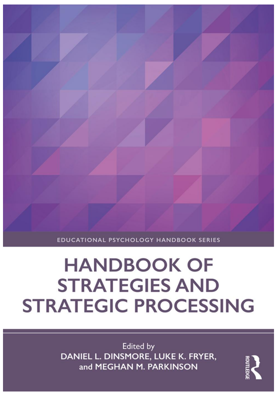

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SCIENCE STRATEGY INTERVENTIONS

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HISTORY OF STRATEGIES AND STRATEGIC PROCESSING IN SCIENCE EDUCATION

Strategic processing involves the use of cognitive and metacognitive strategies in learning. In science learning, learners use cognitive and metacognitive strategies to understand (a) scientific content in physics, chemistry, biology, Earth science, and other natural science domains; and (b) how scientists construct their understanding within these various domains (e.g., the practices of science or nature of what constitutes valid scientific knowledge). Thus, in science learning strategic processing is related to both the scientific domain or topic (see, for example, Greene et al., 2015) and the scientific tasks of investigating, explaining, and evaluating (see, for example, Dinsmore & Alexander, 2016).

Both scientific topics (e.g., force and motion) and tasks (e.g., conducting an experiment) are found at the task level per Dinsmore's (2017) Adaptive Model of Strategic Processing. Other levels in Dinsmore's model also apply to science learning. At the core of the model are strategic processing factors relating to quantity (i.e., how much deep- or surface-level processing), quality (i.e., how well was a strategy executed), and conditional use (i.e., how appropriate was it to use a particular strategy). Strategic processing interacts dynamically with the person-level characteristics, such as an individual's (a) level of interest in science (or a particular science topic, e.g., interest in astronomy), (b) prior knowledge of scientific content, (c) goal orientation toward learning science (e.g., mastery vs. performance orientation), and (d) epistemic thinking about scientific content (e.g., evaluations about coherency of scientific explanations). The person level also interacts with the task level (nature of the science learning task and scientific domain), which in turn interacts with the broader learning environment (e.g., the instructional climate that shapes a classroom, such as use of normative behaviors and instructional scaffolds promoting use of particular learning strategies).

For the purposes of this chapter, we view strategies as composed of an array of tactics that fit a broader task category. Thus, strategies are at a larger grain size than tactics (Winne, Jamieson-Noel, & Muis, 2002; Winne & Perry, 2000), with tactics being simple actions taken by a learner based on a specific task feature (e.g., using Newton's Second Law to calculate an object's acceleration when a physics problem gives the applied force and object's mass). So, an example of a physics learning strategy that is composed of categorically consistent tactics would be the "working-backward" strategy that learners would use to solve all or most physics problems (Taasoobshirazi & Farley, 2013). Furthermore, we will operate under the well-established and researched position that learners construct their knowledge both cognitively and socially (see, for example, Bransford, Brown, & Cocking, 2000; National Academies of Sciences, Engineering, & Medicine, 2018). This chapter will, therefore, focus on strategy interventions that specifically help promote science learning and/or have been used extensively by educational researchers to understand science learning and by practitioners to facilitate science learning. Certainly, there are generalized strategies that science learners and teachers use, such as those associated with reading comprehension (Dinsmore & Alexander, 2016), motivation (Muis, Ranellucci, Franco, & Crippen, 2013; Taasoobshirazi & Farley, 2013), and self-efficacy beliefs (Kıran & Sungur, 2012). However, other authors discuss these generalized strategies in more detail elsewhere in this volume (see, for example, Dumas, this volume).

Concept Development and Conceptual Change Strategies

Research into science concept development and conceptual change widely emerged in the early 1970s. Piaget's (1954, 1964) notions of cognitive knowledge construction were foundational to this research vein. In particular, Piaget's idea that thinking processes (he called them operations) act to form mental structures (i.e., concepts) and constitute the basis of a person's knowledge was highly influential. Concepts form and change through processes of assimilation (incorporating new information into existing cognitive structures) and accommodation (changing existing cognitive structures in response to new information). Furthermore, Piaget pointed out that the processes of assimilation and accommodation can happen spontaneously, which he termed the development of knowledge, or through provocation, which he termed learning.

Much early conceptual change research was also based on the notion that individuals' conceptual knowledge formed and changed similarly to how scientists constructed and changed scientific explanations (e.g., explanatory hypotheses and theories). In particular, some conceptual change researchers (see, for example, Posner, Strike, Hewson, & Gertzog, 1982) used T. Kuhn's (1962) notion of a paradigm shift as an analogy to laypeople's conceptual change learning. With this view, conceptual change is seen as a relatively radical knowledge construction process, where some kind of cognitive conflict or dissonance provokes the learner to be dissatisfied with their existing conceptual understanding (Posner et al., 1982). These early conceptual change researchers posited that once dissatisfied, a learner could proceed through a rational process of conceptual change if they constructed a replacement conception that was intelligible and understandable, more plausible than the prior conception, and open to the possibility of fruitfully solving future problems and opening new lines of inquiry. Therefore, science learning based on Piaget's (1954) notion of accommodation and Posner et al.'s (1982) rational conceptual change model included strategies that moved learners linearly and rationally through steps that addressed these conditions (i.e., individuals progressing through each step—intelligibility, plausibility, and fruitfulness—through reasoned logic based on evidence).

