



**Research Report**  
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**A *CBAL*™ Science Model of Cognition:  
Developing a Competency Model and  
Learning Progressions to Support  
Assessment Development**

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**Lei Liu**

**Aaron Rogat**

**Maria Bertling**

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Lei Liu, Aaron Rogat, and Maria Bertling  
Educational Testing Service, Princeton, New Jersey

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## **Abstract**

The purpose of this report is to describe a science competency model and 3 related learning progressions, which were developed by applying the *CBAL*<sup>TM</sup> approach (Bennett & Gitomer, 2009) to the domain of middle school science. The Cognitively Based Assessment *of, for, and as* Learning (CBAL) science competency model and its related learning progressions were developed by reviewing existing literature on learning sciences and science education, which have placed increasing emphasis on learners' knowledge and ability to apply scientific knowledge to conduct evidence-based reasoning. In this report, we present the 5 competencies in our science competency model that reflect current efforts in the Next Generation Science Standards and the recent reform-based curriculum to promote integrated and generative understanding. In addition, we report 3 hypothesized learning progressions related to our competency model to define the increasing sophistication of both content understanding and the capacity to carry out scientific inquiry. Then we discuss features of assessment prototypes developed under the guidance of the competency model and the learning progressions, by illustrating parts of 1 sample formative assessment task prototype.

Key words: science competency, competency model, learning progressions, cognitively based assessment, formative assessment, summative assessment

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The use of assessments is critical to educators to both inform and guide instruction. The use of a wide variety of assessment tools can enable teachers to determine where students are in their conceptual development and where they might need additional support or whether the instructional strategies in use need modification. In this way, assessments can be used to improve classroom practice, plan the curriculum, and reflect on one's own teaching practice. This reported project is part of the effort of the *CBAL*<sup>TM</sup> (Cognitively Based Assessment *of, for, and as* Learning) initiative, a model for an innovative K–12 assessment system that integrates learning-sciences theories with content standards. The model measures achievement through periodic summative assessments that incorporate computer-delivered, scenario-based tasks. Change in students' thinking and abilities, as well as teachers' practices, are postulated to occur through the use of CBAL competency models, summative assessment, classroom formative assessment, and professional support. The assessment system is intended not only to measure student achievement but also to facilitate it (Bennett, 2010; Bennett & Gitomer, 2009).

Our competency model of science reflects current insight from the cognitive and learning sciences research. We believe any science assessment that focuses predominantly on the *facts* of science fails to provide a rich picture of what proficiency in science looks like. Reformers in science education have advocated that students proficient in science should be able to inquire, to reason scientifically, to apply science concepts to real-world situations, and to communicate effectively what students know about science (Pellegrino, Chudowsky, & Glaser, 2001). Therefore, assessment of scientific concepts and theories must be focused not only on measuring knowledge of subject matter, but on how relevant that knowledge is in building the capacity to apply scientific principles on a daily basis.

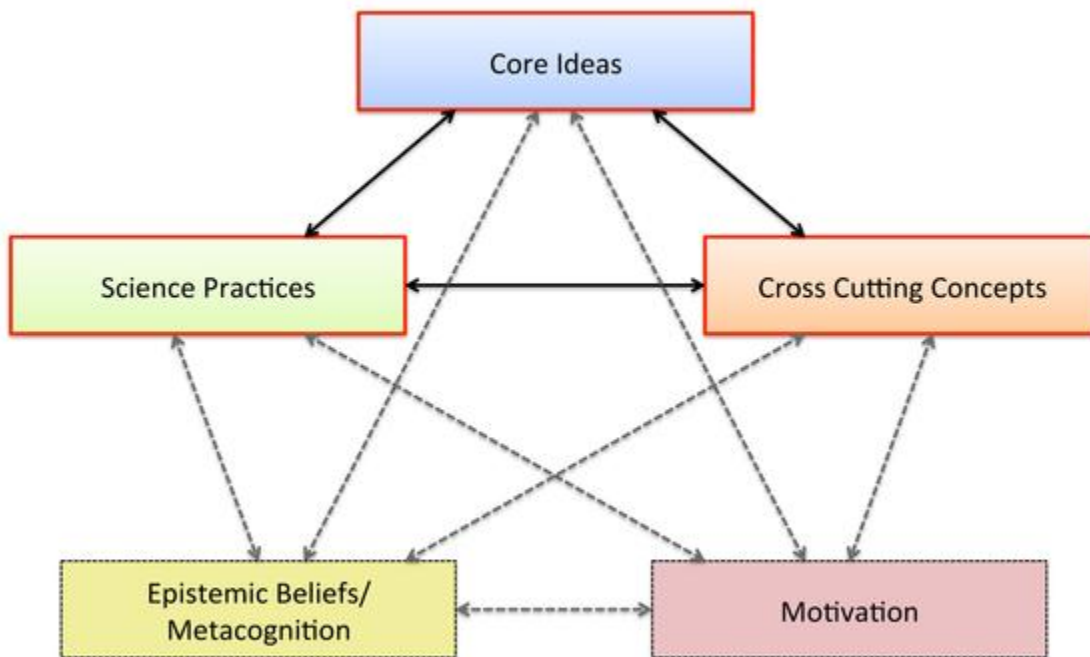
The purpose of this report is to describe a science competency model and its related learning progressions, which were developed by applying the CBAL approach (Bennett & Gitomer, 2009) to the domain of middle school science. The development is consistent with the construct modeling approach (Brown & Wilson, 2011; Shin, Stevens, & Krajcik, 2010), which stresses developing assessments and instruments that are deeply rooted in a specific model of cognition, one in which “the model of cognition is defined by one or more proficiencies represented by unbound continuous latent variables” (Brown & Wilson, 2011, p. 225). Our competency model documents the continuous latent variables in the domain of middle school science. In addition, in a construct modeling approach, learning is conceptualized as improved

competence towards increasingly higher levels of complexity and sophistication, rather than the greater accumulation of information and skills. Therefore, we are also developing hypothesized learning progressions related to our competency model to define the increasing sophistication of both content understanding and the capacity to carry out scientific inquiry. These hypothesized learning progressions describe the nature of student thinking by including nonnormative ideas or misconceptions that students may have. The goal of using learning progressions in assessment is to characterize student thinking in ways that can be used for instructional decision making, rather than just indicating whether students appear to know or not know a given science concept. Therefore, in our project, the purpose of developing hypothesized learning progressions is to design assessment opportunities to gather evidence of where students fall on the learning progressions and use such evidence to inform future instruction. In the following sections, we describe in detail our competency model and its related hypothesized learning progressions. Then we present a formative assessment prototype developed under the guidance of the competency model and the learning progressions.

### **The Competency Model of Middle School Science: Defining and Developing the Constructs**

The CBAL science competency model (Figure 1) and its related learning progressions were developed by reviewing existing literature on learning sciences and science education, which have placed increasing emphasis on learners' developing conceptual knowledge and their ability to apply their scientific knowledge in order to reason with evidence. Our competency model for science includes five general dimensions: core ideas (i.e., disciplinary conceptual knowledge), science practices (i.e., knowledge of how to produce knowledge), crosscutting concepts (i.e., concepts that bridge disciplinary boundaries and provide organizational frameworks for connecting ideas), epistemic beliefs and metacognition (i.e., beliefs regarding knowledge and knowing, and strategies of knowing about knowing), and motivation (i.e., values, interest, and engagement). Our competency model is informed by and is consistent with research on teaching and learning (Duschl, Schweingruber, & Shouse, 2007), as well as current frameworks informing standards for science education in the United States, such as the National Research Council (NRC) Framework for K–12 Science Education (NRC, 2012) and the Next Generation Science Standards (NGSS, 2013). Note that, with our current prototype tasks, we intend to measure only three of these five dimensions: core ideas, science practices, and crosscutting concepts. To be proficient in science, students need to demonstrate their ability to

simultaneously apply the three interconnected competencies (represented as solid lines in Figure 1) to address scientific questions or problems. However, the other two dimensions, epistemic beliefs/metacognition and motivation, will be an important part of the design of the task. Later we may choose to measure these relevant, but hard-to-measure general competencies. Epistemic and emotional aspects are important in science learning because they have mediating effects on such internal psychological processes as acquisition of knowledge and skills (represented as dotted lines in Figure 1), and, thus, will have direct and indirect impact on the validity of assessments.



