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Essay

Drawing-to-Learn: A Framework for Using Drawings to Promote Model-Based Reasoning in Biology

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The drawing of visual representations is important for learners and scientists alike, such as the drawing of models to enable visual model-based reasoning. Yet few biology instructors recognize drawing as a teachable science process skill, as reflected by its absence in the *Vision and Change* report's Modeling and Simulation core competency. Further, the diffuse research on drawing can be difficult to access, synthesize, and apply to classroom practice. We have created a framework of drawing-to-learn that defines drawing, categorizes the reasons for using drawing in the biology classroom, and outlines a number of interventions that can help instructors create an environment conducive to student drawing in general and visual model-based reasoning in particular. The suggested interventions are organized to address elements of affect, visual literacy, and visual model-based reasoning, with specific examples cited for each. Further, a Blooming tool for drawing exercises is provided, as are suggestions to help instructors address possible barriers to implementing and assessing drawing-to-learn in the classroom. Overall, the goal of the framework is to increase the visibility of drawing as a skill in biology and to promote the research and implementation of best practices.

INTRODUCTION

It is difficult to imagine teaching, learning, or doing biology without the use of visual representations. As in physics, chemistry, and other science, technology, engineering, and math (STEM) disciplines, the spatial and temporal dimensions of biology span many orders of magnitude and involve complexity that challenges the limits of human comprehension. Visual representations are a powerful tool, because they help to make the unseen seen and the complex simple.

This power of visuals has been used by scientists from the representational anatomical works of Leonardo da Vinci to the theoretical phylogenetic work of Charles Darwin. In this essay, we encourage biology instructors of students ages K–16 and beyond to explicitly train students not only to *interpret* visual information in textbooks, journal articles, slide presentations, websites, and classroom whiteboards, but also to *create* drawings, for two reasons: 1) drawing is a powerful tool for thinking and communicating, regardless of the discipline (e.g., Roam, 2008); and 2) drawing is a process skill that is integral to the practice of science, used in the generation of hypotheses, the design of experiments, the visualization and interpretation of data, and the communication of results (e.g., Schwarz *et al.*, 2009; Ainsworth *et al.*, 2011).

Even though biology has a rich tradition of illustrating natural history, it lags behind physics and chemistry in acknowledging and explicitly teaching drawing as a skill, especially the drawing of abstract visual models as a tool for reasoning (National Research Council [NRC], 2012). Model-based reasoning is a type of problem solving that enables analysis of complex and/or abstract concepts. Different types of models are used for problem solving across STEM disciplines, including verbal, mathematical, visual, dynamic, and physical models (Table 1; e.g., Harrison and Treagust, 2000; Koba and Tweed, 2009). Model-based reasoning is a powerful tool

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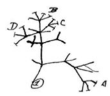
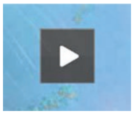
Table 1. Types of models for model-based reasoning

Type of model	Example
Verbal e.g., analogies and metaphors	The cell is like a factory …
Mathematical e.g., equations	$p^2 + 2pq + q^2 = 1$
Visual e.g., graphs, concept maps, flowcharts, phylogenetic trees, maps, situational diagrams, and anatomical illustrations	 Darwin, 1837
Dynamic e.g., simulations	
Physical e.g., molecular and anatomical models	

for fostering conceptual change and meaningful learning in students (e.g., Jonassen *et al.*, 2005; Blumschein, *et al.*, 2009). When used in science, these abstract, explicit representations of systems can be used singly and in combination to generate predictions and explanations (Schwarz *et al.*, 2009).

The vast majority of illustrations in biology texts, in primary literature papers, and on whiteboards in classrooms are abstract, visual models. Many biology instructors draw models in their classrooms and prompt students to draw as well, but rarely with a self-awareness of this strategy as a teachable science process skill and rarely from the perspective of modeling.

In a recent study of faculty perceptions of teaching the process of science in biology, drawing or making models was not included among the 22 science skills assessed, except in the creation of graphs from data (Coil *et al.*, 2010). Likewise, the *Vision and Change* document (American Association for the Advancement of Science [AAAS], 2011) includes Modeling and Simulation as one of the core competencies in biology, yet defines modeling narrowly in the mathematical sense. We advocate for the revision of the *Vision and Change* definition to align with the *Discipline-Based Education Research* report (NRC, 2012) to include visual model-based reasoning as embraced in physics (e.g., vector diagrams), chemistry (e.g., bonding diagrams), engineering (e.g., circuit diagrams), and math (e.g., diagrams to solve word problems).

The goals of this essay are to increase the visibility of drawing as a skill in biology and to provide a framework to promote the research and implementation of best practices. We have experienced a number of barriers to progress as we have researched the literature on drawing-to-learn. These barriers include a diffuse literature scattered across diverse disciplines ranging from nursing and cognitive psychology to secondary education and math; diverse study subjects ranging from kindergarteners to adults; inconsistent use of terminology; lack of clearly articulated goals or best practices for assigning drawing in science class; seemingly contradictory results in drawing studies; and a number of complicating factors that raise the question of transferability of the results from one study to the next. These frustrations have inspired us to distill the complexity of drawing into a "big picture" framework that can serve as a launching point to facilitate future work in biology.

This essay will deliver a framework in three parts: 1) a definition of drawing with an explanation of its facets; 2) a clear articulation of the diverse pedagogical goals of drawing-to-learn; and 3) a proposed set of teaching interventions that can serve both as prompts for interested instructors and also as testable hypotheses for researchers. This essay is not intended as a comprehensive literature review but rather as a sampling and synthesis of insights gleaned from diverse fields.

WHAT IS A "DRAWING"?

There is no consensus in the literature on the definition of "drawing," and many terms (e.g., sketch, diagram, external representation, external model, visualization, illustration, picture) are used differently in different papers. We embrace an inclusive definition of drawing to encourage drawing-to-learn as a parallel endeavor to other pedagogical movements such as writing-to-learn (e.g., Klein, 1999; Libarkin and Ording, 2012; Reynolds *et al.*, 2012; Mynlieff *et al.*, 2014), and talking-to-learn (e.g., Tanner, 2009). That is, we define drawing broadly as

> a learner-generated external visual representation depicting any type of content, whether structure, relationship, or process, created in static two dimensions in any medium.

This definition, while inclusive, masks a number of complicating factors central to the use of drawing in the biology classroom. The following discussion will illuminate four of these factors.

Drawings Vary in the Extent to Which They Are Learner Generated

Visual literacy is the ability of students both to *interpret* visual representations that are provided by instructors and also to *create* visual representations on their own (e.g., Schönborn and Anderson, 2010). But interpretation and creation are not distinct categories—they represent ends of a continuum (Figure 1). At one end of the continuum, students can be asked to view and interpret an instructor-generated or instructor-selected model in class or in homework. At the other end of the continuum, students can be asked to draw their own model starting from a "blank slate." The entire range of the continuum represents *visual learning* (learning using images), but the degree to which students are engaged in *active learning* (constructing their own knowledge based on prior knowledge and experience; e.g., Freeman *et al.*, 2014) increases as the students take on more responsibility for their drawing. For the remainder of this essay, "drawing" will include any visual representation that is either partially or fully learner generated.

Drawings Are External Models That Involve the Formation of Internal Models

It may seem self-evident that drawings are external representations (physically visible outside the mind of the creator);

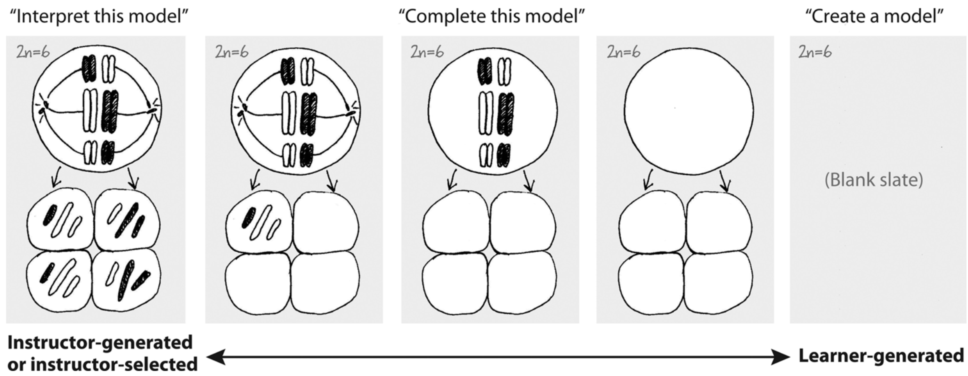


Figure 1. Drawings vary in the extent to which they are learner generated.

however, the literature suggests that an important interaction occurs between external models and internal models (mental models in the "mind's eye"; e.g., Johnson-Laird, 1980; Seel, 2003; Jonassen *et al.*, 2005).

First, consider that the brain naturally uses spatial information to encode other kinds of information, such as verbal information, increasing the brain's capacity for memory and learning (e.g., Chun and Jiang, 1998; Guida and Lavielle-Guida, 2014). It follows, then, that students learn more from combining verbal and visual information than from verbal information alone (Pavio, 1986), which appears to be true regardless of "learning style" (Rohrer and Pashler, 2012; Kirschner and Merriënboer, 2013).