Strategies that focus on only one part of the linear and rational conceptual change process, however, are generally ineffective. For example, strategies that promote contradiction of misconceptions through dissonance and cognitive conflict (e.g., presenting a discrepant event, such as a demonstration that air has mass and exerts a force) have little likelihood of promoting conceptual change because of a variety of psychological responses, such as ignoring or rejecting novel information that is causing cognitive conflict (Chinn & Brewer, 1993). Furthermore, learner characteristics, such as motivation, interest, and epistemological beliefs, may limit engagement when the conceptual change strategy focuses solely on cognitive conflict (Dole & Sinatra, 1998; Limón, 2001). Use of analogies that endeavor to increase the coherence and comprehensibility of the new conception have also shown limited effectiveness. For example, Harrison and Treagust (1993) found that students took transfer analogs from the base to the target too literally (e.g., thinking that atoms are alive and divide like cells).

Given the general ineffectiveness in one single strategy promoting conceptual change, some researchers have called for combination of strategies. Such combined strategies generally promote more gradual and sustained conceptual change and conceptual development. For example, Clement (2008) proposed that learners engage in repeated criticism and revision of explanatory models to engage in all elements of the linear and rational conceptual change sequence. This process, called model evolution, is more gradual and involves a series of iterative dissonance and analogy strategies to help the learner construct a scientific model of a phenomenon over time. Gradual model evolution may involve empirical investigation strategies (e.g., labs) that have the potential to help learners deeply engage in critiquing and revising their explanatory models over time.

Empirical Investigation Strategies

For over a century, learners' participation in empirical investigations has been integral to science instruction in many types of learning environments. Empirical investigations are a general strategy that includes all sorts of activities and tactics that generally relate to asking questions about, collecting data from, experimenting on and the testing of natural phenomena (National Research Council [NRC], 2012). Traditionally, such empirical investigations have often occurred in settings or classrooms that simulate a laboratory environment (e.g., measuring temperatures of water, contained in a glass beaker, heated through various changes of state; Hofstein & Lunetta, 1982).

Empirical investigations can also include field experiences in the natural environment (e.g., collecting water samples in a creek located near a school). Empirical investigations in laboratory and field settings often involve use and manipulation of equipment and materials via methodologies consistent within a scientific domain (e.g., growing and counting bacteria in a petri dish filled with agar; Hofstein & Lunetta, 2004). In recent decades, empirical investigations also include virtual electronic simulations and environments in which learners collect data and conduct tests and experiments (e.g., observing global temperature changes via computer-based climate change models; Hofstein & Kind, 2012).

Learners' engagement in empirical investigations can achieve many learning goals. The National Academies of Science released a report in the mid-2000s that said when learners participate in empirical investigations, they may: (a) gain mastery of science content, (b) develop scientific reasoning skills, (c) understand the complexity and uncertainty inherent in empiricism, (d) develop practical skills, (e) understand the characteristic nature of science, (f) cultivate interest in science and interest in learning science, and (g) foster a sense of teamwork (National Research Council, 2007). Inherent within these goals is an assumption that participating in laboratory activities will help learners learn about both the processes of the scientific empiricism (i.e., how to do scientific investigations) and the products of the scientific empiricism (i.e., the knowledge produced from scientific investigations). However, much prior research (see, for example, Driver & Easley, 1978) showed that participation in empirical investigations fell far short of these goals because learners and teachers often relied on a stepwise sequence of procedures to arrive at a predetermined outcome (e.g., the six steps of the so-called "scientific method": make an observation, generate a question, form a hypothesis, conduct an experiment, analyze the data, and draw a conclusion). Therefore, learners only superficially engaged in this type of learning strategy and would not deeply understand how the stepwise laboratory activity related to fundamental scientific concepts (Lunetta, Hofstein, & Clough, 2007).