**Figure 1. CBAL science competency model.**

Our view of developing proficiency in science builds on the four elements of learning in science as described in the NRC framework (NRC, 2012): *conceptual development*, which involves building connections between different ideas or reconceptualizing ideas in science (e.g., all matter, no matter how small or in what state, has mass and volume); *cognitive development*, which involves developing the ability to reason critically in a scientific manner

(e.g., understanding the relationship between cause and effect or supporting claims with scientific evidence); *epistemic development*, which involves developing ideas about science (e.g., understanding how we know what we know) and the processes, values, and implications of scientific knowledge; and *social and affective development*, which involves developing the ability to work collaboratively and to offer an engaging and stimulating experience (Osborne, 2007). These four elements of learning in science map onto the four strands of science proficiency defined by the comprehensive report on K–8 learning and teaching, *Taking Science to School*: (a) know and interpret scientific explanations of the natural world, (b) generate and evaluate scientific evidence and explanations, (c) understand the nature and development of scientific knowledge, and (d) participate productively in scientific practices and discourse (Duschl et al., 2007; Osborne, 2007). These strands reflect the proficiencies of applying conceptual knowledge structures and using those structures to predict, explain, or model phenomena (the conceptual); constructing knowledge by generating evidence through the process of scientific inquiry—which ultimately leads to the generation and evaluation of evidence to revise and refine explanations or models (the cognitive); reflecting on the nature of science and the status of one’s own knowledge (the epistemic and metacognitive); and collaborating and participating in the discourse and norms of science with the motivation to sustain deep learning (the social and affective).

In summary, the five dimensions in our science competency model reflect current efforts in the NGSS and recent reform-based curriculum (Krajcik & Reiser, 2004) to promote integrated and generative understanding. First, when learning about the core ideas in science, students need to develop connections between explanatory models of scientific phenomena in their daily life and the conceptual understanding of scientific knowledge. Second, through the essential science practices such as making observations, developing hypotheses, designing and conducting investigations, and developing evidence-based explanatory models, students can develop the conceptual, cognitive, metacognitive, and epistemic knowledge, skills, and abilities to understand the natural world (Bransford, Brown, & Cocking, 2000; Duschl et al., 2007). These practices often take place in collaborative learning environments that foster social and affective development (Jones & Issroff, 2004). Third, understanding the crosscutting concepts in science provides students with an organizational framework to connect various disciplinary ideas and consequently build a coherent view of the world. These are the three competencies (core ideas,

science practices, and crosscutting concepts) that we intend to measure in our CBAL assessments. In addition, the other two competencies in our model (epistemic beliefs/metacognition and motivation) are important facets that also influence learning. They both are connected closely with other competencies in our model. If science assessments do not incorporate a constructivist epistemic perspective, they are likely to measure only fixed factual knowledge, which does not provide an adequate picture of what and how students learn. In addition, if science assessments do not consider students' alternative concepts and how they learned scientific knowledge, the science assessments will not provide opportunities for students to build on their prior knowledge to develop new knowledge. Finally, the students' motivation has a direct impact on their achievement (Organisation for Economic Co-operation and Development [OECD], 2004; T. Stevens, Olivárez, & Hamman, 2006; Stipek et al., 1998; Zhu & Leung, 2011). Therefore, it is critical to consider these five dimensions in the design of assessments.

In our competency model, we identify the candidate core ideas, which are categorized into three broad domains of physical science, life science, and earth and space science. The science practices include five central practices: constructing explanations, constructing arguments, developing and using models, engaging in empirical investigations, and collaborating and communicating. The crosscutting concepts that we focus on include systems thinking, cause and effect, and conservation of matter and energy. In the following sections, we describe specific definitions of each competency in the model and their importance to becoming proficient in science.

### **Dimension 1: The Core Ideas**

To avoid targeting conceptual knowledge that is too superficial and reveals little about student learning in our assessments, we have selected a set of foundational core ideas that allow us to explore the sophistication of students' conceptual knowledge and scientific reasoning. One rationale for organizing content around core ideas comes from research that compares the knowledge and problem-solving abilities of experts and novices in certain fields. This research shows that experts tend to use core principles from their discipline to make sense of new information or tackle novel problems, while novices tend to hold isolated and even contradictory pieces of knowledge that are not organized around core principles of the discipline (Bransford et al., 2000). Therefore, to help students shift from novice to expert status, it is essential to help

students learn these core ideas by engaging them in the practices of science. The importance of focusing on core ideas has not been lost on those involved in current reform efforts in science education and, consequently, new frameworks for standards that have been developed—such as *A Framework for K–12 Science Education* (NRC, 2012) and the NGSS (2013).

Here, we identify the candidate core ideas that we will target in CBAL science over the next few years, which are categorized into three broad domains covered in the K–12 standards as described in current reform documents (e.g., National Assessment Governing Board [NAGB], 2009; NRC, 2012): physical science, life science, and earth and space science. In physical science, we plan to target three foundational core ideas: matter, energy, and forces. In life science, we plan to target two foundational core ideas: ecosystems and structures and processes. In earth and space science, we plan to target one foundational core idea: earth systems. Note that each of these core ideas includes subcomponent big ideas (e.g., for matter, there are two big ideas: properties and structure of matter and changes in matter). The reasons for selecting this limited set of core ideas to target in CBAL over the near term are that there are clear and visible connections among these different core ideas that students should be developing and that should be apparent to teachers.

In terms of the assessment prototype development, we are starting with one core idea in physical science: matter. It is particularly important to start with the core idea of matter because it is one of the most foundational and generative ideas in all of science, in particular the atomic-molecular theory of matter. In support of this point, according to Nobel laureate physicist Richard Feynman, if all the world’s scientific knowledge were destroyed and he could only salvage one idea to pass on to future generations, he would keep the atomic-molecular theory (Smith, Wiser, Anderson, & Krajcik, 2006).

## **Dimension 2: The Practices of Science**

Our CBAL science competency model includes five central practices that are aligned with the NRC framework for K–12 science education (NRC, 2012). These practices are constructing explanations, constructing arguments, developing and using models, engaging in empirical investigations, and collaborating and communicating. In this section, we describe each of these five central practices by defining the construct and elaborating its importance in learning about science.

**Science Practice 1: Constructing scientific explanations.** Scientific explanations attempt to answer three questions: what we know (the ontological question), why it happens (the causal question), and how we know (the epistemic question, Osborne & Patterson, 2011). A scientific explanation includes three components: (a) a claim, (b) evidence, and (c) reasoning (McNeill, Lizotte, Krajcik, & Marx, 2006). Therefore, a claim itself is not a complete explanation because it lacks evidence and reasoning. These three components are further elaborated below:

- *Claim:* The claim makes an assertion or conclusion that addresses the original question or problem about a phenomenon.
- *Evidence:* The data from an investigation supports the student's claim. This data can come from an investigation that students complete or from another source, such as observations, reading materials, archived data, or from theoretical sources such as computer simulations. Data need to be *appropriate, sufficient, accurate, and precise* to support the claim. By appropriate, we mean data that are relevant to the problem and help determine and support the claim. Sufficient refers to providing enough data or other kinds of evidence to convince another individual of the claim. Often providing sufficient evidence requires using multiple pieces of data. By accuracy, we mean the degree of closeness of measurements of a quantity to that quantity's true value. By precision, we mean the degree to which repeated measurements under unchanged conditions show the same results.

Different models of scientific explanations may include different kinds of evidence. Braaten and Windschitl (2011) summarized five major models of scientific explanations from the philosophy of science literature that are commonly used in science education. *Three types of evidence* derive from these explanation models. *The first type of evidence is a natural law-like statement* that fosters logical reasoning. Students' first attempts at explanations often follow this form. When students use this type of evidence, it is possible that the reasoning is logical but the evidence is irrelevant or based on students' naïve or unstable knowledge. Due to the unstable nature of the reasoning criteria that students apply, the explanation produced is not robust. *The second type of evidence is a trend or pattern in data from observations or empirical investigations* that can be used to make statistical inferences. *The third type*



*of evidence is that of a major scientific theory* that can be applied to make sense of observed phenomena.

- *Reasoning*: The reasoning links the claim and evidence and shows why the data count as evidence to support the claim. Often, in order to make this link, students must apply appropriate scientific principles or theories.

