust theoretical structure of cellular biology, with minimal input from the instructor.

Identifying Basic Models in Biology—Methods

Identifying the basic models within introductory biology required a metalevel analysis of the content of introductory biology. While models have been described in various ways within biology, there are few descriptions that are aligned with the definition of a basic model provided by Halloun (2006). With this in mind, we undertook a three-part model and theoretical structure identification effort involving exploratory interviews with experts in the domain and a review of two representative introductory biology textbooks, returning with a member check of our proposed basic models.

The first part of the process was exploratory interviews with two biology professors, Charles and Gregor (all names are pseudonyms). Charles holds a PhD in population biology and conducts research that focuses on conservation and restoration and evolutionary and tropical biology. Gregor, a PhD in ecology and evolution, is currently focusing on plant conservation genomics and evolutionary ecology. Both Charles and Gregor are members of large research universities. These interviews were conducted to elicit the participants' expectations about models and theoretical structures they expect their students to understand after completing an introductory biology course sequence.

The interviews were conducted using a semistructured interview format, as described by Rubin and Rubin (2004). Each of the interviews lasted approximately 1 h. These interviews were then transcribed and analyzed to identify areas of theoretical structure, basic models, or areas that needed further refinement through review of representative textbooks.

Following our analysis of the interviews, a review of representative textbooks was conducted to further develop, refine, and support proposed theoretical structures and basic models identified in the interviews. If an additional basic model was identified during the textbook review, it was added to the identified models noted for further consideration in the curricular sequence. The reviewed textbooks included widely used and accepted textbooks from biology courses (Raven *et al.*, 2011; Reece *et al.*, 2011). These combined results were presented to biology faculty for additional feedback and can be found in Table 2.

These combined results after the interview and textbook analysis were presented to biology faculty and to the interview participants for additional feedback. The combined results can be found in Table 2. The interview participants were

presented with these results to allow for a member-checking process during which they were encouraged to verify correct interpretations, correct any incorrect interpretations, and expand on any quotes they felt necessary.

Interview Results

During the analysis of the interview transcripts, we were able to identify multiple basic models and theoretical structures that participants viewed as essential components of an introductory biology course. One of the models that emerged from both interviews was a basic model of transcription and translation. This model emerged from Charles's statement that the process of DNA becoming RNA and then becoming proteins is even "[the] central paradigm of molecular biology." He continued on to say that one could "teach from the 'central dogma' and then take examples of how RNA is turned back into DNA" by reverse transcription. Gregor echoed the importance of this model, saying, "[you can] get them to model [transcription and translation], go the reverse direction with reverse transcriptase, RNA to DNA."

We identified a model of evolution as a focal aspect of an introductory biology course, according to both participants. Gregor said that, "evolution is its own model," while Charles discussed the historical nature of models within the study of evolution. On our member check, Gregor expanded his statement regarding evolution's role as a model to say that, "evolution by natural selection has a long history as a central model for explaining several phenomena that were challenges to non-evolutionary paradigms that preceded Darwin." Further evidence of evolution as a basic model was biology's goals of understanding "what creates, maintains, and leads to the loss of genetic variation with populations" (Charles) and "trying to predict changes in allele frequency over time" (Gregor). In addition, during member check, Gregor mentioned that it is important to consider how evolution has been phrased through various models over time.

Textbook Review Results

We saw the need to draw upon resources beyond the interviews and thus reviewed appropriate biological texts so that we could identify robust models for the intended two-semester introductory course sequence. This sequence can be found in Table 2.

To expand upon the central dogma and the importance of transcription and translation as identified by both

participants, we examined both Reece *et al.* (2011) and Raven *et al.* (2011). In Reece *et al.*, this model and phenomenon is the focus of an entire chapter (chap. 17), in which it is further broken into the processes of DNA becoming RNA through transcription and RNA becoming protein through translation. Raven *et al.* focus on this model in chapter 15, and include a distinction between prokaryotic transcription and eukaryotic transcription, an important element to consider while developing our curriculum. In both textbooks, the discussions of the transcription and translation phenomena are connected with a discussion of reverse transcriptase processes in retroviruses.

Refining the transcription and translation basic model to include the phenomena of retroviruses, such as the AIDS virus, allows students to see the application of this model to a major phenomenon of disciplinary importance. The curriculum is also aimed at having students learn that transcription can also be reversed, taking RNA to DNA, though the use of reverse transcriptase, thus expanding the functionality of the basic model.

We identified an important representation within the model of evolution. As discussed previously, representations are essential to a robust model. During our review of Raven *et al.* (2011) and Reece *et al.* (2011), we identified the Hardy-Weinberg principle and its associated equation as adding to the robustness of the model of evolution. This principle states: “in a large population with no selection and random mating, the proportion of alleles does not change through the generations” (Raven *et al.*, 2011, p. 401). This representational tool provides students with a way to quantitatively describe and predict the genetic variance and frequencies, which are essential abilities of the basic evolutionary model. Both Charles and Gregor discussed the importance of evolution and the Hardy-Weinberg principle/equation.

During our review of textbooks, we identified additional theoretical structures and basic models that did not arise from the interviews. One of the theoretical structures was cellular biology. This was justified by the principles of cell theory, which states that “all organisms are composed of cells, life’s basic units” (Raven *et al.*, 2011, p. 12). Moreover, “the cell theory, one of the basic ideas in biology, is the foundation for understanding the reproduction and growth of all organisms” (Raven *et al.*, 2011, p. 12). Cell theory helped us identify the basic model of mitosis and meiosis, which is included because “all cells arise only from preexisting cells” (Raven *et al.*, 2011, p. 12).

While it is important to identify the theoretical structures and basic models for a UMI course, it is necessary to consider how to organize the content. Drawing upon these identified theoretical structures and basic models, we now propose a course framework for the first semester of a two-semester introductory biology sequence and outline a modeling cycle for each of the basic models.