Next, consider how verbal and visual information are integrated. Mayer (2009) proposes in his cognitive theory of multimedia learning that students create a mental model in their working memory by performing three cognitive tasks: 1) *selecting* verbal and visual information from materials presented (sensory processing) and from prior knowledge (long-term memory), 2) *organizing* verbal and visual information, and 3) *integrating* those elements into a mental model. Van Meter and Garner (2005) extended this theory in their generative theory of drawing construction, proposing that the drawing of a physical model can occur after the creation of a mental model or in parallel with selecting, organizing, and integrating information. We have created a visual model to summarize these ideas in Figure 2. Note that the creation of an external model requires not only mental processes but also motor coordination to manipulate the drawing medium into the desired image.

This framework helps to make sense of seemingly contradictory results in the literature. For example, Leutner *et al.* (2009) observed that students who created only a mental model experienced higher learning gains than students who created a mental model plus a drawing. In this case, it appears that the creation of a mental model was itself the critical step in learning and that the drawing process increased cognitive load in a way that was unproductive to learning (Sweller, 1988; de Jong, 2010), possibly because the students had little experience or confidence with drawing and used their time inefficiently. Other studies suggest that the generation of an external model is important both as a catalyst to create a mental model, and as a way to improve cognitive efficiency while learning. For example, drawings can be used to offload information to free up working memory (Larkin and Simon, 1987; Harrison and Treagust, 2000; Jonassen *et al.*, 2005; Koba and Tweed, 2009). Further, it is difficult to assess a student's internal model.

In sum, it is important to recognize that when an instructor assigns a drawing exercise to a student or when a scientist draws a model to think with, the actual drawing that results may be the desired outcome (e.g., to communicate to instructors or colleagues) or may be a means to the creation of a mental model (to construct knowledge) and, therefore, an effective strategy for instructors to access and assess the student's learning and identify misconceptions (e.g., Köse, 2008; Dikmenli, 2010).

Drawings Vary in the Extent to Which They Are Representational or Abstract

One variable that contributes to the varied use of terms for drawings is the extent to which the drawings are intended to be representational ("true to life") or abstract (analogical). Some authors use "drawings" to refer only to representational drawings (e.g., Van Meter and Garner, 2005), wherein drawings are a subset of the larger category, diagrams

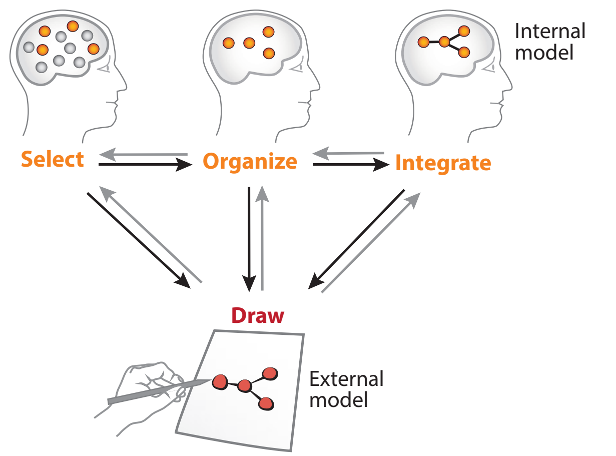
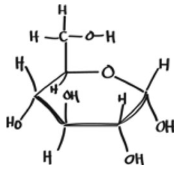
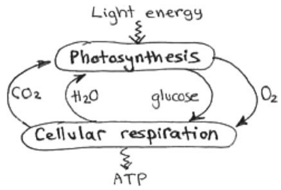
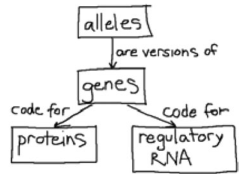
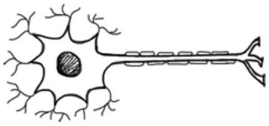
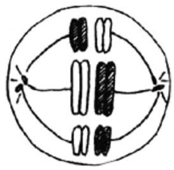
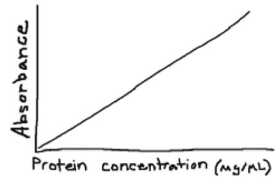
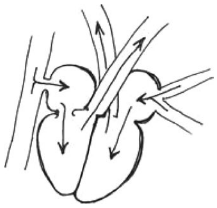
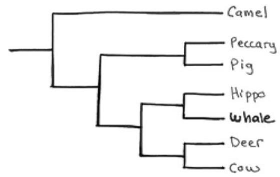
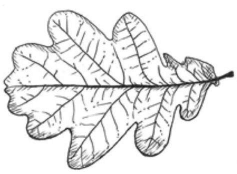


Figure 2. Visual framework for the generative theory of drawing construction. In this model, the circles represent verbal and/or visual information. The arrows show that a drawing may be an endpoint, developed after the creation of a mental model, or a means to creating a mental model—that is, creation of internal and external models can be linear or iterative.

Table 2. Examples of biology content that can be explored via drawings, including references as an entrée to the literature in these areas[a]

Structures	Processes	Relationships
 **Molecular structures** Schönborn and Anderson, 2010	 **Flow of energy and matter** Ekici *et al.*, 2007; Köse 2008	 **Concept maps** Novak and Cañas, 2006; Dauer *et al.*, 2013
 **Cell structures** Hay *et al.*, 2013	 **Meiosis and mitosis** Kindfield, 1994; Dikmenli, 2010	 **Graphs** Padilla *et al.*, 1986; Stern *et al.*, 2003
 **Animal anatomy** Lerner, 2007	 **Physiological processes** Pelaez *et al.*, 2005	 **Phylogenetic trees** Novick and Catley, 2006; Baum and Offner, 2008
 **Plant anatomy** Baldwin and Crawford, 2010		

[a]Sample drawings by K.Q.

(e.g., Uesaka and Manalo, 2011). Others use "drawings" to refer to any learner-generated visualization, including those with quantitative information, such as graphs (e.g., Ainsworth *et al.*, 2011). We embrace the latter approach for drawing-to-learn, with "drawings" embracing the full continuum from representational to abstract (Figure 3).

Structures or objects are often the first category to come to mind when a student or instructor thinks of drawings, but processes and relationships can also be depicted and explored via drawings. For example, students in a biology lab may be asked to draw cells or anatomical structures as viewed through a microscope, but they may also be asked to draw a flowchart to understand the process of meiosis or a phylogenetic tree to decipher the relationships among taxa. A few examples are illustrated in Table 2.

When viewing these examples from biology, there are three points to recognize: drawings can vary across scale; drawings can vary in their integration of text; and drawings can vary in the level of abstraction that is suitable to the context. First, consider that, because drawings can be used across scales and all levels of organization from atomic to global—even within the same representation—they are appropriate for all fields of biology, ranging from biochemistry and molecular biology to genetics, evolution, and ecology. Further, some drawing types, such as flowcharts, graphs, and concept maps, can be applied to all disciplines.

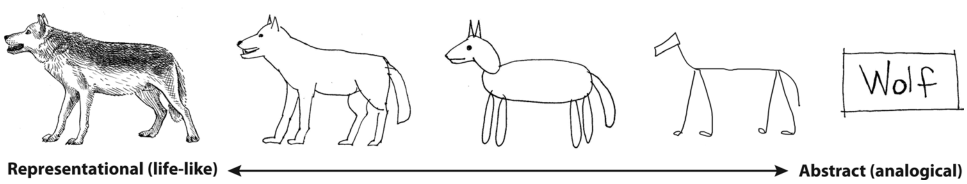


Figure 3. Drawings range in the extent to which they are representational or abstract. In theory, all drawings are analogical, because they cannot truly represent the real world, but they vary in the extent to which they are intended to be representational.

Drawings can also range in the extent to which they contain words. Some drawings contain no words at all, such as a drawing depicting the wing pattern of a particular species of butterfly or the leaf morphology of a particular species of oak tree. Other drawings contain a few labels, such as a drawing of a cell containing labeled organelles or a drawing of a flower containing labeled reproductive structures. At the other end of the spectrum, some drawings are composed mostly of words, numbers, lines, and/or arrows, but with obvious spatial relationships, such as in flowcharts, concepts maps, graphs, and phylogenetic trees (see Table 2).

Finally, drawings can vary to the degree in which they should be representational or abstract, depending on context. For example, a highly representational drawing of a wolf might be appropriate to a study of wolf behavior (where the stance and position of ears and tail is germane to the point), but a mere box with the word "wolf" might be appropriate in a food web or concept map (Figure 3). This distinction is important, because many students and instructors are insecure about their ability to draw. Artistry is not a prerequisite for most uses of drawing as a tool. In many cases, structures or processes can be represented by simple shapes that are easy to create. Thus, the fear of drawing is a barrier that can be overcome with transparency about intended use in a given context ("A box with 'wolf' is all that is needed!") and practice in the intended use in that context (K.Q., unpublished data).

Drawings Can Be Made in Any Two-Dimensional Medium

Just as there is variation in the level of abstraction of drawings, so too is there variation in how they are produced. The word "drawing" often suggests paper and pencil—reminiscent of art class—but student drawings can vary in medium from pencil on paper to marker on whiteboard to stylus on tablet. An increasing number of programs enable students to draw/construct images online and in classroom management systems, improving the number of options available to instructors, especially of large-enrollment or digitally delivered courses (e.g., BeSocratic, Learning Catalytics). Three-dimensional physical models and kinesthetic activities are closely related to drawing and are certainly of educational and scientific value but are beyond the scope of this essay, as are dynamic animations and computer simulations.

In terms of cognitive processes, the principle of selecting, organizing, and integrating information (Figure 2) applies to drawing no matter the medium (e.g., Mayer, 2009). However, this does not mean that all students (or instructors or scientists) will draw equally well in all media. There are two types of barriers that might be important regarding medium. One is experience—the ability of a student to draw in one medium, such as pencil on paper, does not necessarily transfer to ability in another medium, such as stylus on tablet, and depends on the student's familiarity with the new medium. Differences in the sensory-motor experience, the needed hand–eye coordination, and knowledge of the functional capacity of the medium could require practice to master.