The process of constructing effective scientific explanations is considered an effective approach to constructing knowledge as it moves beyond descriptions of observable natural phenomena into theoretical accounts of how phenomena unfold the way they do (Braaten & Windschitl, 2011; Chi, 2000; Chi & Bassok, 1989). The researchers observed that undergraduates who demonstrate proficiency in problem solving often tend to produce more self-explanations, which are defined as “content-relevant articulation uttered by the student after reading a line of text” (Chi, 2000, p. 165). In addition, a number of researchers developing curriculum materials at the middle school level have found engaging students in developing written explanations is a useful and valid assessment strategy to probe student thinking, as well as an effective strategy to support learning by encouraging students to make connections between evidence and theory—and, therefore, generate cognitive connections (Lombrozo, 2006; McNeill et al., 2006; Strevens, 2006; Trout, 2007). Finally scientific explanations often require students to apply deep principles or scientific theories to account for natural phenomena.

Unfortunately, students have little experience constructing explanations, nor have they been exposed to the explanation framework above—even fewer have been asked to reflect on the nature of explanation in science—therefore, to assess explanations and students’ ability to construct explanations, it might be necessary to provide scaffolds for students during formative assessment and later assess students without the scaffolds. One such scaffold is to make the explanation framework explicit to students. In addition, researchers have shown that the process of evidence evaluation is very messy and requires an understanding of error and variation. In particular, Kuhn and her colleagues (Kuhn et al., 1988) found that students have a variety of strategies for keeping theory and evidence in alignment with one another when they were, in fact, discrepant. One tendency is to ignore, distort, or selectively attend to evidence that is inconsistent with a favored theory. Therefore, it is important to help students understand what is counted as appropriate, sufficient, accurate, and precise evidence that can support or reject a claim. One possible strategy is to give examples of how to answer the explanatory questions using prompts

such as “My evidence is consistent with ... and thus supports my claim because ...” or “I believe my evidence is valid and reliable because ...”

**Science Practice 2: Constructing scientific argumentation.** Scientific argumentation is a social and collaborative process that is at the heart of scientific inquiry (Duschl & Osborne, 2002). It examines the question of whether the explanation is valid—that is, whether it succeeds in generating understanding and whether it is better than competing accounts (Osborne & Patterson, 2011). Argumentation includes any dialog that addresses “the coordination of evidence and theory to support or refute an explanatory conclusion, model, or prediction” (Osborne, Erduran, & Simon, 2004, p. 995). According to Walton (1989), there are two goals of argumentation: The first is to secure commitments from the opponent that can be used to support one’s own argument; the second is to counter an opponent’s position by identifying and challenging weakness in the opponent’s argument. Argumentation often consists of three major components: (a) claims, (b) grounds, and (c) rebuttal (Osborne et al., 2004; Toulmin, 1958).

- *Claims:* Claims are statements in the form of declarative sentences that answer the controversial questions.
- *Grounds:* Grounds include data, warrants, and backings.
- *Rebuttal:* Rebuttals include attacks on the grounds of a claim or attacks directly on a claim.

We intentionally treat argumentation and explanation as distinct practices. Consistent with Berland and Reiser (2008), we believe the practices of explanation and argumentation are complementary. Explanation provides a product around which the argumentation can occur. However, argumentation creates a context in which robust explanations are valued. Osborne and Patterson (2011) also attempted to make a rigorous distinction between these two practices. They pointed out that a “defining feature of an explanation is that the phenomenon to be explained is not in doubt” (p. 629), while “there is always a substantial degree of tentativeness associated with any argument” (p. 629). Although, in our competency model, we are not making this rigorous distinction between explanation and argumentation, we agree that argumentation focuses more on the tentative nature of science and explanation focuses more on the power of using evidence to interpret a scientific phenomenon. Therefore, explanation and argumentation are two closely related, but distinct, practices. We agree with Osborne and Patterson that one major purpose of argumentation is to judge the coherence, plausibility, and comprehensiveness

of alternative explanations. However, we disagree that a statement about scientific phenomenon cannot serve as a claim in the process of constructing an explanation. In our view, a claim can be a statement that describes a scientific phenomenon, a statement that accounts for a tentative scientific theory, or a prediction that needs to be confirmed. For example, students can argue about the following claim: sugar does not cease to exist when it gets dissolved in the water. In this example, the claim is a true statement that is not tentative. However, it is still debatable for students because of the misconceptions or nonnormative ideas that they may hold. Based on these assumptions, we apply the claim, evidence, and reasoning framework to practices of constructing explanations and practices of constructing arguments. Nevertheless, there are several significant distinctions between explanation and argumentation. In argumentation, it is important to include rebuttals. However, the context of an argument task is open-ended and does not suggest an absolute correct or incorrect answer. Another key difference is that argumentation moves to interchanges in a social context; therefore, when students engage in argumentation activities, they may find themselves defending, debating, or critiquing products or ideas of their peers.

Argumentation is not only a critical part of science, it also supports science learning and, therefore, we must assess students' ability to engage in argumentation. Learning is viewed by many as having a social dimension; studies have shown that students often construct meaning through interaction with their peers or other community members (Jones & Issroff, 2004). Studies have shown that students not only have to learn to develop valid arguments, but they will also learn science while arguing (e.g., Erduran, Simon, & Osborne, 2004; Jiménez-Aleixandre & Pereiro-Munhoz, 2002; Osborne, Erduran, Simon, & Monk, 2001). Other studies have shown that when students debate other students' ideas publicly, requiring them to verbalize and defend their own ideas, or to identify flaws in others' ideas, this interchange can promote sense-making (Bransford et al., 2000; Duschl et al., 2007; Michaels, Shouse, & Schweingruber, 2008).

Unfortunately, students in most classrooms have little experience engaging in argumentation. Thus, assessments that attempt to probe students' ability in this area are likely to require multiple opportunities for students to encounter alternative ideas and a social context to communicate ideas. In assessment settings, particularly assessments taken by individual students, one possible approach to assess students' argumentation ability is to present a student with multiple alternative opinions from virtual students and ask the student to critique them. Another

more authentic approach is to log the dialogue or interactions between students when they engage in critiquing or defending each other's ideas and then score those conversations or interactions.

**Science Practice 3: Developing and using models.** The value of scientific models and modeling has been increasingly recognized among the science education reform movements (American Association for the Advancement of Science, 1993; Duschl et al., 2007; NRC, 1996; National Science Board Commission on Precollege Education in Mathematics Science and Technology, 1983) because scientific models are useful tools for formulating hypotheses to be tested and for describing scientific phenomena (Gilbert, 1995). Scientists use models to represent their understanding of a phenomenon, including facilitating the development of research questions, explanations, predictions, and communications with others. A scientific model is an abstraction or a simplification of a system that makes its central features explicit and visible (Harrison & Treagust, 2000).

In science education, the term *model* is typically used in two related ways (Gobert & Buckley, 2000). First, a mental model refers to an individual's internal representation, or that individual's understanding of a phenomenon, which is often implicit to people. Second, a conceptual model is an explicit external representation (such as a diagram or computer simulation) of the mental model, which is often analogous to the phenomena of interest. Such mental models and conceptual models are the product of scientific modeling. Therefore, we define scientific modeling as the construction of mental models of phenomena through the use of conceptual models. Constructing a model—by identifying the salient features of the system or phenomenon under consideration and determining how those features, and the relationships among them, can be depicted or represented—is accompanied by using the model to illustrate a system, explain a system or phenomenon, or to make predictions about a phenomenon. This model construction leads to evaluating and revising models in light of findings so they will better achieve their intended purposes.

With the development of technology, modeling often takes place in virtual worlds using computer simulations. Computer simulations are programs that contain a model of a system (natural or artificial, e.g., equipment) or a process. In simulation-based learning environments, the main task of the learner is to infer the characteristics of the model underlying the simulation. The learners' basic actions are changing values of input variables and observing the resulting

changes in values of output variables. De Jong and van Joolingen (1998) found that computer simulations provide support in the following areas of learning: generating hypotheses, designing experiments, making predictions, and regulating learning processes. Computational thinking has been increasingly stressed in learning sciences literature. Papert (1980) argued that simulation-supported environments bring in such *mindstorms* in which students can formulate and test alternative hypotheses and reconcile the discrepancy between their ideas and the observations in a microworld. That is, the computers help students to discover the discrepancy by providing contexts for students to test out their original hypotheses and showing the consequences of actions based on their hypotheses.