Inquiry-based Strategies

Inquiry-based science learning strategies emerged from research about learning via empirical investigations. Researchers proposed the learning cycle to weave development of understanding about scientific concepts with development of more abstract and complex reasoning that is reflected in empirical investigations (Karplus & Butts, 1977; SCIS, 1974). The learning cycle consisted of three phases: (a) exploration, where teachers introduced a scenario requiring science students to interact with phenomenon by encountering a problem, generating questions, observing, measuring, etc.; (b) concept introduction, where science students and teachers made sense of their interactions with the phenomenon of interest in an explanation; and (c) concept application, where students elaborated and extended the explanation to other contexts and phenomena. The developers designed the learning cycle to act as a strategy to help students self-regulate their science learning through a guided process of scientific inquiry, including discovery, explanation, and elaboration (Karplus & Butts, 1977). Although guided inquiry-based science strategies came under criticism for a variety of reasons (e.g., focusing solely on manipulation of materials and pieces of equipment to arrive at a pre-defined solution; see, for example, Tobin, Tippins, & Gallard, 1994), the learning cycle heavily influenced science interventions in the 1990s and early 2000s, including, among others, predict-observe-explain (White & Gunstone, 1992), authentic science tasks (Songer, 1996), and project-based science (Marx, Blumenfeld, Krajcik, & Soloway, 1997). The learning cycle is currently manifest in many science classrooms as the BSCS 5E Instructional Model (Bybee et al., 2006), consisting of five phases: engagement, exploration, explanation, elaboration, and evaluation.

Scientific Expertise Strategies

Engaging learners in inquiry-based instruction is closely related to the notion that developing learners' scientific expertise is critical for deep science understanding. Strategies for developing expertise aim to develop learners' thinking skills that reflect the core attributes of authentic scientific reasoning (Chinn & Malhotra, 2002). To develop such expert reasoning, learners need to construct, conceptually organize, and retrieve relevant knowledge about phenomena consistent with scientists who practice within a particular topic domain (Bransford et al., 2000). For example, learners who develop astronomy expertise will be able to construct and relate models of celestial motions that can be accurately applied to astronomical systems at planetary, stellar, and galactic scales. As such, strategies that seek to develop expertise should have students engage in cognitive processes and practices that reflect scientific inquiry (e.g., designing experimental conditions to investigate relations among variables; Künsting, Wirth, & Paas, 2011) and scientific epistemic beliefs (e.g., coordinate theoretical models with multiple lines of evidence; Chinn & Malhotra, 2002).

Developing such scientific expertise through tasks that engage students in authentic inquiry has proved to be a daunting task for both educators and educational researchers. Chinn and Malhotra (2002) found that many science inquiry-based tasks were rather simplistic, with the potential to reinforce non-scientific epistemic beliefs (e.g., scientific knowledge is simple, certain, and algorithmic). However, to facilitate learners' development of scientific expertise, learners should engage in tasks that elicit authentic reasoning strategies over sustained periods of time (see, for example, Chen & Wu, 2012). To aid in this sustained strategy of authentic scientific inquiry, the learning sciences and science education research communities called for the development of instructional scaffolds to facilitate cognitive apprenticeship, where "complex tasks can be distributed … to minimize obstacles and compensate for limitations by providing assistance at opportune moments" (Quintana et al., 2004, p. 340). This call paved the way for contemporary science learning strategies that incorporated argumentation, modeling, and socio-scientific concepts. In fact, a recent report by the NRC (2018) recommended that "science investigation and engineering design should be *the* [emphasis added] central approach for teaching and learning science and engineering" (p. S-4), with scaffolds needed for learners to develop deep understanding of "phenomena and evidence-based solutions to challenges … over time" (pp. 3–4).

CONTEMPORARY STRATEGIES AND STRATEGIC PROCESSING IN SCIENCE EDUCATION

Strategies and strategic processing associated with scientific inquiry and expertise have set the stage for science education's present state. For example, the NRC (2012) proposed a three-dimensional framework for K-12 science education integrating:

> [s]cientific and engineering practices; crosscutting concepts that unify the study of science and engineering through their common application across fields; and core ideas in four disciplinary areas: physical sciences, life sciences, earth and space sciences, and engineering, technology, and applications of science.
>
> (p. 2)

This conceptual framework served as the foundation for the development of the *Next Generation Science Standards* (NGSS Lead States, 2013), with some aspect of each dimension combined to form a standard (called a "performance expectation" by the NGSS authors). The scientific and engineering practices are particularly connected to the notion of developing learners' scientific expertise through engagement in scientific inquiry during classroom learning. Although the framework includes eight scientific and engineering practices in which students should engage, they reflect two broad strategic processing categories: science learning through argumentation and science as modeling. We will discuss each of these broad contemporary categories in the remainder of this section, and then in the next section, use an example to demonstrate authentic learning via socio-scientific topics that includes these two strategies.

Science Learning through Argumentation Strategies

Learning science through the practice of argumentation has seen increased emphasis since the late 1990s. For example, the *National Science Education Standards* (NRC, 1996) emphasized that a critical component of scientific literacy is "the capacity to pose and evaluate arguments based on evidence and to apply conclusions from such arguments appropriately" (p. 22). More recent reform-based reports, such as *A Framework for K-12 Science Education* (NRC, 2012), have elevated the construction of evidence-based explanations as a scientific practice in which students should engage during classroom learning. This framework featured argumentation within a centralized hub of scientific activity, in which:

> [a]rgumentation and analysis that relate evidence and theory are also essential features of science …[These argumentation processes] include appraisal of data quality, modeling of theories, development of new testable questions from those models, and modification of theories and models as evidence indicates they are needed.
>
> (p. 27)

The framework also included argumentation within the social enterprise of science, and asserted "the norms for building arguments from evidence are developed collectively in a vast network of scientists working together over extended periods" (p. 27).