Second, some media have inherent limitations. Color coding is not possible when only a black pen is available, and precise markings are not possible using a fingertip on a touch screen. More research on the effects of drawing medium on learning is needed (e.g., Mayer *et al.*, 2005; Templeman-Kluit, 2006; Ainsworth, 2008). Meanwhile, instructors should be mindful of the opportunities and limitations of different drawing media.

WHY ASK STUDENTS TO DRAW?

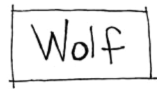
With the definition of drawing established, the next task is to make sense of the many reasons for using drawing. The effective use of drawing in the classroom and the effective measurement of drawing as a tool depend on the alignment between desired outcomes, assessment, and activities (e.g., Cohen, 1987; Wiggins and McTighe, 1998). Thus, transparency regarding goals is essential. We have created a matrix (Table 3) to serve as a framework for distinguishing the variety of pedagogical goals found in the literature (Table 4). The matrix categorizes the goals according to whether drawings are on the *representational* or *abstract* ends of the continuum (Figure 3) and whether they are intended as *formative* or *summative* exercises. Formative exercises are used to help students build their own knowledge and practice skills and are used by instructors to enable targeted feedback to students. Summative exercises are used by students to communicate their knowledge and skills and are used by instructors for evaluating student performance, such as for course grades.

One common goal cited in the formative-representational quadrant is the use of drawings to enhance observational skills (e.g., Baldwin and Crawford, 2010; Ridley and Rogers, 2010). Louis Agassiz of the Harvard Museum of Comparative Zoology captured this sentiment in his assertion that "A pencil is one of the best eyes" (Lerner, 2007, p. 382). For example, students can be asked to draw cells as seen through the microscope to explore cell structure.

The summative-representational quadrant focuses less on seeing and more on communicating what has been observed and learned. Before the advent of photography, representational drawing was essential to science as a means of recording and disseminating knowledge. In terms of teaching and learning, representational drawings are a means of assessing student performance, such as the accuracy and completion of a lab exercise on plant growth. Overall, seeing and communicating are distinct, but aligned, goals—a student (or instructor or scientist) with more practice seeing will be better equipped to communicate what has been seen.

Goals for drawings are quite diverse in the formative-abstract quadrant of the matrix, in the top, right-hand section of Table 3. For students, the goal of this quadrant is to make visual models to help them construct their own knowledge, which involves the creation of both internal and external models (Figure 2). The creation of these models helps students to acquire and remember content knowledge, connect concepts into a big picture, process data, solve problems, and design and interpret experiments. Drawing models can also help motivate students and make them more self-aware of their own learning. For instructors, this quadrant can be used as a diagnostic tool to elicit students' mental models, such as their conception of the relationship between genes and evolution (Dauer *et al.*, 2013), and to reveal misconceptions, such as the common misconception that photosynthesis turns CO_2 into O_2 (Köse, 2008) or that DNA replication occurs during

Table 3. Pedagogical goals for assigning drawing exercises with sample instructor prompts[a]

	Representational drawings	Abstract drawings
		
Formative exercises (help students to construct their own knowledge and skills; help instructors provide students with feedback to improve performance or understanding)	Foster active learning Foster observational skills Foster memorization Foster understanding of spatial relationships Foster motivation/enjoyment of learning	Foster active learning Foster motivation/enjoyment of learning Foster construction of mental model Foster acquisition of content knowledge Foster connection of concepts/ideas Foster creation of big picture Foster processing of data; graphing Foster problem-solving skills Foster process of science skills Foster metacognition (awareness of own learning) Reveal misconceptions for correction
	"Using a microscope, draw an Elodea cell and a potato cell in your lab notebook and compare their structures."	*"Now that we have reviewed the steps of meiosis for a 2n = 4 cell, draw all the stages of meiosis I and II for a 2n = 6 cell. We will review a couple of samples at the end of class."*
Summative exercises (help instructors to evaluate student performance)	Record observations Reveal knowledge	Reveal mental model Reveal understanding of the big picture Reveal content knowledge Reveal data Reveal problem-solving skills Reveal process of science skills
	"In your lab report, draw a representative radish seedling from the control group and the treatment group and point out relevant differences (4 pts)."	*"Draw a 2n = 6 cell during metaphase of Meiosis I and predict the outcome if non-disjunction were to occur (4pts)."*

[a]See references in Table 4.

mitosis and meiosis (Dikmenli, 2010). Instructors can then design interventions appropriate to students' needs.

The abstract-summative goals are aligned with many of the abstract-formative goals; they are similar in their use, yet distinct. The focus of this quadrant is for students to reveal their knowledge and problem-solving skills to the instructor, to fellow students, or to others, usually for points that determine grades. Familiarity with the visual conventions that are used in the discipline and acceptable for the audience dictates how well the students can accurately communicate concepts through abstract representations. In this manner, the student experience in this quadrant prepares them for the communication of scientific information that is integral to the practice of science.

To our knowledge, there has been no formal measure of instructor practice in the formative and summative use of drawing in biology classrooms nationally. However, our informal surveying of colleagues around the United States has revealed a diversity of practices. For example, one college biology instructor said that she uses abstract drawings on exams but does not give students formative opportunities to draw in class. Another instructor said that he uses extensive abstract drawing in class but not on exams due to his large class sizes. Further, some instructors use drawings extensively all semester, while others use them only in one topic area. And some instructors are extremely enthusiastic and purposeful about their use of drawings, outlining several pedagogical goals for their use, while others were surprised by this novel topic and had to consider for a few moments whether or not they used drawing ("What does 'drawing' mean exactly?") in class. This variety of practices reveals a need for alignment between formative and summative elements of Table 3. If drawing skills are an important skill, they should be part of a summative assessment of students. And if drawing skills are part of a summative assessment, they should be aligned with formative experiences in the same drawing category (i.e., representational or abstract).

In sum, the purpose of the matrix is to help add clarity to discussions of why instructors would invest time and effort into assigning and assessing drawing exercises. Assigning drawings to students to help them engage (improve motivation) or see (improve observation skills) are very different pedagogical goals than assigning drawings to help students understand (lower-order cognitive skill) or solve a problem (higher-order cognitive skill), but all are important. Likewise, assigning drawings to students to help them learn (student-centered goal) and assigning drawings so that instructors can assess learning (instructor-centered goal) are very different pedagogical goals, but both can be used to improve student learning. Finally, teaching drawing as a learning tool (such as the use of concept maps to help memorize content or see the big picture) is a different goal than teaching drawing as a science process skill (such as drawing models to design an experiment), but both are valid and worthwhile. Overall, the key is for instructors and researchers to articulate goals clearly so that appropriate interventions can be

Table 4. A sample of references for entrée into the drawing-to-learn literature

Topic	Sample of References
Interpreting visual information	Tufte, 1983, 1990, 2003; Mayer and Sims, 1994; Baum and Offner, 2008; Gilbert *et al.*, 2008; Mayer, 2009; Schönborn and Anderson, 2010; Kress and van Leeuwen, 2006; Rose, 2012; Stephens, 2012
Drawing to enhance motivation	Glynn and Muth, 2008; Alias *et al.*, 2002
Drawing to reveal misconceptions	Rennie and Jarvis, 1995; Palaez *et al.*, 2005; Ekici *et al.*, 2007; Köse, 2008; National Science Foundation, 2008; Shepardson *et al.*, 2009; Dikmenli, 2010
Drawing to elicit or reveal students' mental models	Hmelo-Silver *et al.*, 2007; Hay *et al.*, 2008; Shepardson *et al.*, 2009, 2011; Ifenthaler *et al.*, 2011; Dauer *et al.*, 2013; Anderson *et al.*, 2014
Drawing as a learning tool	Gobert and Clement, 1999; Hyerle, 2000; Novick, 2000; Van Meter and Garner, 2005; Van Meter *et al.*, 2006; Koba and Tweed, 2009; Edens and Potter, 2010; Ridley and Rogers, 2010; Schwamborn *et al.*, 2010, 2011; Eddy *et al.*, 2013
Drawing as a science process skill	Tufte, 1983; Grosslight *et al.*, 1991; Harrison and Treagust, 2000; Löhner *et al.*, 2005; Hmelo-Silver *et al.*, 2007; Ridley and Rogers, 2010; Ainsworth *et al.*, 2011; NRC, 2012
Drawing to enhance observation	Edwards, 1979; Van Meter and Garner, 2005; Lerner, 2007; Baldwin and Crawford, 2010; Ridley and Rogers, 2010
Drawing to enhance model-based reasoning	Grosslight *et al.*, 1991; Kindfield, 1994; Harrison and Treagust, 2000; Hmelo-Silver *et al.*, 2007; Uesaka *et al.*, 2007; Roam, 2008; Rosengrant *et al.*, 2009; Schwarz *et al.*, 2009; Schönborn and Anderson, 2010; Uesaka and Manalo, 2011; Bassok and Novick, 2012; NRC, 2012
Drawing to connect concepts/ideas	Hmelo-Silver *et al.*, 2007; Dauer *et al.*, 2013; Long *et al.*, 2014
Drawing to enhance metacognition	Stow, 1997; Kiyokawa *et al.*, 2012
Drawing to show quantitative information	Tufte, 1983; Padilla *et al.*, 1986; Stern *et al.*, 2003; Picone *et al.*, 2007; Uesaka *et al.*, 2007; Uesaka and Manalo, 2011
Drawing to communicate	Roam, 2008; Watson and Lom, 2008 (student photos); Ridley and Rogers, 2010; Ainsworth *et al.*, 2011
Practice improves drawing-to-learn; it is a teachable skill	Mioduser and Santa María, 1995; Gobert and Clement, 1999; Harrison and Treagust, 2000; Van Meter and Garner, 2005; Van Meter *et al.*, 2006; Uesaka *et al.*, 2007; Rosengrant *et al.*, 2009; Schwarz *et al.*, 2009; Chittleborough and Treagust, 2007; Hegarty, 2011; Dauer *et al.*, 2013; Hay *et al.*, 2013
Visual design for scientists	Tufte, 1983, 1990, 2003; Frankel, 2002; Fry, 2008; Frankel and DePace, 2012

designed and aligned between the formative and summative quadrants to achieve those goals.