Scientific modeling, therefore, can be decomposed into several components: constructing, using, evaluating, and revising models (Schwarz et al., 2009). These components are further elaborated below:

- *Constructing models*: One can use a hypothesis informed by principles or theories to construct models and apply appropriate principles, theories, or evidence.
- *Using models*: One can use multiple models to explain and predict aspects of a group of related phenomena.
- *Evaluating models*: One should consider the predictive or explanatory power of a model and determine whether a model makes accurate and reliable predictions, whether it accounts for all available evidence, and/or whether there is consistency with all available evidence.
- *Revising models*: One should revise a model when predictive power or explanatory power is called into question or when new evidence is available that challenges predictive or explanatory power.

Some researchers have collected evidence that modeling does support students' ability to learn concepts (Penner, Giles, Lehrer, & Schauble, 1997; White, 1993) because modeling requires students to express and test ideas by collecting and evaluating evidence. This process of model testing and revising is believed to facilitate conceptual development.

We expect that students may have some experience constructing models (particularly physical models) in classrooms; however, few students may have experience using, testing, or revising models. Therefore, when assessing students' modeling skill, it is necessary to provide some examples of how scientists use, test, and revise their models. In addition, being proficient

in modeling includes self-conscious separation of a model and its referent, as well as the explicit consideration of measurement error, and consideration of alternative models (Lehrer & Schauble, 2000). Therefore, when assessing students' modeling skills, it is also important to prompt students to consider alternative models and limitation of models.

**Science Practice 4: Engaging in empirical investigations.** Scientists often design and conduct investigations to develop and test theories that answer questions about how the world works. Students need opportunities to engage in empirical investigations to test explanatory theories of the world and gather data to support or refute their predictions. Engaging in empirical investigations is a multifaceted activity that includes a set of procedural and conceptual activities, such as asking questions; generating hypotheses; designing experiments; collecting and recording data; analyzing, representing, and interpreting results; coordinating theory and evidence; and formulating and revising theories or models (Duschl et al., 2007). Below, we elaborate on a few of these subcomponents included in the practice of engaging in empirical investigations:

- *Asking questions* is an important component of science literacy because an essential aspect of science is to develop explanations or models that address questions about phenomena in the natural world. We emphasize that the questions scientists attempt to account for occur in the natural world, not the human-made world (the latter is the domain of engineering or a technological field such as computer science). The type of question that a student can ask can indicate the level of sophistication in that student's thinking (Yarden, Brill, & Falk, 2001). In classrooms, questions usually are initiated by teachers and rarely by the students. Therefore, students are not likely to ask questions. Even if they do ask questions, the nature of questions that most students ask reflect a desire to seek clarification or declarative knowledge (e.g., what are bacteria?), rather than a desire to understand underlying scientific mechanisms or procedural knowledge (e.g., how do seasons form?). Cuccio-Schirripa and Steiner (2000) suggested that "Questioning is one of the ... processing skills which is structurally embedded in ... critical thinking, creative thinking, and problem solving" (p. 210). Thus, questioning may contribute in important ways to the development of a scientific theory because it is one potential bridge between theoretical ideas and the empirical investigation that includes data collection, interpretation, and evaluation of

- evidence needed to test or revise ideas (a key feature of critical thinking and problem solving). Accordingly, it is important to help students ask well-formulated questions that can be answered through empirical investigation.
- *Generating a hypothesis* involves proposing a rational and tentative explanation of an observed phenomenon that has not been proved. A hypothesis is often produced to identify the relationship between a dependent variable and the independent variable. Many hypotheses are stated in the form of “if a particular independent variable is changed, there is also a change in a certain dependent variable.” The hypothesis developed is the goal of the designed experiment. Such practice helps students plan their data collection by considering variables and expected observation involved in their inquiry.
  - *Designing experiments* involves identifying causal variables and generating interpretable observations that will serve as evidence—evidence that can be related to a hypothesis about the proposed questions. One important aspect of design is to isolate variables so as to rule out competing hypotheses. A well-designed investigation often includes controlled variables that allow valid inferences and narrows the number of possible experiments to consider (Klahr, 2000). Another important aspect of designing investigations is selecting appropriate measures or tools to examine the phenomena of interest (e.g., determining if the total mass or the density of a material might be a better measure of a property to identify a material’s identity, or determining if height or mass is a better measure of growth). Students may also need to understand certain aspects of measurement error and the need for accurate and precise measurements that might require appropriate or specific tools (e.g., a balance is a more accurate measure of the comparative masses of two different objects than relative heft in a person’s hand). There might also be a need to appreciate sample size (i.e., are there enough observations to make a generalizable inference) and the role of randomness in selecting a sample (i.e., the potential for bias because the sample is unlikely to be a true representation of the population).
  - *Collecting and recording data* is also an important component of engaging in empirical investigation because access to interpretable, useful, valid, and reliable data is essential to making effective evidence-based explanations or arguments. A datum is

an observation or measurement of a natural system or of a designed and constructed experimental situation recorded for subsequent analysis. Research has shown that students were unlikely to check if a current hypothesis is not consistent with experimental results (Dunbar & Klahr, 1988). The access to collected data may help students realize such gaps. Students must identify the best ways to record data accurately and reliably.

- *Analyzing and interpreting data* often follows after data collection. This is when students make sense of data and connect the data as evidence to support their hypothesis. This process is often related to students' skills of using mathematical and computational tools. The NRC framework states that *mathematical tools* (e.g., formulas, mathematical rules behind the simulational programming) enable students to express ideas in a precise form, and *computational tools* (e.g., simulations, animations) enable students to represent data and scientific phenomena visually. Both types of tools allow students to explore and identify patterns in data and their observations. It is also recognized that students' ability to engage in mathematical thinking is related to their ability to identify patterns in data and represent data in appropriate ways. In the domain of science, mathematical thinking skill is also related to the ability to effectively design or select a measure for a given variable, particularly in simulations. For example, students need to apply their mathematical thinking skills to consider what value should be set for the variable of the amount of water and salt in a simulation that helps to understand the concept of density.

Computational tools, such as computer simulations, provide cost-effective ways of doing experiments. Students can use simulations to observe scientific phenomena that cannot be observed easily in real time (e.g., volcano eruption, protein synthesis, and spread of disease). The enabled visualization of scientific phenomena and interactive opportunities provided by computer simulation has been associated with gains in conceptual understanding and enhances epistemological understanding about the nature of science as exploring and discovering knowledge through multiple trials of experimentation and evidence-based reasoning (Wilensky & Reisman, 2006; Zacharia, 2007). From the aspect of assessment, computer simulations also allow testing of both conceptual understanding and the ability to engage in the central



practices of science that are not well tested in traditional assessments (Quellmalz & Pellegrino, 2009).

One major challenge with the practice of engaging in empirical investigation is that often there is little classroom instruction focused on designing and carrying out a high-quality investigation and analyzing and interpreting data collected from the investigation. Therefore, it is necessary to scaffold students as they attempt to complete assessment tasks that target students' ability to engage in empirical investigations. Another challenge is that it takes time to engage students in a full cycle of empirical investigation, a particular problem for short assessments. One possible approach is to target pieces of the practice of engaging in empirical investigation, such as asking questions, designing an investigation, or analyzing data in one task. Alternatively, we may also use surrogate methods to measure individual practices (e.g., using multiple-choice items asking students to choose from a list of potential procedures). In addition, we might design extended tasks that will be completed across multiple class periods so that students have time to engage in the various aspects of empirical investigation. Furthermore, we may ask students to conduct an experiment in a simulation-based setting in which they can take less time than in a traditional real-time lab.