In short, educational reformers, researchers, and practitioners view scientific argumentation as an authentic scientific practice and a key science learning strategy.

Scientific argumentation is an inherently constructive process, and as a science learning strategy, it builds upon the notion of cognitive and social construction of evidence-based explanations. Toulmin (1958, 2003, p. 87) proposed a domain-general "layout" of argumentation that educators use widely. In this layout, Toulmin positioned argumentation as a process by which people validate a claim via data and backed warrants. Claims are implicit in assertions (i.e., claiming unalienable rights, such as life, liberty, and the pursuit of happiness), and specifically aim to make a "claim on our attention and our beliefs" (Toulmin, 1958, 2003, p. 11). Science education researchers and practitioners often view claims as scientific explanations (e.g., accounts of how phenomena unfold that may lead to a feeling of understanding; Braaten & Windschitl, 2011; Brewer, Chinn, & Samarapungavan, 1998). As an explanation, claims may also answer questions relating to a particular phenomenon (e.g., the cause of current climate change). Toulmin views data as the "facts … [that act] as a foundation to a claim" (p. 90). Toulmin's use of the term data may be somewhat confusing in a science education framework because of the very specific connection of data as a quantifiable signal (e.g., a quantity obtained from a measurement or modeling simulation). Therefore, researchers and science education practitioners often use the term evidence (or evidence lines) in lieu of the term data or facts. Furthermore, in science, backed warrants are generally referred to as scientific reasoning, such as reasoning that evaluates and justifies connections between lines of evidence and claims. In essence, such reasoning would support the scientific "rules, principles, [and] inference[s]" that act as the tools to evaluate connections between evidence and explanations per Toulmin's layout (Toulmin, 1958, 2003, p. 91). Thus, when thinking about the Toulmin model of argumentation within the context of science learning, claims, data, and backed warrants become claims, evidence, and reasoning.

Many science educators use claims-evidence-reasoning (CER) as a strategy to promote their students' engagement in scientific argumentation. McNeill and Krajcik (2008) first introduced this strategy to facilitate students' construction of explanations about a phenomenon. CER is often used in conjunction with classroom-based inquiry activities, such as investigations where students collect and analyze data (e.g., experiments, problem-based learning scenarios). Teachers can use scaffolds to facilitate students' engagement in the CER strategy, such as answering specific questions that relate to each component (McNeill & Martin, 2011). For example, a question prompt could ask students to generate a claim, such as "what statement can you write to describe why X occurred?" where X is a phenomenon observed in the classroom (e.g., an observation that the temperature of boiling water stays the same even when increasing amounts of energy are applied to a hot plate). Another question could ask students to develop a statement of the evidence related to their claim, such as "what scientific data support your claim?" Finally, the scaffold would then use a question asking students to justify their claim by explicitly connecting the evidence to it, such as "how does the evidence support your claim?" Through this scaffolded CER process, students generate a scientific argument.

The CER process can include a fourth element, counterargument. When evaluation of alternative explanations become part of the CER strategy, students are more fully participating in scientific argumentation (Nussbaum & Edwards, 2011). Consideration of alternatives specifically helps students to develop their critical thinking skills (Lombardi, Bailey, Bickel, & Burrell, 2018; Lombardi, Bickel, Bailey, & Burrell, 2018) and deepen their learning on a particular topic through cognitive elaboration (i.e., making multiple connections with their background knowledge; Nussbaum, 2008). Such critical thinking and cognitive elaboration may also facilitate students' scientifically accurate knowledge construction and reconstruction (Nussbaum, Sinatra, & Poliquin, 2008) and metacognition (D. Kuhn, Zillmer, Crowell, & Zavala, 2013). However, consideration of counterarguments and rebuttals is challenging for students. Therefore, developmental scientists suggest that instruction promoting evaluation of alternative explanations should often begin at early adolescence (i.e., after a student has increasing cognitive control over the coordination of lines of evidence and theory; D. Kuhn & Pearsall, 2000).

Engaging in scientific argumentation is difficult for students because coordination of evidence and theory is a challenge. Furthermore, using argumentation to promote science learning is also challenging for teachers. For example, research has shown that students can make claims without justifications, including not using credible lines of evidence and scientific reasoning (Fischer et al., 2014). Therefore, recent research projects have focused on developing and testing instructional scaffolds that promote students' participation in collaborative and productive scientific argumentation in classroom settings (see, for example, D. Kuhn, 2010; Lombardi, Bailey, et al., 2018; Lombardi, Bickel, et al., 2018; McNeil & Krajcik, 2009; Nussbaum & Edwards, 2011; Rinehart, Duncan, Chinn, Atkins, & DiBenedetti, 2016). When viewing argumentation as a process that promotes deep understanding of both scientific content and skills, Manz (2015) says that development of scaffolds should "shift argumentation from a procedure conducted after scientific work has been done, or conducted in the absence of scientific work, and instead embed it in the scientific enterprise" (p. 20). In doing so, these scaffolds may help students to become more critical evaluators of the connection between lines of evidence and explanations, and potentially with more than one alternative explanation in the context of controversial and complex socio-scientific issues (e.g., causes of climate change).