WHAT ARE SOME SUGGESTED PRACTICES FOR TEACHING DRAWING FOR MODEL-BASED REASONING IN BIOLOGY?

With the goals for drawing-to-learn in mind, the next step is to consider how to scaffold drawing skills to meet those goals—that is, how can instructors provide a sequence of support that helps students to eventually achieve mastery of the skill on their own? It is beyond the scope of this essay to propose teaching practices to support all of the diverse goals for drawing-to-learn. For the remainder of this essay, we will focus on using drawings for model-based reasoning, because this is an area with enormous, yet unrealized potential (e.g., Ainsworth *et al.*, 2011; NRC, 2012; see *Introduction*). This example also serves to model how drawing could be scaffolded to help achieve other pedagogical goals in biology.

When planning an intervention to help students draw models for model-based reasoning, it is helpful to have an endpoint in mind in terms of desired modeling skills. The literature has articulated some of the differences between novice and expert learners regarding the drawing and use of models in various STEM disciplines (e.g., NRC, 2012; see other references in Table 4). We have simplified and synthesized these differences into a framework in Table 5 to show where students typically start, and where we intend for them to end up. In general, novice learners tend to view models as static summaries of reality created by others, which they must memorize, whereas expert learners tend to view models as flexible thinking tools. Explicit instruction can help novice learners to develop more expert-like skills in model-based reasoning.

Given the goal of moving students to more expert-like practices, and based on the constellation of factors discussed in the literature (see Table 4 and the discussion here), we propose three major categories of interventions that may improve the ability of students to draw models to learn. These interventions can serve as a starting framework for interested instructors and also as testable hypotheses for biology education researchers. To ground these interventions in learning theory, we invoke the theory of cognitive capacity (see Sweller, 1988; de Jong, 2010). This theory predicts that learning will be efficient when distractors to learning are minimized and the full cognitive capacity of the student is focused on the learning goal. Conversely, learning will be inefficient if the learner experiences cognitive load that is unproductive to the learning goals (e.g., Mayer *et al.*, 2001; Mayer, 2009). Thus framed, the three interventions are as follows:

1. Affect: interventions to improve student motivation and attitudes toward drawing-to-learn will encourage students to assign more cognitive capacity to these activities.
2. Visual literacy: interventions that explicitly teach the skill of translating verbal-to-visual information and visual-to-verbal information as well as accepted symbol use within biology subdisciplines will enable students to spend more of their cognitive capacity on important concepts and principles rather than on the act of drawing.
3. Model-based reasoning: interventions that model and give students practice with the flexibility of models as

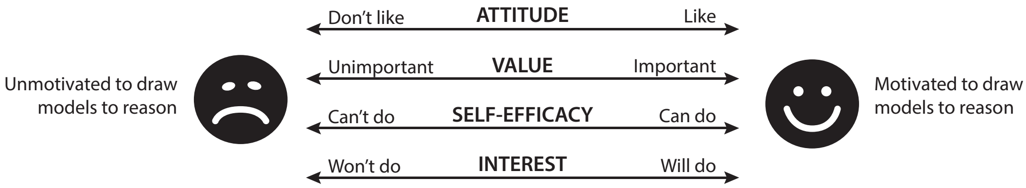


Figure 4. How does the student feel about drawing models?

reasoning tools, as well as feedback on the efficacy of their models, will enable students to spend more of their cognitive capacity on problem solving rather than the act of modeling and will increase the likelihood that students will draw models to solve problems on their own, without prompting.

First, we will outline the teaching and learning challenges in each of these categories, and then we will offer suggestions for practices that might address these challenges. At the end, we will consider some of the practical considerations to ease the use of drawing-to-learn in the classroom.

Affect

A student's affect, or emotional state, is critical to learning success, because it influences motivation—the amount of time and effort a student is willing to commit to learning (Bransford *et al.*, 2000). Affect changes over time and context and can be positively or negatively influenced by instructor behavior and interventions in the classroom (Anderson and Bourke, 2000). While some aspects of affect are resistant to change, such as strongly held values or deep anxieties stemming from childhood experiences, others can be influenced relatively quickly and effectively, providing instructors with opportunities to improve student motivation and thus learning (Kobella, 1989).

There are multiple interacting dimensions to affect, which are beyond the scope of this paper (see Anderson and Bourke, 2000). Here we offer a framework of four affective dimensions as an introduction to the subject: attitude, value, self-efficacy, and interest (Figure 4).

For example, a student might have a poor attitude toward drawing models because of negative associations or experiences or simply because they do not enjoy the activity. Some students feel so uncomfortable drawing that they do not want to participate (e.g., Mohler, 2007; Baldwin and Crawford, 2010). Other students may like drawing in general but feel that drawing is something to be done in art class, not in science class (K.Q., unpublished data). As such, they will not value the approach and will not be motivated to use it.

Similarly, students may be unmotivated to draw models, because they have poor self-efficacy. "I'm not good at drawing" is a common classroom refrain. Students with low self-efficacy may also suffer anxiety due to the threat of harsh judgment of their work (Anderson and Bourke, 2000). Further, students may not be interested in drawing models due to a perception that the costs outweigh the benefits. For example, some students do not bother to draw models to help them solve math problems due to the perception that drawing models will be difficult, even though students are more likely to solve problems correctly when using models (Uesaka *et al.*, 2007; Uesaka and Manalo, 2011). Similarly, in physics, students must be consistently encouraged and incentivized to draw models to solve problems early on but eventually create their own models spontaneously, even when credit is not given to do so (Rosengrant *et al.*, 2009). Affective instruments have been used in other STEM disciplines to measure attitudes toward drawing (e.g., engineering; Alias *et al.*, 2002), but there are little published data on student affect toward drawing in biology (but see Lovelace and Brickman, 2013; Trujillo and Tanner, 2014).

By applying the general principles of affect (e.g., from Anderson and Bourke, 2000) toward, drawing, we propose

Table 5. Differences between novices and experts in how they draw and use models

Aspect of models	Novice learners	Expert learners
Relationship to reality	Think there is a 1:1 correspondence between models and reality	Understand that no model is wholly "right," so multiple models should be used
Relationship to other models	Struggle to translate among multiple models at the same scale, and between models at different scales	Can easily translate among multiple models
Salient features	Tend to focus on surface features of the models (such as model organism used or other case study context)	Tend to focus on underlying relationships, processes, functions, and principles in the models
Flexibility	View models as static and fixed	View models as dynamic tools that can be manipulated and changed
Purpose	View models as endpoints that are "right" and can be memorized as facts	View models as thinking tools
Spontaneous use	Tend not to make their own models to solve problems unless explicitly instructed to do so	Tend to make models spontaneously to solve problems on their own
Metacognition	When creating models, tend not to be self-aware of the quality or utility of their models	When creating models, can evaluate the quality or utility of their models

Table 6. Proposed interventions for improving affect regarding drawing models to reason

	Proposed interventions for instructors	Example
Attitude	Clearly define intentions for drawing in class to disassociate any prior negative perceptions from use of drawing in class	"Drawing models to reason in science is different from drawing a still life in art class …"
	Use positive and encouraging language when referring to drawing to learn in the classroom	"We're going to draw a model to make it easier to understand the regulation of the lac operon …"
Value	Refer to visuals used the classroom or homework explicitly as models to show their pervasiveness and value	"This model of DNA structure shows …")
	Use persuasion (such as call to authority by referring to famous or familiar scientists) to communicate the value of drawing models in biology	"Darwin drew the first ever model of relationships among species to help him formulate his theory of evolution by natural selection …"
	Allow students to discover the value of drawing for themselves, for example by assigning problems that are most readily solvable by use of models	"After trying to solve the problem in your head, draw a Punnett square to predict the frequency of offspring that will result from …"
Self-efficacy	Explicitly define expectations to assuage students concerns about their drawing ability (see Figure 1)	"Don't worry if you are not good at drawing. All you need to do is make a simple stick figure …"
	Model the expected behavior and provide opportunities for practice with sufficient scaffolding for complex models	"Draw the same model that I drew on the board, then modify it to show …"
Interest	Reduce the perceived costs or actual costs of drawing-to-learn	Provide sufficient time and space for students to use models
	Increase the perceived rewards or actual rewards of drawing to learn	Provide extrinsic rewards such as praise or course credit for using models

several interventions for addressing problems of affect in Table 6. The efficacy of these interventions is testable using the methods outlined in Lovelace and Brickman (2013).

Overall, the goal is to be explicit with students about the importance of models, to scaffold their use in class to make models easier to use, and to be transparent about expectations to avoid frustration and fear on the part of the students.