**Science Practice 5: Communicating and collaborating.** Communicating and collaborating is an essential competency to achieve. Knowledge-building theorists have emphasized the social aspect of learning. Scardamalia and Bereiter (2006) summarized six themes that underlie a shift from treating students as individual learners to regarding them as members of a knowledge-building community: (a) knowledge advancement as a community rather than individual achievement; (b) knowledge advancement as idea improvement rather than as progress toward true or warranted belief; (c) *knowledge of science (the ability to do science, e.g., knowing how to construct, evaluate, and revise a model of matter)* in contrast to *knowledge about science (declarative knowledge, e.g., knowing that atoms are subcomponents of molecules)*; (d) discourse as collaborative problem solving rather than argumentation; (e) constructive use of authoritative information; and (f) understanding as an emergent process. All these themes recognize the fundamental role of communication and collaboration in creating a knowledge-constructing culture. Roschelle (1992) defined collaboration as a practice conducted by two or more people whose goal is to reach convergent understanding or to construct shared meanings through communication. We take the broader definition of collaborative learning as “a situation in which

two or more people learn or attempt to learn something together” (Dillenbourg, 1999, p. 1). In this definition, there are two important aspects of collaborative learning. First, it is about interactions between two or more people. As Dillenbourg (1999) argued, true collaboration includes both interactivity and negotiability. Interactivity refers to the impact of interactions on group members’ thinking and learning. Negotiability refers to the important role of negotiation among group members in order to reach convergent or shared understanding. In other words, instead of imposing one’s knowledge on other group members, new knowledge is built upon individual group members’ contributions and further modified through negotiation. Second, it is about learning together as a group with a shared learning goal. In this sense, collaborative learning is different from cooperative learning. In cooperative learning, students work in structured groups to complete a task by breaking apart the task into different pieces and assigning these different pieces to individuals within groups. However, in collaborative learning, students work together to achieve a common group goal. Individual group members contribute to the group task and each contribution is considered and discussed by all group members for agreement or disagreement.

Productive collaborative learning requires both individuals’ independent skills and their interdependent skills. Essential independent skills include the capability of listening to and evaluating feedback to others’ opinions, openly considering modifying one’s own thinking based on the feedback from others, and assimilating and accommodating one’s own thinking with others’ thinking. Some important interdependent skills include communicating one’s own ideas to the audience, communicating to better understand other members’ ideas (e.g., paraphrasing the contributions of others and asking clarification questions), and efforts to help achieve group learning goals.

Communication and collaboration have been emphasized in the skills framework for 21st century learning (Partnership for 21st Century Skills, 2007) because it is important for scientists, engineers, and technology professionals (as well as citizens working in the global workplace) to be able to articulate and listen to thoughts and ideas effectively and to collaborate with diverse teams. Effective collaboration involves sharing responsibility for work and valuing the individual contributions made by other team members. The distributed nature of cognition suggests that learning requires communication among people (Pea, 1993). Collaborative communication creates an awareness of the need for knowledge revision and encourages deep processing; therefore, it is a powerful tool to facilitate conceptual change (Liu & Hmelo-Silver, 2010;

Roschelle, 1992). Intersubjective meaning making (i.e., negotiating between participants to reach convergent understanding or identify and resolve disagreements) in collaborative communication helps create joint interpretations through phases of negotiation focused on shared information (Suthers, 2006). As Liu and Hmelo-Silver (2010) summarized, peer collaborative interactions promote learning by arousing an awareness of the need to revise knowledge, initiate knowledge reconstruction, and encourage deep processing. Peer communication provides opportunities to recognize such needs.

There is a lot of research about collaborative learning with a focus on assessing students' learning outcomes in collaborative settings or evaluating the impact of specific collaborative learning environments or tools. However, few studies focus on assessing students' practice of collaboration and communication. In general, it is quite challenging to address the issue of assessing collaboration and communication because collaborative learning includes complex interactions among multiple participants and can involve a diversity of learning goals. It is important for us to understand these challenges and think about possible solutions. One major challenge to assessing collaboration and communication is that there are different kinds of collaborative activities. For example, collaboration may take place when groups of students investigate a scientific phenomenon, when students engage in game-like tasks or simulations, or when students participate in discussion groups with a goal to construct knowledge bases. All these learning activities can be assessed at individual and group levels (D. W. Johnson & Johnson, 1992). Another challenge with assessing this practice is that the data collected during students' collaboration and communication are quite different from traditional assessment data. Therefore, different analysis methodologies need to be applied.

### **Dimension 3: The Crosscutting Concepts**

The crosscutting concepts provide one way of linking across the domains in science. They include concepts that bridge disciplinary boundaries and/or an organizational framework for connecting knowledge across domains into a coherent view of the world. We identified three crosscutting concepts to be included in our competency model: systems thinking, cause and effect, and flow and conservation of matter and energy. We identified these crosscutting concepts from the work by Duschl et al. (2007). We focus on only three crosscutting concepts initially because we see them as having particular relevance to the content focus of our current CBAL science work (e.g., matter in the physical sciences and, later, structures and processes and

ecology in the life sciences). One crosscutting concept in particular, systems thinking, has been given some attention by researchers in the learning sciences.

**Crosscutting Concept 1: Systems thinking.** To foster science literacy, it is essential to engage learners in systems thinking (Sabelli, 2006) because it facilitates integrating knowledge across science domains and provides a unifying concept for learners to make sense of the natural world and relate microscopic components underlying a particular phenomenon to macroscopic observations detected in our visible world. For example, it is often challenging for students to understand how the interactions among particles at the microscopic level (or, as some would say, the nanoscopic level) are related to the properties of matter at the macroscopic level. Systems thinking is required to develop such an understanding. Unfortunately, most of our current K–12 science instructional materials do not intentionally target systems ideas.

Systems thinking is derived from the simulation modeling field of system dynamics (Forrester, 1961; Sterman, 2000). A system is “an entity that maintains its existence and functions as a whole through the interactions of its parts” (Assaraf & Orion, 2005, p. 519). Many scientific phenomena around us are examples of systems, such as ecosystems, moon phase formation, and energy transfer. How one perceives the phenomena often is related to systems thinking skills. Systems thinking tends to involve the analysis of scientific phenomena and problems in wider contexts, considers multiple and nonlinear cause-and-effect relationships, and understands change over time (Hogan, 2000; NRC, 1996). Systems thinking is a skill that is related to both the nature of science and nature itself, but it is often neglected in the design of learning and assessment environments (Golan & Reiser, 2002; Wilensky & Resnick, 1999).

**Crosscutting Concept 2: Cause and effect.** Most scientific investigations are to answer questions that explore cause-and-effect relationships, such as the following: Why did that happen? How did that happen? What mechanisms caused that to happen? Therefore, the application of science is dependent on understanding the cause-and-effect relationships between events and elucidating the mechanism for mediating the relationship between two components of investigation in a system or in a particular phenomenon. Research shows that it is human beings’ innate nature to explore the causal relationships between events (Ofer & Durban, 1999). Students at a very young age tend to develop some causal explanations to make meaning of the world, although their explanations often concern the superficial features of events. It may be simple to identify patterns in events, in which events occur together, and such patterns might represent real

cause and effect relationships, but proving such relationships or elucidating the details of the relationship requires more investigation. The formal science education aims to help students appreciate standard scientific theories that explain the causal mechanisms under study and develop arguments based on evidence when attributing an observed phenomenon to a specific cause.

**Crosscutting Concept 3: Flow and conservation of matter and energy.** According to the law of conservation of matter, matter can be transformed from one form to another, but it cannot be created or destroyed. Similarly, according to the first law of thermodynamics, energy can be transformed from one form to another, but it cannot be created or destroyed. The concept of flow and conservation of matter and energy can be informative in understanding systems in all science domains—such as life science, physical science, and earth science—thus, tracking the transfers of matter and energy has important implications for developing interdisciplinary understanding. Conservation is a particularly important principle to apply to all phenomena involving matter and energy, yet students often fail to apply or use it appropriately. For example, when it comes to matter, students often fail to recognize that matter is conserved during a chemical reaction or a phase change that results in the production of a gas. In such cases, many students believe that what they cannot see simply disappears from existence in the universe, when, in fact, the opposite is true. Students should be able to track or account for energy and matter in terms of inputs, outputs, flows, or transfers within a system or process (NRC, 2012). With the proper understanding and application of the flow of matter and energy, students in middle school should, for example, be able to recognize that a plant or animal cannot grow properly without a sufficient input of matter and energy, and students should be able to account for where the matter is coming from and where it ends up as it is transformed inside of organisms.