Science as Modeling Strategies

Modeling and argumentation strategies emerged somewhat concurrently in association with 1990s science education reform efforts (American Association for the Advancement of Science, 1993). In the mid-2000s, the NRC (2007) and others (e.g., Windschitl, Thompson, & Braaten, 2008) presented scientific modeling and theory building as a classroom practice that more authentically represented the scientific enterprise than the oft-used, and so-called, scientific method. The NRC (2007) specifically recommended that teachers should present science "as a process of building theories and models using evidence, checking them for internal consistency and coherence, and testing them empirically" (p. 5). Therefore, for many lines of scientific inquiry, modeling is a quintessential process (Nersessian, 2008). The NRC (2012) more recently stated that scientists use models as tools to "visualize and understand a phenomenon under investigation" (p. 56). Furthermore, models that deepen understanding have compatibility among a variety of scientific fields, are parsimonious, are supported by scientific evidence, and have predictive power (i.e., are supported by future lines of empirical evidence; Pluta, Chinn, & Duncan, 2011). In general, scientific models help people understand "the way the natural and human-engineered world operates" and act as "simplifications of complex laws or theories that [people translate] as general ideas" (Moulding, Bybee, & Paulson, 2015, pp. 62–63).

The science as modeling strategy extends the use of models (including physical, pictorial, graphical, mathematical, and computerized replications of phenomena) to the central focus in inquiry-based learning. Schauble (2018) views science as modeling as a bottom-up strategy for science learning, where students develop models in specific domains, even specific topics, through which they then develop a more general set of heuristics for scientific knowledge construction. Therefore, science instruction must include classroom practice in model use, together with the metacognitive aspects of modeling in science. To encompass the two components of practical use and metacognitive reflection of scientific models, Schwarz et al. (2009) proposed that students simulate scientific activities by constructing models via extant evidence and theory, using models to explain and predict, evaluating models through their ability to predict future observations, and revising models to increase their explanatory and predictive power. In doing so, the science as modeling strategy facilitates learners' participation in scientific discourse and reasoning, critical thinking about alternative representations, and reflectivity about their own understanding (Louca & Zacharia, 2012). Promoting deep cognitive and metacognitive engagement with science content has the potential to move learners' model use beyond purely illustrative and demonstrative purposes toward more meaningful scientific knowledge construction.

Researchers and practitioners often link the modeling as science strategy with argumentation. Windschitl et al. (2018) suggested that the evidence-based argumentation strategy informs students' participation in scientific modeling. These researchers see the practice of argumentation in simultaneously developing models that are predictive of a phenomenon and written explanations that provide additional insight into the phenomenon. For example, consider a situation in which students use a simple computer simulation to predict future climate change and develop a written explanation of the causes of current climate change and future impacts. While doing this work, students could also engage in collaborative argumentation that critiques and parameterizes model uncertainties to develop a revised explanation that establishes a range of possible impacts. Mendonça and Justi (2013) found that students can engage in scientific argumentation when they justify their initial model construction, further calibrate the model with extant evidence, test the model with novel evidence, and evaluate the strengths and weaknesses of the model in explaining a phenomenon. Furthermore, their classroom-based research is consistent with others' linking modeling and argumentation (for an overview, see Jiménez-Aleixandre & Erduran, 2008). However, a more recent review of the linkage of modeling and argumentation found relatively few connections between the two strategies in the literature (Campbell, Oh, Maughn, Kiriazis, & Zuwallack, 2015), with classroom implementation also of likely low frequency. One reason for the lack of connection may be that these learning and teaching strategies are challenging to implement. Much like other strategies that require higher-order thinking skills, argumentation, modeling, and scientific inquiry may be quite difficult for students to learn and for teachers to teach (see, for example, Erduran & Dagher, 2014; Klopfer, 1969). Because of this difficulty, instructional scaffolds may be required to help students learn how to fully engage in science learning strategies. Such scaffolds include, but are not limited to, the use of computer-based tools to promote scientific thinking (Greene, Hutchison, Costa, & Crompton, 2012); employment of teacher moves to promote scientific discourse and argumentation (Duschl, 2008; Li et al., 2016); and regular assignment of science journals in which students can build an ongoing record of their investigations (Sandoval & Reiser, 2004).