Visual Literacy

Models are composed of multiple elements that are abstractions of the real world. To successfully interpret and draw visual models, students must develop visual literacy—the skill to read and write visual or symbolic language, including the ability to translate verbal to visual (e.g., Stern *et al.*, 2003; Van Meter *et al.*, 2006; Schwamborn *et al.*, 2010), visual to visual (e.g., Johnstone, 1991; Novick and Catley, 2007; Hegarty, 2011), or visual to verbal (e.g., Schönborn and Anderson, 2010). These components of visual literacy are illustrated in Figure 5.

When a student translates visual to visual, the translation process can be "horizontal," from one drawing to another at the same scale (such as two different representations of "chromosome"), or "vertical," from a drawing at one scale to a drawing at another scale (such as a condensed chromosome viewed at the cellular level vs. a chromosome viewed as a segment of DNA double helix; see Figure 5). Students across STEM disciplines struggle particularly with vertical translations (e.g., NRC, 2012).

Note that these visual translation steps may occur internally as a student develops an internal model or can require the additional translation from internal model to an external model (see Figure 2), which involves not only sensory and cognitive modalities, but also motor coordination and familiarity with the drawing medium used.

Symbols vary in the degree to which they are representational, or isomorphic, to the concepts they represent. For example, a wolf in a food web can be represented with varying levels of detail (see Figure 3); each wolf symbol is nonetheless easily interpreted. Visual language also differs across subdisciplines of biology (e.g., Novick, 2006; NRC, 2012). For example, an arrow used to represent transcription in a diagram of biology's central dogma infers base pairing of DNA and RNA nucleotides; an arrow in a food web infers the transfer of energy and matter via consumption in a trophic relationship; and an arrow in a chemical reaction indicates a change in the state of matter. This heterogeneity can lead to misunderstandings and misconceptions, such as the interpretation of a DNA→RNA arrow in the central dogma

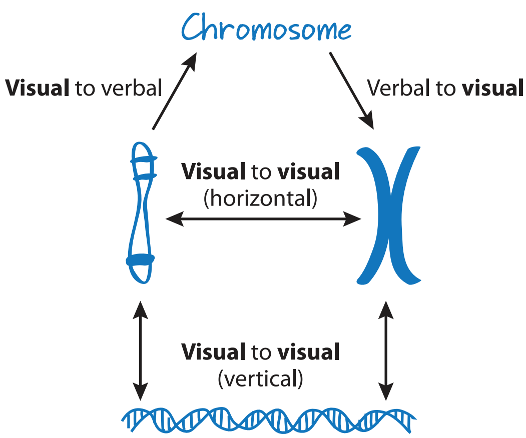
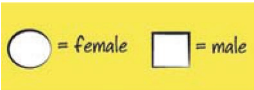


Figure 5. Visual literacy requires translation (→) from verbal to visual, visual to visual, and visual to verbal.

Table 7. Proposed interventions for improving visual literacy when drawing models

	Proposed interventions for instructors	Example
Definitions	Explicitly define the symbols used in class, both "generic" symbols (such as axes in a graph) and subdiscipline-specific symbols (such as branches in a phylogenetic tree)	"In this model, the arrow represents the use of the DNA molecule as a template for the base-pairing of an RNA molecule …"
Practice with translation	Give students opportunities to practice translating text to drawings, with appropriate scaffolding and feedback	"Draw a model that represents homologous, replicated chromosomes …"
	Give students opportunities to practice translating "horizontally" from one drawing to another at the same scale, with appropriate scaffolding and feedback	"Use this matrix of 1s (presence of character) and 0s (absence of character) to construct a phylogenetic tree …"
	Give students opportunities to practice translating "vertically" from a drawing at one scale to a drawing at another scale, with appropriate scaffolding and feedback	"Draw a simple model of a plant cell including at least five organelles, then enlarge a section of the cell membrane to show the structure of the bilipid layer …"
	Give students opportunities to practice translating drawings to text, with appropriate scaffolding and feedback	"Write a sentence that represents the take-home message of this graph …"
Practice with the drawing medium	Give students opportunities to practice using the drawing medium that will be used and assessed in class, whether pencil or pen on paper, chalk or pen on board, and/or mouse or stylus on screen in a particular software program	"Use a pencil or pen to sketch a model of the outcome of meiosis you ended up with at the completion of your bead exercise …"

to mean that DNA is itself converted into RNA (Wright *et al.*, 2014).

Visual literacy is rarely taught explicitly by instructors; this occurs, in part, because instructors tend to be experts in their discipline and do not experience the foreign language–like appearance of visual representations to some students (e.g., Mioduser and Santa María, 1995; Schönborn and Anderson, 2010; Wright *et al.*, 2014). Unfortunately, when students lack the skill to create effective external models, the creation of external models can hinder learning compared with the creation of mental models alone, either due to the increased cognitive demands incurred from the unscaffolded mental processes (Leutner *et al.*, 2009) or due to the creation of inaccurate models that impair learning (e.g., Schwamborn *et al.*, 2010).

With practice, however, students can learn to pick out important information, avoid distraction by surface features, and focus on making connections among important concepts (Mioduser and Santa María, 1995; Gobert and Clement, 1999; Harrison and Treagust, 2000; Van Meter *et al.*, 2006; Hegarty, 2011; Dauer *et al.*, 2013). We offer some proposed interventions for addressing problems of visual literacy in Table 7.

Model-Based Reasoning

As Table 5 summarized, novice learners tend to view models as static, authoritative "truths" and tend to be distracted by surface features, whereas expert learners view models as a flexible abstraction of reality that can be manipulated and used as a thinking tool. Overall, novices allocate more time and effort to creating models, whereas experts allocate more time and effort to using their models to find solutions (NRC, 2012). Modeling is challenging, because it requires the investment of cognitive effort (e.g., Uesaka and Manalo, 2011) and cognitive flexibility (DeHaan, 2009). Fortunately, this skill can be improved with instruction and practice (see references in Table 4).

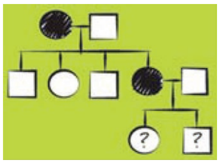
The creation and use of models can be parsed into four tasks: *construction*, *use*, *evaluation*, and *revision* (Schwarz *et al.*, 2009). To succeed in drawing models to reason, students must not only be able to create a model, but must also apply it to solve a problem or make a prediction, evaluate its efficacy, and revise as necessary. For example, students who draw highly accurate models benefit more from drawing models than those who draw low-accuracy models (Van Meter *et al.*, 2006; Rosengrant *et al.*, 2009), so iteration and revision is needed to develop expert-like modeling skills. Table 8 proposes some interventions for instructors in each of the four categories. Overall, the goal for instructors is to be transparent with students about what they are asking them to do and to give students plenty of practice and feedback.

HOW CAN DRAWING-TO-LEARN BE MADE MORE PRACTICAL FOR INSTRUCTORS?

The above discussion is framed in terms of the student experience, but the same principles apply to instructors, who vary in their experiences and skills. Thus, interventions in affect, visual literacy, and model-based reasoning have the potential to help instructors (and scientists) improve their skills in using drawings to reason in the same way that they are helpful to students (see references in Table 4).

What else can help instructors? Fortunately, some minor changes to instruction have the potential to produce meaningful learning gains for students. For example, the mere reference to illustrations in the textbook as "models" could possibly help to move a student closer to an expert

Table 8. Proposed interventions for improving visual model-based reasoning via drawing

	Proposed interventions for instructors	Example
Drawing of model	Explicitly point out the difference between surface features and structural features (the underlying relationships, processes, functions, and principles in the models)	"Draw a model showing cell respiration and photosynthesis in an ecosphere containing shrimp and algae. The biochemical processes are what are important here, *not* the appearance of the shrimp and algae …"
	Explicitly walk through the process of creating a model for students before asking them to make their own	"Let's make a model of a wetland food web. First, consider the conventions ecologists use when drawing food webs …"
	Demonstrate the flexibility of models in the classroom by showing and prompting alternate versions of the same model	"Draw three different phylogenetic trees that have different branch rotations, but all show the same relationships …"
	Demonstrate metacognitive value of drawing models	"What parts of the model are you struggling with? Are there concepts or other aspects that you need help with before you proceed? …"
Use of model	Prompt students to use the models they create as tools to answer questions	"How will increased cloud cover affect your model of the greenhouse effect? …"
	Prompt students to add or change an element in their models as a tool for solving a problem	"Modify your model of the greenhouse effect to predict how a decrease of ice coverage at the poles would influence atmospheric temperatures …"
Evaluation of model	Prompt students to check the quality of their models to ensure that they include all the essential elements in an accurate way	"Use the rubric to determine if you included all the essential ideas in your concept map of DNA regulation …"
	Prompt students to check the quality of their models to ensure that they are including only what is relevant	"Exchange models with your neighbor and see if you can identify any elements of the model that are not relevant to the concept of genetic drift …"
Revision of model	Prompt students to make improvements on their models based on their (or someone else's) evaluation of it	"Now draw a revised model of transcription to make improvements based on your group discussion …"

perspective on the dynamic nature of knowledge in science. Similarly, increased attention to the affect of students regarding the drawing of visual models could result in a valuable increase in motivation (Anderson and Bourke, 2000). We have consolidated the prompts from Tables 6–8 and formatted them into a summary timeline (Figure 6) to