#### **Dimension 4: Epistemic Beliefs/Metacognition**

Epistemic beliefs refer to beliefs about knowledge (including its structure and certainty) and knowing (including sources and justification of knowledge; Buehl & Alexander, 2001; Duell & Schommer-Aikins, 2001; Hofer, 2000; Hofer & Pintrich, 1997). Increasingly, educational researchers have become interested in how epistemic beliefs about knowledge and knowing are a part of the process of learning and instruction and how these beliefs affect or mediate the knowledge acquisition and knowledge construction processes. There need to be changes in

students' and teachers' epistemic cognition and views about the nature of science (Duit & Treagust, 2003) in order to construct new knowledge effectively in science. Most students do not seem to have an epistemology of science that is consistent with current inquiry-based approaches to learning science, and few students see science as a process of building and testing models and theories. Instead, science is seen as a steady accumulation of facts about the world as piecemeal information that is unconnected to everyday experience and is to be accepted because of the authority of the teacher or text (Carey & Smith, 1993; Driver, Leach, Millar, & Scott, 1996; Hammer, 1994; Linn & Songer, 1993; Liu & Hmelo-Silver, 2009; Smith, Maclin, Houghton, & Hennessey, 2000). Research has shown that students' epistemic beliefs about the structure of knowledge, as well as the construction and stability of scientific knowledge, predict better learning gains and that only students holding constructivist epistemic beliefs achieve a deep conceptual understanding of scientific knowledge, such as Newtonian dynamics (Stathopoulou & Vosniadou, 2006).

To improve students' epistemic understanding of the nature of science, it is essential to promote teachers' understanding in this area (Yoon, Liu, & Goh, 2009). Research shows that teachers who believe that knowledge is derived from experts and that one's learning ability is innate are more likely to engage in traditional, teacher-centered instructional practices. In contrast, teachers who believe that knowledge is constructed from one's experiences and judgment, that knowledge is tentative and changing, and that one's ability can be changed tend to conduct progressive instructional practices that are student-centered (Chan & Elliott, 2004). Therefore, educational researchers and practitioners call for approaches to shifting teachers' and students' epistemic beliefs from an absolutist (knowledge is objective, located in the external world, and certain) to a constructivist (knowledge is constructed and uncertain) view. We propose an approach to using formative assessment that includes many opportunities to engage students in epistemic practices, learning experiences that focus on the development of personal epistemologies through engaging learners in learning activities of doing science, to help foster the shift of epistemic beliefs. The assumption is that if students are taught science in the context of inquiry, they will know what they know, how they know it, and why they believe it (Duschl, 2003). This approach requires that instruction be continuously modified while learning is taking place. This continuous modification is where formative assessment comes into effective instruction—when appropriately designed and implemented formative assessment involves

gathering, interpreting, and acting on information about students' learning so that it may be improved (Bell & Cowie, 2001; Duschl, 2003) and can support learning (Black & Wiliam, 1998).

Epistemic beliefs are often related to one's metacognitive knowledge (metacognition). Metacognition is often referred to as *thinking about thinking* and can be used to help students *learn how to learn*. Specifically, metacognition refers to students' automatic awareness of their own knowledge and their ability to understand, control, and manipulate their own cognitive processes (Flavell, 1979). Metacognition consists of several essential elements: planning (developing a plan of action), monitoring (maintaining the plan), and evaluating (evaluating the progress). Below, we elaborate on these elements:

- *Planning*: During the planning process, students need to have an understanding of what prior knowledge they have and whether it is useful for a particular task. They also need to know what other knowledge is needed to complete the task.
- *Monitoring*: During the monitoring process, students attempt to keep themselves on the right track of problem solving and iterate back and forth between the planning process, the use of knowledge, and the learning strategies needed to achieve the targeted learning goals.
- *Evaluating*: During the evaluating process, students assess whether they have reached their goals; assess what gaps in their knowledge, skills, or abilities still need to be filled in; and, most importantly, recognize how they obtained the necessary knowledge for problem solving.

Metacognition has been interchangeably used with the term *self-regulation*, which emphasizes students' ability to adjust their learning processes in response to their perception of feedback regarding their current status of learning.

Engaging students in metacognitive processes guides students' thinking as they work through a problem and make decisions. Davidson and Sternberg (1998) have argued that metacognitive knowledge allows the problem solver to better encode and represent the givens in a problem context (i.e., what information is provided in the problem), break down the problem into smaller questions that are relevant, and therefore derive a better solution.

It is particularly challenging to assess students' metacognitive processes, as those processes are often hidden in thinking. Traditionally, students' metacognition is assessed through

Likert-type self-report surveys (Pintrich, Smith, Garcia, & McKeachie, 1993; Weinstein, Zimmermann, & Palmer, 1988). Other research has focused on providing metacognitive scaffolds to make evidence of students' thinking visible by asking students to think aloud verbally or to write down their thinking (e.g., Azevedo & Hadwin, 2005; Saye & Brush, 2001). To this end, some virtual learning environments in science, such as ThinkerTool and WISE (Slotta, 2004; White, 1993), build in functions to log students' pathways to problem solving so that students can visualize their thinking process during problem solving. Although there have been some advances in the measurement of metacognition, more work establishing the reliability and validity of the available measures is needed.

### **Dimension 5: Motivation**

According to Brophy (1988), motivation to learn is “a student’s tendency to find academic activities meaningful and worthwhile and to try to derive the intended benefits from them” (pp. 205–206). In our competency model, we define motivation as the values, interest, and student engagement aroused by an assessment prototype. Poor motivation in assessment prototypes leads to low achievement on them. Therefore, in assessment development, special attention needs to be paid to improving student motivation. For example, designing an authentic and meaningful scenario context is essential to engaging students in applying scientific knowledge to explain scientific events related to their daily life. Another strategy to increase students’ motivation in taking an assessment is to provide immediate feedback. If students have experienced success in earlier performance, they are more likely to feel positively toward a new task. It is important to provide feedback that can help students realize what knowledge they have mastered and what knowledge they need to master or construct to be able to complete the task. In other words, the feedback should be task-oriented rather than person-oriented. In addition, new interactive technologies provide opportunities to actively involve students in problem solving by *doing science* (e.g., designing and conducting experiments). Such interactive features in science assessment can also help to maintain students’ motivation during the task.

### **Learning Progressions**

Learning progressions (LPs) in science have been defined as “empirically grounded and testable hypotheses about how students’ understanding of, and ability to use, core scientific concepts, explanations, and related scientific practices grow and become more sophisticated over



time, with appropriate instruction” (Corcoran, Mosher, & Rogat, 2009, p. 20). Essentially, an LP is a road map that shows how students’ qualitative understanding of particular ideas or practices is likely to change over time with appropriate instruction. Therefore, LPs can serve as a guide for educators as they design instruction and monitor students’ progress toward the targeted levels of understanding and ability. According to an expert panel review of the work in this field, a learning progression must include the following elements:

1. Target performances or learning goals that are the end points of a learning progression and are defined by societal expectations, analysis of the discipline, and/or requirements for entry into the next level of education.
2. Progress variables, which are the dimensions of understanding, application, and practice, that are being developed and tracked over time. These may be big ideas that constitute core concepts in the discipline or critical aspects of practices central to scientific work.
3. Levels of achievement that are intermediate steps in the developmental pathway(s) traced by a learning progression. These levels may reflect levels of integration or common stages that characterize the development of student thinking. There may be intermediate steps that are noncanonical but are stepping stones to canonical ideas.
4. Learning performances that are the kinds of tasks students at a particular level of achievement should be capable of performing. They provide specifications for the development of assessments and activities that identify the scientific ideas and practices by which students will demonstrate their proficiency in science.
5. Assessments are the specific measures used to track student development along the hypothesized progression. Assessments are integral to the development, validation, and use of LPs.
6. They can be validated and empirically tested (Corcoran et al., 2009).