Framework for the First-Semester Curricular Content of UMI-Bio

Here, as well as in Table 2 above, we present the results of our ongoing work on identification of the theoretical structures, basic models, and specific models within introductory biology. We view these elements of a model-centered biology epistemology as essential components of introductory biology,

and they are a synthesis of results of our interviews of biology faculty and textbook analysis. We present these results as the framework for the content of the first semester of an introductory biology sequence.

The first theoretical structure that is essential for students to encounter is cellular biology, which comprises the ontological assumptions of structure and function and pathways and transformation of energy and matter, as described in *Vision and Change* (AAAS, 2011). This theoretical structure is composed of the basic model of a prokaryotic cell, which allows for a refined model in future classes to distinguish between an archaea cell model and a bacterial cell model. Additional models in the cellular biology theoretical structure are the plant and animal cells. Students will first engage with the prokaryotic cell model by building a specific model of an *Escherichia coli* cell. This specific model will introduce students to cellular structure, scale, and energy obtainment.

Following the construction of this *E. coli*-specific model, students will explore other bacterial and archaea species, looking at these same phenomena of scale, energy obtainment, and structure. The aim is for students to be deploying and revising their model until a point is reached at which they are able to generalize these specific models to a basic model of a prokaryotic cell. Students will then be presented with a plant cell and asked to deploy their prokaryotic cell model. However, the students’ basic model of a prokaryotic cell cannot explain the cellular structure or scale, and the modeling cycle must begin anew for the development of a basic plant cellular model. This basic cellular model, as well as the animal cell model, again focuses students on the structure, scale, and energy obtainment of these basic cell types. The same process of model development, model deployment, and model revision is repeated for the animal cell as described in the vignette above. The descriptive representations of cell structure for each of these cellular biology models came from the textbook review, specifically from Raven *et al.* (2011, pp. 67–68) and Reece *et al.* (2011, pp. 100–101).

The theoretical structure of cellular biology is concluded when students have developed three robust basic models that describe three of the major categories of life-forms. Students should be able to deploy these models to describe, predict, and explain the basic cell types and to compare and contrast these basic models. The model-centered hierarchical structure for this theoretical structure can be found in Table 2.

Genetics is the second theoretical structure students will encounter during the first semester of introductory biology. The genetics theoretical structure comprises the basic models of transcription and translation, mitosis and meiosis, and evolution. This structure also focuses on the ontological elements of information flow, exchange, and storage; evolution; mutation; and reproduction and replication.

To begin, the curriculum will have students learn the basic model of mitosis and meiosis by developing specific models of the stages of yeast cells and cell division, as well as these same stages in lily anther and ovulatory cells, as seen in Table 2. In developing these specific models, students will interact with the ontological elements of information flow and exchange, and evolution. In particular, evolution raises the ideas of the “three mechanisms that contribute to the genetic variation arising from sexual reproduction: independent assortment of chromosomes, crossing over, and random fertilization” (Raven *et al.*, 2011, p. 257). Through the

development of these models, the curriculum will guide students toward the need to develop a basic model for transcription and translation.

As part of the genetics theoretical structure, students will also develop a basic model of evolution. To do this, students will develop a specific model for the rock pocket mouse (*Chaetodipus intermedius*) evolutionary phenomenon. The rock pocket mouse has evolved via genetic mutation and natural selection pressures and is found in two distinctly different colors that match its native habitat: tan, the color of sand, or dark gray, the color of volcanic rock. Rock pocket mouse evolution is one of the most straightforward examples of evolutionary phenomena; it allows students to develop a model of evolution that includes but is not limited to the Hardy-Weinberg principle, genotypic mutation, and phenotypic trait expression. Once a basic model of evolution is developed, students will deploy this model to explore cheetah genetic diversity, and evolution in Darwin's classic example of finches.

The full sequence and list of theoretical structures, basic models, and examples of specific models for each of the basic models are found in Table 2.

CONCLUSIONS

In response to the call for increased attention to students' ability to model (AAAS, 2011; NRC, 2012), we have presented an argument regarding the importance of models and modeling within biology. We aver that modeling is the essential way in which scientists reason, argue, and structure their knowledge, and that the process of modeling is the central activity of scientists.

Because modeling is a central activity of scientists, it is essential for our students—our future scientists—to engage in the activity of modeling. To provide students with something to model, we have presented a curricular framework for the first semester of a two-semester sequence of introductory biology. This framework, the product of faculty interviews and textbook review, presents the foundations of the theoretical structures, basic models, and specific models that are to shape the first semester. It aims to engage students in developing and deploying several essential basic biological models. This format adapts the model-centered epistemology described by Halloun (2006) and is shaped around the four theoretical structures of cell biology, genetics, organismal biology, and ecology. The curricular framework presented here is adapted from a currently implemented and successful curricular framework from physics known as UMI-Physics.

FUTURE DIRECTIONS

We plan to continue the identification, explanation, and development of the essential basic introductory biology models identified here, as well as those for the second semester of introductory biology. We also intend to further validate these proposed biology models through additional interviews and surveys of biology faculty and to further develop the course materials for UMI-Bio. On further development of these course materials, the efficacy of the curriculum will be tested by exploring both conceptual understanding changes and attitudinal belief shifts in students.

We also want to extend this work by further exploration of the synergy and coherence between the themes and content in UMI for physics and biology. This will include the development of interdisciplinary representations, similar to the example of energy pie charts, which should aid conceptual transfer across disciplines. Exploring the interdisciplinary nature of representations establishes a link between the disciplines for students' understanding of energy conservation and transfer. In addition, it is consistent with the field of biology, which has become more interdisciplinary.

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