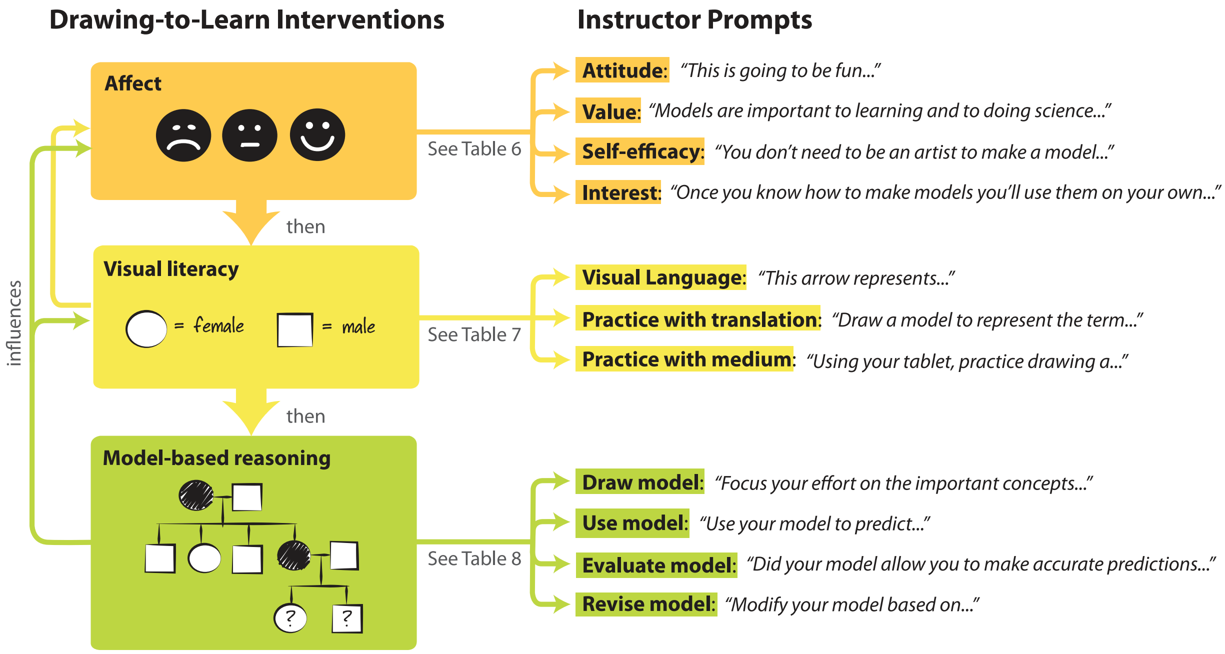
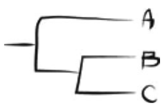
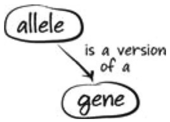
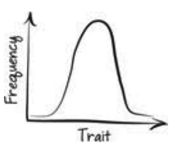


Figure 6. Visual guide on drawing-to-learn for instructors.

Table 9. Blooming Biology Tool for drawing visual models to reason[a]

	Knowledge[b]	Comprehension	Application[c]	Analysis	Synthesis	Evaluation[d]
Mitosis/meiosis diagrams 	Draw a $2n = 4$ cell during prophase of mitosis (using symbols as shown in lecture).	Draw a $2n = 4$ cell and indicate which chromosomes carry the same genes.	Draw a $2n = 8$ cell during metaphase of mitosis.	Draw $2n = 8$ cells comparing metaphase of mitosis and metaphase I of meiosis.	Draw meiotic cells to show how an egg could end up with an extra chromosome.	Evaluate a peer's drawing to determine whether it reveals misconceptions about genetic information.
Cell structures 	Draw a generalized animal cell (as shown in your homework assignment) and label the names of organelles.	Draw an animal cell and indicate the functions of at least eight organelles.	Pancreas cells are specialized for the export of digestive enzymes. Predict what a pancreas cell would look like under the microscope.	Draw a plant cell and an animal cell and highlight their differences.	George Palade created a "pulse-chase" method to follow the pathway of labeled proteins from creation to secretion. Make one or more cell drawings to explain how this might have looked.	Evaluate a cell drawing based on established criteria or rubric.
Phylogenetic trees 	Draw and label a cladogram showing relationships among three taxa A, B, and C (as shown in class).	Draw two equivalent cladograms showing the relationships among three taxa A, B, and C.	Draw a cladogram showing the relationships among black bears, polar bears, mice, and goldfish.	Compare your drawn cladogram with the one provided and determine whether they have the same meaning.	Given a data matrix, create a cladogram, identifying where on the tree the shared derived characteristics were acquired.	Evaluate a cladogram based on established criteria or rubric.
Concept maps 	Draw a concept map to represent "subject—links to→object" (as shown in your online homework).	Draw a linking phrase to connect the given subject and object.	Draw a concept map organizing the provided concepts and linking phrases.	Draw a concept map organizing the concepts provided, adding appropriate linking phrases.	Draw a concept map summarizing a given topic.	Rank the importance of different concepts in a map based on an established function.
Graphs 	Given independent and dependent variables, draw and label the axes of a graph (as shown in lab).	Given independent and dependent variables, draw and label the axes of a graph and explain what a data point would represent.	Draw a graph based on a given set of data.	Draw a graph based on a given set of data and determine whether the data support or reject a given hypothesis.	Design an experiment to answer a question and sketch a graph of your predictions.	Evaluate a graph to determine whether its construction is appropriate to the data set.

[a]Questions are modified from Crowe *et al.* (2008) to focus specifically on drawing visual models. Note that questions may include drawings or may be verbal. Either way, the questions assume prior instruction of the drawing conventions (e.g., introduction to the conventions used to create a concept map, graph, or phylogenetic tree).

[b]Note that the knowledge examples in this table test a student's knowledge of the drawing conventions appropriate to the topic, as explicitly demonstrated by the instructor, not content knowledge.

[c]The assumption in application-level questions is that the student has not seen this question or solution before.

[d]The examples in this category show how students can be asked to evaluate their own or peer drawings.

Table 10. A selection of proposed solutions to facilitate assessment of drawn models

Teaching challenge	Proposed solution
Drawings are difficult to assess, because they are so variable and/or complex.	Prescribe drawing activities by giving students a key of symbols to use or other explicit instructions. Prescribe drawing activities by giving students a starting point for their drawings (see Figure 3). Prescribe drawing activities by keeping the content area focused. Use a rubric to assess drawn models (and give the students the rubric ahead of time so they understand the objectives and criteria). Note that sometimes it is easier to assess a simple drawing than a verbal response.
The instructor does not have the technical or cognitive capacity to collect visual information, only verbal information.	Ask students to make a model, then write a caption describing the structure or outcome of the model, then submit only the caption. Ask students to make a model, then answer verbal questions based on the model (e.g., via clickers).
Course enrollment is too large to give feedback to all students on their drawn models.	Assign a model, then present one solution to the model and ask students to compare their own models with the sample solution. Ask students to submit drawn models, then select just a few examples to present and critique in class ("random call" method). Ask students to swap their models with their neighbors and peer evaluate the models based on stated criteria. Use classroom management software (e.g., Learning Catalytics, BeSocratic) that allows students to submit drawn answers to questions. Hand a random student a tablet in class and ask him or her to draw; the student's image will appear on the screen.

serve as a visual guide to help instructors scaffold drawing-to-learn in the classroom. Other resources in the literature provide alternate teaching guides (Harrison and Treagust, 2000) and learning progressions (Schwarz *et al.*, 2009) for drawing models to learn in science.

To further facilitate both the scaffolding and assessment of drawing models to learn, we have adapted the Blooming Biology Tool created by Crowe *et al.* (2008) to focus specifically on several commonly used modeling topics in biology (Table 9). Because drawing exercises can occur at all levels of thinking as defined by Bloom's taxonomy (Bloom *et al.*, 1956; Anderson *et al.*, 2001), an instructor can scaffold modeling by first introducing formative exercises at lower-order cognitive levels and then working up to assignments at higher-order cognitive levels.

The assessment of drawings can be daunting to instructors, especially those teaching large-enrollment courses. For example, it is important that students receive quality formative feedback on their models to make sure they are not harboring misconceptions or are not adrift from the intent of the exercise. But how is an instructor to give thoughtful feedback on graphs, concept maps, phylogenetic trees, or meiosis diagrams in a class of 500 students?

In an effort to suggest some possible solutions, we have generated a list of strategies from our own experience, from colleagues teaching undergraduate biology, and from the literature (Table 10). For example, we have learned from personal experience that it helps to prescribe drawing activities by providing a starting point (see Figure 1) or key of symbols to use, both to help students understand expectations and to limit the possible range of solutions. Instructors can also use different technology-based modeling tools to help their students build models (e.g., Jonassen *et al.*, 2005) and a rubric to facilitate assessment (see Allen and Tanner, 2006). Other colleagues have had success with a random-call method, selecting a few student models at random to critique in class. Peer review can also be effective, especially when used in combination with a rubric, with the caveat that this method tends to be more successful with lower-order cognitive tasks than higher-order cognitive tasks (Freeman and Parks, 2010). In sum, there are a number of possible solutions to facilitate assessment, the effectiveness of which will depend on context in the class. These proposed solutions represent hypotheses that can be tested and ranked under different conditions and with different student populations via biology education research.

CONCLUSION AND NEXT STEPS

Every biology instructor asks his or her students to interpret biological models, because we all offer visuals to students, and many of these visuals are models. Further, many instructors ask their students to draw their own models at some point—whether lipid bilayers, chromosomes in meiosis, graphs, phylogenetic trees, concept maps, or food webs—either as formative or summative activities. Biology instructors do this because model-based reasoning is intuitively a powerful tool for conceptual change and is inherent to the process of science. However, many instructors are not self-aware of drawing as a science process skill, and thus do not value the skill and do not scaffold it explicitly for their students.