Based on this consensus and the goals of CBAL, we presume that learning progressions should be based on learning theories of how students gain particular core knowledge and skills (or practices) within a domain, as well as on the developmental theories of how students develop particular cognitive skills over time. In sum, LPs are working hypotheses of how students’ ideas and abilities change over time as the effect of instruction, learning, and cognitive development. In addition, LPs are continually revised based on the collection of new evidence from the

students. The empirically based revisions enable LPs to provide more accurate and general descriptions of sequentially different patterns, or levels, in thinking and ability, as students make progress toward the upper level of understanding defined in standards. In the field of assessment, LPs provide a framework to guide the design of tasks that are sensitive to progress toward a desired level of proficiency. In particular, LPs can help design assessments that provide a range of information about students' intermediate knowledge, rather than evaluate students' ability and knowledge as an oversimplified all-or-nothing category of response. Additionally, LPs can guide the development of scoring rubrics and suggest ways to elicit evidence of student thinking. Furthermore, LPs can also provide teachers with an opportunity to think critically about what students know, and can do, and realize where students might be coming from and where they need to go; therefore, LPs can serve an important role in supporting the formative assessment process (Furtak, 2012).

A review of the work on LPs in science shows that only a few dozen hypothetical LPs have been developed (Corcoran et al., 2009). Even fewer LPs have been developed that span all grades in school (K–12). Moreover, only a small proportion of hypothetical LPs have been tested and validated. There certainly are not enough hypothetical LPs to cover all the current NGSS standards. The biggest gaps are in the earth and planetary sciences, where there are very few hypothetical LPs. There are more hypothetical LPs in the life sciences (in particular, ecology and evolution) and the physical sciences (in particular, the structure of matter). However, there are some very fundamental topics for which we do not have LPs (in particular, energy and cell theory). Perhaps the most well validated LPs that extend to middle school are for the flow of matter and energy in an ecosystem, that is, the carbon cycle (Mohan, Chen, & Anderson, 2009), and for food webs and food chains (Gotwals & Songer, 2006; Songer, Kelcey, & Gotwals, 2009). In the physical sciences, there is a fair amount of research on students' alternative conceptions of matter and how students' conceptualization of matter changes across elementary and middle school—enough research, in fact, to inform a provision K–8 LP for matter (Smith et al., 2006). Current work at the elementary and middle school levels is attempting to validate parts of this LP (S. Y. Stevens, Delgado, & Krajcik, 2010; Wisner, Smith, & Doubler, 2012). Unfortunately, while ideas such as matter are believed to be critical to developing conceptual knowledge in other disciplines of science, such as the earth sciences, very little work has been done to examine the interactions between a matter LP and an LP for any other core idea. In fact, there are no studies

looking at the interactions between LPs for any two core ideas in science; hence, this is also a major gap in the literature (Corcoran et al., 2009). Furthermore, little work has been done to examine the interactions between specific LPs in science and those in very different domains, such as mathematics or English language arts.

Many researchers argue that, parallel with developing conceptual knowledge, students' ability to engage in and understand particular science practices, such as constructing models, constructing evidence-based explanations, designing investigations, or constructing arguments, also grows in sophistication over time. A few researchers have developed LPs that foreground and focus on the development of science practices, such as the work by Schwarz and colleagues on modeling (Schwarz et al., 2009) or on explanations (Berland & McNeill, 2010), but, again, there are only a few learning progressions focused on particular science practices. However, if meaningful competency models are to be developed that are consistent with current policy recommending students engage in these science practices (NRC, 2012), then progressions covering such practices should be included. The term *progression*, in this case, would refer to students' increasing capacity to engage productively in the practice (e.g., developing more sophisticated models), as well as students' increasing ability to reflect on the nature of the practice (e.g., developing more sophisticated epistemological understandings of models). Some researchers have proposed progressions that intimately connect the development of content knowledge and the development of students' ability to engage in science practice, in particular, the work by Lehrer and Schauble (2012) on data modeling and biodiversity; however, this work is limited to the early and middle elementary grades.

For this early stage of the project, we have focused on one core idea (matter, including the structure and properties of matter, and changes and conservation of matter). We have focused on matter because it is one of the most foundational core ideas in the natural sciences, and there is considerable research to draw from.

Based on reviewing existing literature, we drafted a hypothesized LP for the core concept of matter and its interactions and a hypothesized LP for the science practice of constructing scientific explanations. Based on external feedback from advisory committees, we made multiple revisions to the hypothesized progressions. We chose to keep the progressions for content and practice separate, given that it might be difficult to disentangle the constructs if they were present in a fused progression.

Tables 1 and 2 present the LPs for two big ideas that make up the core idea of matter and its interactions: (a) properties and structure of matter and (b) change and conservation of matter. The development of both LPs is based on theoretical and empirical scholarly work, although they still need to be tested and validated, which is planned in our future work when we pilot and implement the tasks. The theoretical work for the matter LPs is largely based on work by Smith et al. (2006) and Rogat et al. (2011). The Smith et al. work theorized a K–8 learning progression for the atomic-molecule model of matter. This work identified several big ideas as key aspects of student thinking that our progression addresses, such as material identity, properties of matter relevant to structure of matter, and conservation and transformation of matter. The more recent work by Rogat et al. also had important impact on developing our progression. This work theorized K–12 progressions for properties and structure of matter, change in matter, and more current understanding of how students come to understand matter. Furthermore, this work is well aligned with *A Framework for K–12 Science Education* (NRC, 2012).

The development of the LPs was also based on empirical work (P. Johnson, 1998, 2000, 2002; Krajcik, McNeill, & Reiser, 2008; Krnel, Watson, & Glazar, 1998; Liu & Lesniak, 2005; Merritt, 2010; Nakhleh & Samarapungavan, 1999; Papageorgiou & Johnson, 2005; Stavy, 1990, 1991; S. Y. Stevens et al., 2010; Wiser & Smith, 2008; Wiser et al., 2012). These different empirical pieces range from cross-sectional and short-term longitudinal studies examining students' conceptions of matter through interviews and drawings, to curriculum interventions that attempt to support and examine students' conceptions of matter through drawings and/or explanations.

In sum, our LPs for matter and its interactions show a progression from early macroscopic notions of matter that include no conception of the nanoscopic particles of matter, or their structure or behaviors (e.g., Levels 1–2 in the structure and properties LP as well as in the change and conservation LP), to a variety of intermediate conceptions of matter that include increasingly more sophisticated notions of the nanoscopic particles of matter and their structure and behaviors (e.g., Levels 3–4 in the structure and properties LP and Levels 3–5 in the change and conservation LP). Finally, at the top level of the progression are the most sophisticated models of matter expected from middle school science students as articulated in the NGSS (Level 5 in the structure and properties LP and Level 6 in change and conservation LP). At these

top levels, students are capable of explaining, predicting, or modeling the properties and behavior of a variety of natural phenomena involving matter.

**Table 1**

***The Learning Progression for Properties and Structure of Matter***

Achievement	Gap/challenge	Instructional experience to support progression
<b>Level 1—Macroscopic compositional model</b>		
<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Has a macroscopic notion of material identity: realizes some materials can change form and still remain the same material (e.g., by melting) or realizes that an object broken into smaller pieces that still have perceptual properties of the original material (e.g., a piece of paper cut into small pieces) is still the same material identity.</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>Recognizes that objects can be broken down into smaller pieces that have weight and volume.</li> </ul> <p><i>Properties of matter in different states</i></p> <ul style="list-style-type: none"> <li>Can distinguish general properties of solids and liquids (e.g., liquids are running but solids are not).</li> </ul> <p>Key words: observable macroscopic properties of liquids and solids, historical thinking</p>	<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Conceives of matter or materials as what you can touch and feel.</li> <li>Tends to classify different types of materials based on historical thinking (i.e., tend to think about where materials came from to classify them— e.g., plastic is man-made and therefore is a material, whereas wood is from nature and therefore is not a material).</li> <li>May not distinguish extrinsic from intrinsic properties (e.g., mass and volume may be viewed as intrinsic properties).</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>Does not recognize that objects can be broken down into very much smaller pieces (e.g., the size of a grain of sand) that have weight and volume.</li> </ul> <p><i>Properties of matter in different states</i></p> <ul style="list-style-type: none"> <li>Sees solids and liquids as fundamentally different.</li> </ul>	<ul style="list-style-type: none"> <li>Help students understand that if one divides an object into very small pieces that appear not to have the perceptual properties of the original object (e.g., the size of sand grains from grinding a rock), those tiny pieces still have the same physical intrinsic properties of the original object (color, texture, hardness, etc.) and can be seen by using sensitive instruments such as magnifying glasses. Also help students realize these tiny pieces also have weight and volume by using sensitive instruments like scales or graduated cylinders.</li> <li>Help students understand that liquids and solids of the same material are fundamentally similar (e.g., solid and liquid butter or solid and liquid water) by visualizing the state change from liquid to solid and vice versa and exploring the intrinsic properties of the material; students should work with evidence that intrinsic properties of matter are constant, even though the extrinsic properties like mass and volume can change.</li> <li>Help students realize that solids and liquids are fundamentally similar in that they both have mass and volume; bridging analogies can also be helpful, such as exploring aggregates to show how volume and mass are extrinsic properties of both solids and liquids and both can be divided into smaller units that, if added up, can equal the sum of the original object or sample.</li> </ul>
<b>Level 2—Microscopic compositional model</b>		
<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Has a microscopic compositional notion of material identity: realizes that an object broken into smaller pieces that no longer have the perceptual properties of the original object is still the same material identity (e.g., wood vs. sawdust).</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>Recognizes that an object can be</li> </ul>	<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Still may conceive of matter or materials as what you can touch and feel.</li> <li>May sometimes classify different types of materials based on historical thinking.</li> <li>Does not recognize that different properties of matter are determined by the arrangement and motion of</li> </ul>	<ul style="list-style-type: none"> <li>Help students understand that intrinsic properties are unique to matter and are related to the nanoscopic particles that compose matter by using physical and/or computer modeling tools.</li> <li>Help students understand that gas is another form of matter by constructing models and using representations to explore and make sense of the state change from liquid to gas and vice versa.</li> </ul>