AN EXAMPLE OF SCAFFOLDS TO FACILITATE SCIENCE LEARNING STRATEGIES

The following is a short discussion about instructional scaffolds that we have adapted and expanded in our projects, called the Model-Evidence Link (MEL) diagram. The original structure and mode of the MEL was developed by a team of educational psychologists, learning scientists, and science education researchers at Rutgers University (see Chinn & Buckland, 2012, for an overview). Lombardi and colleagues (Lombardi, Bailey, et al., 2018; Lombardi, Bickel, et al., 2018; Lombardi, Sinatra, & Nussbaum, 2013) discuss the adaptations and expansions that we made to the MEL in some detail, and we highlight some of the MEL features in the following discussion. However, prior to discussing the MEL, we enthusiastically acknowledge and support similar efforts of other researcher teams who are developing or have developed instructional scaffolds that facilitate argumentation and/or science as modeling strategies (e.g., *Quality Talk in Science*, Murphy et al., 2018; *Promoting Reasoning and Conceptual Change in Science*, Chinn, Duncan, & Rinehart, 2018).

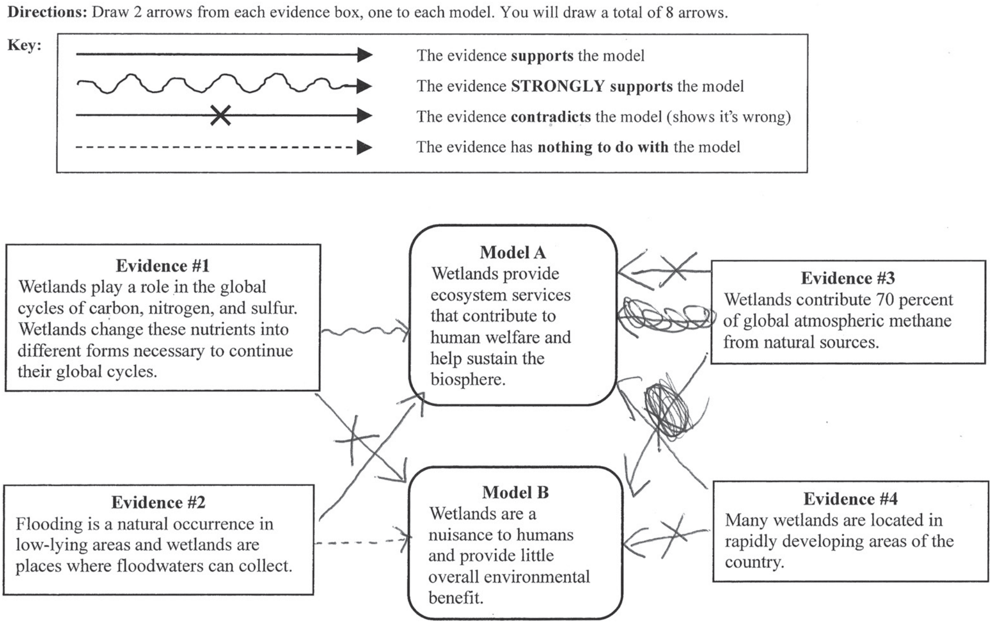


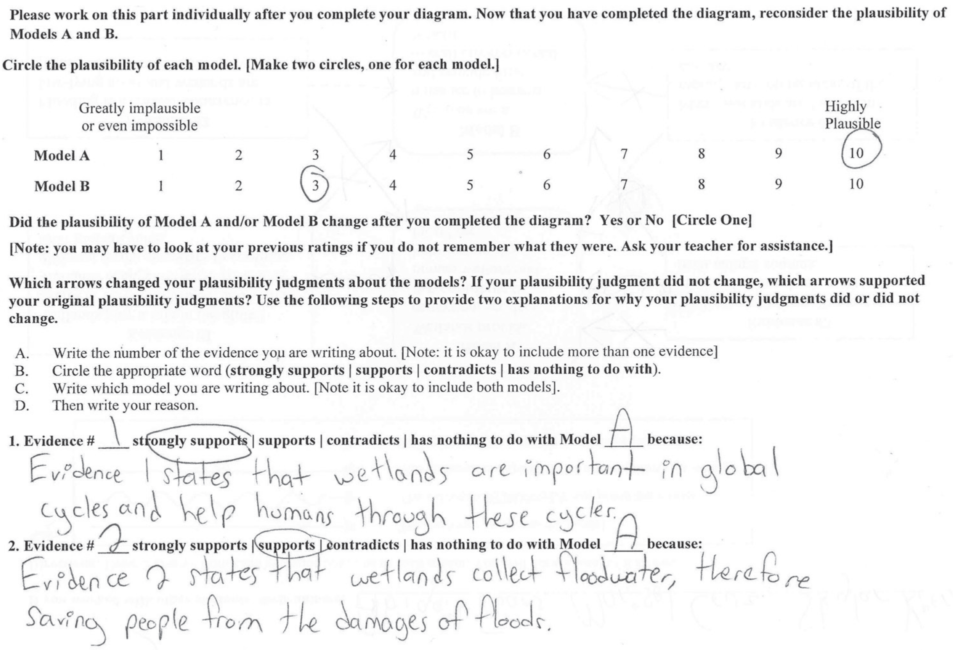
Figure 11.1 A student example of the Wetlands Model-Evidence Link (MEL) diagram