We have argued in this essay that the drawing of visual models deserves more attention as a science process skill in biology, akin to efforts in other STEM disciplines. The *Vision and Change* list of core competencies (AAAS, 2011) should be augmented to reflect this change, as supported by evidence in the *Discipline-Based Education Research* report (NRC, 2012) and elsewhere. We have also provided a synthetic, multifaceted framework to help structure future use of drawing-to-learn and further research on best practices in biology.

There is a great deal that we do not know about drawing-to-learn in biology, and thus a wealth of opportunities for more work, including the testing of many of the hypotheses proposed in this essay and in the literature. For example, which types of interventions are most successful in improving students' ability to draw and reason with their models? What are the barriers that limit the utility of drawing exercises in class? How do gender, ethnicity, background experience, and content knowledge influence student abilities and/or affect regarding drawing-to-learn? Are insights from research on drawing one type of model transferable to other types?

We look forward to lively and productive discussions of drawing-to-learn in biology as part of the larger movement toward teaching problem solving (not just memorization) and science process skills (not just content) to cultivate the next generation of educated scientists and citizens.

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REFERENCES

Ainsworth S (2008). How should we evaluate complex multimedia environments? In: Understanding Multimedia Comprehension, ed. JF Rouet, R Lowe, and W Schnotz, New York: Springer.

Ainsworth S, Prain V, Tytler R (2011). Drawing to learn in science. Science *333*, 1096–1097.

Alias M, Gray DE, Black TR (2002). Attitudes toward sketching and drawing and the relationship with spatial visualisation ability in engineering students. Int Educ J *3*, 165–204.

Allen D, Tanner K (2006). Putting the horse back in front of the cart: using visions and decisions about high-quality learning experiences to drive course design. Cell Biol Educ *6*, 85–89.

American Association for the Advancement of Science (2011). Vision and Change in Undergraduate Biology Education: A Call to Action, Washington, DC.

Anderson JL, Ellis JP, Jones AM (2014). Understanding early elementary children's conceptual knowledge of plant structure and function through drawings. CBE Life Sci Educ *13*, 375–386.

Anderson LW, Bourke SF (2000). Assessing Affective Characteristics in the Schools, London: Routledge.

Anderson LW, Krathwohl DR, Bloom BS (2001). A Taxonomy of Learning, Teaching, and Assessing: A Revision of Bloom's Taxonomy of Educational Objectives, New York: Longman.

Baldwin L, Crawford I (2010). Art instruction in the botany lab: a collaborative approach. J Coll Sci Teach *40*, 226–31.

Bassok M, Novick LR (2012). Problem solving. In: Oxford Handbook of Thinking and Reasoning, ed. KJ Holyoak and RG Morrison, New York: Oxford University Press.

Baum DA, Offner S (2008). Phylogenics and tree-thinking. Am Biol Teach *70*, 222–229.

Bloom BS, Krathwohl DR, Masia BB (1956). Taxonomy of Educational Objectives: The Classification of Educational Goals, New York: McKay.

Blumschein P, Hung W, Jonassen D, Strobel J, eds. (2009). Model-Based Approaches to Learning: Using Systems Models and Simulations to Improve Understanding and Problem Solving in Complex Domains, Rotterdam, The Netherlands: Sense.

Bransford JD, Brown AL, Cocking RR (2000). How People Learn: Brain, Mind, Experience, and School, Washington DC: National Academies Press.

Chittleborough G, Treagust DF (2007). The modeling ability of non-major chemistry students and their understanding of the sub-microscopic level. Chem Educ Res Pract *8*, 274–292.

Chun MM, Jiang Y (1998). Contextual cueing: implicit learning and memory of visual context guides spatial attention. Cogn Psychol *36*, 28–71.

Cohen SA (1987). Instructional alignment: searching for a magic bullet. Educ Res *16*, 816–20.

Coil D, Wenderoth MP, Cunningham M, Dirks C (2010). Teaching the process of science: faculty perceptions and an effective methodology. CBE Life Sci Educ *9*, 524–535.

Crowe A, Dirks C, Wenderoth MP (2008). Biology in Bloom: implementing Bloom's taxonomy to enhance student learning in biology. CBE Life Sci Educ *7*, 368–381.

Darwin C (1837). Notebook B: Transmutation of Species (1837–1838). http://darwin-online.org.uk/content/record?itemID=CUL-DAR121.- (accessed 5 March 2014).

Dauer JT, Momsen JL, Bray Speth E, Makohon-Moore SC, Long TM (2013). Analyzing change in students' gene-to-evolution models in college-level introductory biology. J Res Sci Teach *50*, 639–659.

DeHaan RL (2009). Teaching creativity and inventive problem solving in science. CBE Life Sci Educ *8*, 172–181.

de Jong T (2010). Cognitive load theory, educational research, and instructional design: some food for thought. Instr Sci *38*, 105–134.

Dikmenli M (2010). Misconceptions of cell division held by student teachers in biology: a drawing analysis. Sci Res Essay *5*, 235–247.

Eddy SL, Crowe AJ, Wenderoth MP, Freeman S (2013). How should we teach tree-thinking? An experimental test of two hypotheses. Evo Educ Outreach *6*, 13.

Edens KM, Potter EF (2010). Using descriptive drawings as a conceptual change strategy in elementary science. School Sci Math J *103*, 135–144.

Edwards B (1979). The New Drawing on the Right Side of the Brain, New York: Jeremy P. Tarcher.

Ekici F, Ekici E, Aydin F (2007). Utility of concept cartoons in diagnosing and overcoming misconceptions related to photosynthesis. Int J Environ Sci Educ *2*, 111–124.

Frankel F (2002). Envisioning Science: The Design and Craft of the Science Image, Cambridge, MA: MIT Press.

Frankel F, DePace AH (2012). Visual Strategies: A Practical Guide to Graphics for Scientists and Engineers, New Haven, CT: Yale University Press.

Freeman S, Eddy SL, McDonough M, Smith MK, Okoroafor N, Jordt H, Wenderoth MP (2014). Active learning increases student performance in science, engineering, and mathematics. Proc Natl Acad Sci USA *111*, 8410–8415.

Freeman S, Parks JW (2010). How accurate is peer-grading? CBE Life Sci Educ *9*, 482–488.

Fry B (2008). Visualizing Data, Sebastopol, CA: O'Reilly Media.

Gilbert JK, Reiner M, Nakhleh M (eds.) (2008). Visualization: Theory and Practice in Science Education, New York: Springer.

Glynn S, Muth KD (2008). Using drawing strategically: drawing activities make life science meaningful to third- and fourth-grade students. Sci Children *45*, 48–51.

Gobert JD, Clement JJ (1999). Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. J Res Sci Teach *36*, 39–53.

Grosslight L, Unger C, Jay E, Smith CL (1991). Understanding models and their use in science: conceptions of middle and high school students and experts. J Res Sci Teach *28*, 799–822.

Guida A, Lavielle-Guida M (2014). 2011 space odyssey: spatialization as a mechanism to code order allows a close encounter between memory expertise and classic immediate memory studies. Front Psych *5*, 1–5.

Harrison AG, Treagust DF (2000). A typology of school science models. Int J Sci Educ *9*, 1011–1026.

Hay D, Kinchin I, Lygo-Baker S (2008). Making learning visible: the role of concept mapping in higher education. Stud High Educ *33*, 295–311.

Hay DB, Williams D, Stahl D, Wingate RJ (2013). Using drawings of the brain cell to exhibit expertise in neuroscience: exploring the boundaries of experimental culture. Sci Educ *97*, 468–491.

Hegarty M (2011). The role of spatial thinking in undergraduate science education. Paper presented at the third Committee Meeting on Status, Contributions, and Future Directions of Discipline-Based Education Research, held December 3–4, 2010, in Irvine, CA.

Hmelo-Silver CE, Marathe S, Liu L (2007). Fish swim, rocks sit, and lungs breathe: expert-novice understanding of complex systems. J Learn Sci *16*, 307–331.

Hyerle D (2000). A Field Guide to Using Visual Tools, Alexandria, VA: Association for Supervision and Curriculum Development.

Ifenthaler D, Maskuki I, Steel NM (2011). The mystery of cognitive structure and how we can detect it: tracking the development of cognitive structures over time. Instruct Sci *39*, 41–61.

Johnson-Laird PN (1980). Mental models in cognitive science. Cog Sci *4*, 71–115.

Johnstone AH (1991). Why is science difficult to learn? Things are seldom what they seem. J Comput Assist Learn *7*, 75–83.

Jonassen D, Strobel J, Gottdenker J (2005). Model building for conceptual change. Interact Learn Environ *13*, 1–215–37.

Kindfield ACH (1994). Biology diagrams: tools to think with. J Learn Sci *3*, 1–36.

Kirschner PA, van Merriënboer JJG (2013). Do learners really know best? Urban legends in education. Educ Psychol *48*, 169–183.

Kiyokawa S, Kura Y, Uesaka Y, Manalo E (2012). Does construction of diagrams deepen understanding by raising awareness of insufficiency in learning? In: Staging Knowledge and Experience: How to Take Advantage of Representational Technologies in Education and Training? ed. E de Vries and K Scheiter, Grenoble, France: Laboratoire des Sciences de l'Education, Université Pierre-Mendès-France, 100.

Klein PD (1999). Reopening inquiry into cognitive processes in writing-to-learn. Educ Psychol Rev *11*, 203–270.