The MEL is an instructional scaffold that facilitates students' scientific evaluations about the connections between multiple lines of scientific evidence and alternative explanatory models about an observed phenomenon (Figure 11.1; Holzer, Lombardi, & Bailey, 2016; Lombardi, 2016). In the context of a particular topic (e.g., causes of current climate change, the link between fracking and earthquakes, the role of wetlands in ecosystem services, and formation of the Moon), the MEL diagram and associated support activities present students with two conceptual models, each providing an explanation for a phenomenon. For example, in the Wetlands MEL, two models provide competing explanations about how wetlands affect humans and the environment: Model A, where wetlands provide ecosystem services that contribute to human welfare and help sustain the biosphere; and Model B, where wetlands are a nuisance to humans and provide little overall environmental benefit. When using the MEL diagram as a scaffold, students draw arrows in one of four different shapes to indicate their evaluation about how well each line of evidence supports each model. Straight arrows indicate that evidence supports the model; squiggly arrows indicate that evidence strongly supports the model; straight arrows with an "X" through the middle indicate the evidence contradicts the model; and dashed arrows indicate the evidence has nothing to do with the model.

The MEL promotes students' cognitive and behavioral engagement in several science learning strategies, including science as inquiry, argumentation, and science as modeling. For example, the MEL diagram prompts students to evaluate the connections between line of evidence and two alternative explanatory models about a phenomenon. This allows students to critique explanatory models much like the scientific community does. Researchers and practitioners have given little attention to critiquing of alternatives in science learning; however, "as all ideas in science are evaluated against alternative explanations and compared with evidence, acceptance of an explanation is ultimately an assessment of what data are reliable and relevant and a decision about which explanation is the most satisfactory" (National Research Council, 2012, p. 44). In fact, our empirical studies show that the MEL results in deeper learning when students consider connections between lines of evidence and alternative explanations, over and above when they consider the same lines of evidence and only one alternative (i.e., the scientific explanation; Lombardi, Bailey, et al., 2018; Lombardi et al., 2013).

The inherent mode of critique initiated by the MEL is also related to students' argumentation and modeling as science strategy use. The NRC (2012) specifically states that "Engaging in argumentation from evidence about an explanation supports students' understanding of the reasons and empirical evidence for that explanation, demonstrating that science is a body of knowledge rooted in evidence" (p. 44). The MEL expands upon this central notion of argumentation involving claims, evidence, and reasoning in argumentation, by introducing claims, evidence, reasoning, *and* critique of alternatives. We have examined both students' depth of reasoning and critique in a task that students complete after drawing their MEL diagram. In this explanation task (Figure 11.2), we prompted students to describe evidence to model links they consider important or interesting. Using a sentence prompt for each explanation, participants indicated the model and evidence number that they chose to discuss, as well as the evidence-to-model connection strength they drew on the diagram (i.e., strongly supports, supports, contradicts, or has nothing to do with). This preface served as the beginning of participants' written explanations, next prompting evaluation with the word "because." For example, a full written explanation from one middle school student participant said, "Evidence #1 strongly supports Model A because atmospheric greenhouse gases have been rising for the past 50 years because of humans" (Lombardi, Bickel, Brandt, & Burg, 2017, p. 319). In our iterative and qualitative content analyses of these written explanations, we found four increasing levels of evaluation from erroneous to critical (Lombardi, Bailey, et al., 2018; Lombardi, Bickel, et al., 2018; Lombardi, Brandt, Bickel, & Burg, 2016), with interesting relations between evaluations and learning when students specifically wrote about lines of evidence that contradicted an explanatory model. These results suggest that contradictory evidence is important in changing students' epistemic judgments (e.g., a plausibility judgment about a particular explanatory model compared to another) to facilitate the process of scientific evaluation in argumentation and collaborative knowledge construction of models (Erduran & Dagher, 2014).

Although our research has shown that the MEL increases students' use of science learning strategies within the course of the activity, we have not yet been able to ascertain whether students transfer their strategy use outside of the classroom context. Our recent development and testing efforts are examining ways to internalize the MEL scaffold into students' mental representations, enabling them to transfer their use of scientific and critical evaluations beyond the specific activities. We are purposely incorporating the idea of conceptual agency (Pickering, 1995), where learners who exercise such agency are authors of their own contributions, accountable to the learning community, and have the authority to think about and solve problems



Please work on this part individually after you complete your diagram. Now that you have completed the diagram, reconsider the plausibility of Models A and B.

Circle the plausibility of each model. [Make two circles, one for each model.]