Koba S, Tweed A (2009). Hard-to-Teach Biology Concepts: A Framework to Deepen Student Understanding, Arlington, VA: NSTA Press.

Kobella TR Jr (1989). Changing and Measuring Attitudes in the Science Classroom: Research Matters—to the Science Teacher, Publication no. 8901, Reston, VA: National Association for Research in Science Teaching.

Köse S (2008). Diagnosing student misconceptions: using drawings as a research method. World Appl Sci J *3*, 283–293.

Kress G, van Leeuwen T (2006). Reading Images: The Grammar of Visual Design, 2nd ed., New York: Routledge.

Larkin JH, Simon H (1987). Why a diagram is (sometimes) worth ten thousand words. Cogn Sci *11*, 65–99.

Lerner N (2007). Drawing to learn science: legacies of Agassiz. J Technol Writ Com *37*, 379–394.

Leutner D, Leopold C, Sumfleth E (2009). Cognitive load and science text comprehension: effects of drawing and mentally imagining text content. Comput Human Behav *25*, 284–289.

Libarkin J, Ording G (2012). The utility of writing assignments in undergraduate bioscience. CBE Life Sci Educ *11*, 39–46.

Löhner S, van Joolingen WR, Savelsbergh ER, van Hout-Wolters B (2005). Students' reasoning during modeling in an inquiry learning environment. Comput Human Behav *21*, 441–461.

Long TM, Dauer JT, Kostelnik KM, Momsen JL, Wyse SA, Speth EB, Ebert-May D (2014). Fostering ecoliteracy through model-based instruction. Front Ecol Environ *12*, 138–139.

Lovelace M, Brickman P (2013). Best practices for measuring students' attitudes toward learning science. CBE Life Sci Educ *12*, 606–617.

Mayer RE (2009). Multi-media Learning, 2nd ed., Cambridge, UK: Cambridge University Press.

Mayer RE, Hegarty M, Mayer S, Campbell J (2005). When static media promote active learning: annotated illustrations versus narrated animations in multimedia instruction. J Exp Psychol *4*, 256–265.

Mayer RE, Heiser J, Lonn S (2001). Cognitive constraints on multimedia learning: when presenting more material results in less understanding. J Educ Psychol *93*, 187–198.

Mayer RE, Sims VK (1994). For whom is a picture worth a thousand words? Extensions of a dual-coding theory of multimedia learning. J Educ Psychol *89*, 389–401.

Mioduser D, Santa María M (1995). Students' construction of structured knowledge representations. J Res Comput Educ *28*, 63–84.

Mohler DL (2007). An instructional strategy for pictorial drawing. J Indust Teach Educ *44*, 5–26.

Mynlieff M, Manogaran AL, St. Maurice M, Eddinger TJ (2014). Writing assignments with a metacognitive component enhance learning in a large introductory biology course. CBE Life Sci Educ *13*, 311–321.

National Research Council (2012). Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering, Washington DC: National Academies Press.

National Science Foundation (2008). Picture This: Explaining Science through Drawings. www.nsf.gov/news/news_summ.jsp?cntn_id=111410&org=NSF&from=news (accessed 5 March 2014).

Novak JD, Cañas AJ (2006). The origins of the concept mapping tool and the continuing evolution of the tool. Inf Vis *5*, 175–184.

Novick LR (2000). Spatial diagrams: key instruments in the toolbox for thought. Psychol Learn Motiv *40*, 279–325.

Novick LR (2006). The importance of both diagrammatic conventions and domain-specific knowledge for diagram literacy in science. The hierarchy as an illustrative case. In: Diagrammatic Representation and Inference, ed. D Barker-Plummer, R Cox, and N Swoboda, Berlin: Springer-Verlag, 1–11.

Novick LR, Catley KM (2006). Interpreting hierarchical structure: evidence from cladograms in biology. In: Diagrammatic Representation and Inference. ed. D Barker-Plummer, R Cox, and N Swoboda, Berlin: Springer-Verlag, 176–180.

Novick LR, Catley KM (2007). Understanding phylogenies in biology: the influence of Gestalt perceptual principle. J Exp Psychol *13*, 197–223.

Padilla MJ, McKenzie DL, Shaw EL Jr (1986). An examination of the line graphing ability of students in grades seven through twelve. School Sci Math *86*, 20–26.

Pavio A (1986). Mental Representations: A Dual-Coding Approach, Oxford, UK: Oxford University Press.

Pelaez NJ, Boyd DD, Rojas JB, Hoover MA, Nancy J, Boyd DD, Rojas JB (2005). Prevalence of blood circulation misconceptions among prospective elementary teachers. Adv Physiol Educ *29*, 172–181.

Picone C, Rhode J, Hyatt L, Parshall T (2007). Assessing gains in undergraduate students' abilities to analyze graphical data. Teach Issues Exper Ecol *5*, 1–54.

Rennie LJ, Jarvis T (1995). Children's choice of drawings to communicate their ideas about technology. Res Sci Educ *25*, 239–252.

Reynolds JA, Thaiss C, Katkin W, Thompson RJ Jr (2012). Writing-to-learn in undergraduate science education: a community-based, conceptually driven approach. CBE Life Sci Educ *11*, 17–25.

Ridley P, Rogers A (2010). Drawing to Learn: Science, Technology, Engineering & Math, Center of Teaching and Learning, Brighton, UK: University of Brighton Centre for Learning and Teaching.

Roam D (2008). Back of the Napkin: Solving Problems and Selling Ideas with Pictures, New York: Penguin.

Rohrer D, Pashler H (2012). Learning styles: where's the evidence? Med Educ *46*, 34–35.

Rose G (2012). Visual Methodologies: An Introduction to Researching with Visual Materials, 3rd ed., Los Angeles: Sage.

Rosengrant D, Van Heuvelen A, Etkina E (2009). Do students use and understand free-body diagrams? Phys Rev Spec Top Phys Educ Res *5*, 010108.

Schönborn KJ, Anderson TR (2010). Bridging the educational research-teaching practice gap: foundations for assessing and developing biochemistry students' visual literacy. Biochem Mol Biol Educ *38*, 347–354.

Schwamborn A, Mayer RE, Thilmann H, Leopold C, Leutner D (2010). Drawing as generative activity and drawing as a prognostic activity. J Educ Psychol *102*, 842–879.

Schwamborn A, Thillmann H, Opfermann M, Leutner D (2011). Cognitive load and instructionally supported learning with provided and learner-generated visualizations. Comput Human Behav *27*, 89–93.

Schwarz CV, Reiser BJ, Davis EA, Kenyon L, Achér A, Fortus D, Scwartz Y, Hug B, Krajcik J (2009). Developing a learning progression for scientific modeling: making scientific modeling accessible and meaningful for learners. J Res Sci Teach *46*, 632–654.

Seel NM (2003). Model-centered learning and instruction. Technol Instruct Cogn Learn *1*, 59–85.

Shepardson DP, Niyogi D, Charusombat U (2011). Seventh grade students' mental models of the greenhouse effect. Environ Educ Res *17*, 1–17.

Shepardson DP, Niyogi D, Choi S, Charusombat U (2009). Seventh grade students' conceptions of global warming and climate change. Environ Educ Res *15*, 549–570.

Stephens S (2012). From tree to map: using cognitive learning theory to suggest alternative ways to visualize macroevolution. Evol Educ Outreach *5*, 603–618.

Stern E, Aprea C, Ebner HG (2003). Improving cross-content transfer in text processing by means of active graphical representation. Learn Instruct *13*, 191–203.

Stow W (1997). Concept mapping as a tool for self-assessment? Prim Sci Rev *49*, 12–15.

Sweller J (1988). Cognitive load during problem solving: effects on learning. Cogn Sci *12*, 257–285.

Tanner KD (2009). Talking to learn: why biology students should be talking in classrooms and how to make it happen. CBE Life Sci Educ *8*, 89–94.

Tempelman-Kluit N (2006). Multimedia learning theories and online instruction. Coll Res Libr *67*, 364–369.

Trujillo G, Tanner KD (2014). Considering the role of affect in learning: monitoring students' self-efficacy, sense of belonging, and science identity. CBE Life Sci Educ *13*, 6–15.

Tufte ER (1983). The Visual Display of Quantitative Information, Cheshire, CT: Graphics Press.

Tufte ER (1990). Envisioning Information, Cheshire, CT: Graphics Press.

Tufte ER (2003). Visual Explanations: Images and Quantities, Evidence and Narrative, 2nd ed., Cheshire, CT: Graphics Press.

Uesaka Y, Manalo E (2011). Task-related factors that influence the spontaneous use of diagrams in math word problems. Appl Cogn Psychol *26*, 251–260.

Uesaka Y, Manalo E, Ichikawa S (2007). What kinds of perceptions and daily learning behaviors promote students' use of diagrams in mathematics problem solving? Learn Instr *17*, 322–335.

Van Meter P, Aleksic M, Schwartz A, Garner J (2006). Learner-generated drawing as a strategy for learning from content area text. Contemp Educ Psychol *31*, 142–166.

Van Meter P, Garner J (2005). The promise and practice of learner-generated drawing: literature review and synthesis. Educ Psychol Rev *17*, 285–325.

Watson FL, Lom B (2008). More than a picture: helping undergraduates learn to communicate through scientific images. CBE Life Sci Educ *7*, 27–35.

Wiggins G, McTighe J (1998). Understanding by Design, Alexandria, VA: Association for Supervision and Curriculum Development.

Wright LK, Fisk JN, Newman DL (2014). DNA → RNA: What do students think the arrows mean? CBE Life Sci Educ *13*, 338–348.