	Greatly implausible or even impossible									Highly Plausible
Model A	1	2	3	4	5	6	7	8	9	[✓ 10]
Model B	1	2	[✓ 3]	4	5	6	7	8	9	10

Did the plausibility of Model A and/or Model B change after you completed the diagram? Yes or No [Circle One]

[Note: you may have to look at your previous ratings if you do not remember what they were. Ask your teacher for assistance.]

Which arrows changed your plausibility judgments about the models? If your plausibility judgment did not change, which arrows supported your original plausibility judgments? Use the following steps to provide two explanations for why your plausibility judgments did or did not change.

A. Write the number of the evidence you are writing about. [Note: it is okay to include more than one evidence]
B. Circle the appropriate word (**strongly supports | supports | contradicts | has nothing to do with**).
C. Write which model you are writing about. [Note it is okay to include both models].
D. Then write your reason.

1. Evidence # 1 **[✓ strongly supports] | supports | contradicts | has nothing to do with Model** A **because:**

Evidence 1 states that wetlands are important in global cycles and help humans through these cycles.

2. Evidence # 2 **strongly supports | [✓ supports] | contradicts | has nothing to do with Model** A **because:**

Evidence 2 states that wetlands collect floodwater, therefore saving people from the damages of floods.

Figure 11.2 A student example of the Wetlands MEL Explanation Task

(Nussbaum & Asterhan, 2016). In this newer version of the scaffold, students build their own MEL diagram from a set of lines of evidence and explanatory models. Our hope is that through building and using their own MEL, students will become agents of model evaluation, which is a key component of both the argumentation and science as modeling strategies.

ISSUES AND FUTURE RESEARCH DIRECTIONS

As previous researchers have noted, the implementation of scientific argumentation and science as modeling strategies can be challenging for teachers (e.g., Erduran & Dagher, 2014; Fischer et al., 2014; McNeill & Krajcik, 2008). Teachers may not have the pedagogical knowledge to engage students in argumentation, despite a stated belief that it is an important aspect of student learning in science. In interviews with 30 high school teachers, Sampson and Blanchard (2012) identified a number of perceived barriers to implementing argumentation, such as the achievement level of their students, students' lack of prior experience with argumentation, time and curricular limitations, or teachers' own inexperience with the strategy.

The existence of scaffolds and curricula designed to facilitate either argumentation or science as modeling should support teachers in moving toward using these strategies more often, but there may be additional challenges beyond simply getting such supports into teachers' hands. Once there, what teachers enact in the classroom may not align with what was intended by curriculum developers or researchers (Remillard, 2005). However, Osborne, Erduran, and Simon (2004) demonstrated that directed scaffolds to support argumentation help not only the students improve in their argumentation skills but also the teachers in facilitating argumentation. Lortie (1975) described an "apprenticeship of observation" for teacher education, in that teachers have had 16+ years in the role of students, during which time they have developed ideas and beliefs about what teaching is and what teachers do (Ball, 1988). These ideas may or may not be aligned with the theoretical underpinnings or best practices espoused by either teacher education generally or science education more specifically, and if not, the formal teacher education program may be insufficient for overcoming conflicting beliefs that have developed over this observational period. Explicit and routine inclusion of both science strategies, such as argumentation and science as modeling, and more domain-general strategies and strategic processes in preservice teacher education and inservice professional development programs may be needed to provide teachers with experiences that allow them to carry the strategies forward into their own teaching.

CONCLUDING THOUGHTS

Facilitating widespread use of contemporary science intervention strategies is challenging for many educational researchers and leaders. For deeper cognitive and metacognitive engagement, learners should experience socio-scientific issues (e.g., connections between increased occurrence of extreme weather events and human-induced climate change), which include fundamental science concepts, through argumentation and modeling strategies. Engagement in these deeper science learning strategies is complex, but scaffolding argumentation and modeling instruction may facilitate learners' deep understanding of science. For example, the NRC (2012) suggests that young learners can begin constructing arguments by interpreting observations and collected data. As learners reach adolescence, they can begin to evaluate alternative explanations through gauging how well each is supported by various lines of evidence. Finally, learners should be able to identify flaws in their own arguments, as well as in other arguments, by using scientific norms of logic, analysis, and evaluation. Similarly and relatedly, the NRC (2012) said that:

> [e]ngagement in modeling and evidence-based argumentation invites and encourages students to reflect on the status of their own knowledge and their understanding of how science works …[and] as they involve themselves in the practices of science …[e.g., through scientific inquiry], their level of sophistication in understanding how any given practice contributes to the scientific enterprise can continue to develop across all grade levels.
>
> (p. 79)

Therefore, researchers and designers need to create instructional scaffolding that supports effective employment of science learning strategies, as well as teacher education and professional learning opportunities for educators to become well-versed in these strategies. This will enable teachers and learners to develop robust scientific literacy, with deep understanding about what scientists know and how scientists know what they know.

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