Achievement	Gap/challenge	Instructional experience to support progression
Level 1—Macroscopic compositional model		
<p>broken down into very small pieces (e.g., grains of sand) that have weight and volume.</p> <p><i>Properties of matter in different states</i></p> <ul style="list-style-type: none"> <li>Recognizes that all solids and liquids are fundamentally similar in that they all have mass and volume and recognizes that matter may come in solid or liquid forms.</li> </ul> <p>Key words: material kinds of solids and liquids, mass and volume, historical thinking</p>	<p>particles making up the matter.</p> <ul style="list-style-type: none"> <li>May ignore some intrinsic properties of matter (such as odor).</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>Does not have a nanoscopic notion of material identity, but has a microscopic notion of material identity.</li> </ul> <p><i>Properties of matter in different states</i></p> <ul style="list-style-type: none"> <li>Does not recognize gases as a form of matter or materials.</li> </ul>	
Level 3—Developing particle model		
<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Has a developing nanoscopic notion of material identity: sometimes recognizes that different materials are made of different particles (e.g., wax is made of wax particles and water is made of water particles).</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>Conceives of matter as made of particles that have mass and volume.</li> <li>Sometimes thinks of empty space between particles for some materials.</li> <li>Sometimes recognizes that particles of matter move.</li> </ul> <p><i>Properties of matter in different states</i></p> <ul style="list-style-type: none"> <li>Recognizes that all three states of matter (i.e., solid, liquid, gas) are fundamentally similar in that they all occupy space and have mass and volume.</li> </ul> <p>Key words: particles with macro properties</p>	<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Sometimes may not recognize some materials or substance as being composed of particles.</li> <li>May associate macroscopic properties (e.g., hardness or temperature) with individual particles.</li> <li>Does not recognize the properties of materials are determined by the collection of the particles' moving and interacting with each other.</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>May not recognize that there is empty space between particles in all conditions, although having a nanoscopic notion of material identity.</li> <li>May not recognize particles move for all substances and all states of matter.</li> </ul> <p><i>Properties of matter in different states</i></p> <ul style="list-style-type: none"> <li>May not effectively incorporate ideas about motion and spacing of particles to matter that exists in different states.</li> </ul>	<ul style="list-style-type: none"> <li>Help students understand that different properties of matter are determined by the arrangement and motion of particles making up the matter by using computer simulations. Provide investigative opportunities for students to explore the relations between properties of matter and the arrangement and/or motion of particles.</li> <li>Using computer-based visualization tools, help students recognize that there is empty space between particles in all three states, but the space between particles in the three states is different.</li> </ul>
Level 4—Particle model		
<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Has an established nanoscopic notion of material identity: consistently recognizes different materials are made of particles.</li> <li>Recognizes the properties of a material are determined by the collection of the particles' moving and interacting with each other.</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>Consistently conceives of matter as made of particles that have mass and volume.</li> <li>Consistently thinks there is empty space between the particles.</li> <li>Consistently recognizes that particles of matter move. (Note: students are not</li> </ul>	<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>May not recognize that different properties of matter are determined by the type and arrangement of atoms.</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>May not consistently recognize that different materials are made of specific atoms, or combinations of atoms forming molecules, although may have a general particle model.</li> </ul>	<ul style="list-style-type: none"> <li>Help students construct an atomic-molecular model that different particles are made of specific atoms or combinations of atoms forming molecules. Using physical or computer models to help them understand the difference between molecules and atoms.</li> <li>Provide investigative opportunities for students to construct arguments about the behaviors of matter undergoing chemical change by using an atomic-molecular model to evaluate which argument better explains and predicts chemical change.</li> </ul>

Achievement	Gap/challenge	Instructional experience to support progression
Level 1—Macroscopic compositional model		
<p>expected to think about absolute zero.)</p> <ul style="list-style-type: none"> <li>Recognizes that temperature is a product of the average kinetic energies of the particles of the substance.</li> </ul> <p><i>Properties of matter in different states</i></p> <ul style="list-style-type: none"> <li>Recognizes the macroscopic properties of solids, liquids, and gases are a result of the spacing and speed of nanoscopic particles.</li> </ul> <p>Key words: particles with mass and volume, properties as a result of a collection of particles, interactions between particles, consistent application of nanoscopic level of material identity</p>		
Level 5—Atom-molecular model		
<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Has a refined nanoscopic notion of material identity: recognizes that different materials are made of specific atoms or combinations of atoms forming molecules and that the arrangement of the atoms and molecules determines the properties of the material.</li> </ul> <p><i>Pieces of matter</i></p> <ul style="list-style-type: none"> <li>Conceives of matter as made of atoms, or molecules composed of atoms, and that the atoms have mass and volume.</li> <li>Consistently thinks there is empty space between molecules.</li> </ul> <p><i>Properties of matter in different states</i></p> <ul style="list-style-type: none"> <li>Recognizes different properties are determined by the arrangement and motion of particles making up the substance.</li> <li>May include notion of attractive forces between particles to explain some properties of matter.</li> </ul> <p>Key words: particles with mass and volume, properties as a result of a collection of particles, interactions between particles, consistent application of nanoscopic level of material identity</p>	<p><i>Material identity and characteristic properties of matter</i></p> <ul style="list-style-type: none"> <li>Does not recognize that atoms may be composed of smaller particles, such as electrons, neutrons, protons. (Note: this notion is high school content and would not be expected for middle school.)</li> <li>May not include notion of attractive forces between atoms and/or molecules.</li> </ul>	N/A

**Table 2**

***The Learning Progression for Change and Conservation of Matter***

Achievement	Gap/challenge	Instructional experience to support progression
Level 1—Macroscopic compositional model		
<p><i>Reshaping matter—a precursor to physical changes</i></p> <ul style="list-style-type: none"> <li>Realize that cutting an object into pieces that still have perceptual properties of the original material (e.g., a piece of paper cut into small pieces) or reshaping or reordering the object does not change the <i>amount</i> and the material type of the object. (Note: we emphasize a general notion of <i>amount of stuff</i> not quite conservation of mass here.)</li> </ul> <p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>Realize that some solid materials can melt, and the substances in the liquid form are still the same substance.</li> </ul> <p>Key words: cutting, reshaping, melting.</p>	<p><i>Reshaping matter</i></p> <ul style="list-style-type: none"> <li>May not realize micro level small pieces (e.g., sand grains or sawdust) still have mass and volume.</li> </ul> <p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>May not realize that the material type does not change during melting process of all solid objects.</li> </ul>	<ul style="list-style-type: none"> <li>Help students understand conservation of <i>amount of stuff</i> when grinding things into micro level pieces by engaging them in investigations that allow them to measure and record the mass during state change.</li> <li>Help students understand conservation of material identity across all melting and freezing events.</li> </ul>
Level 2—Microscopic compositional model		
<p><i>Reshaping matter—a precursor to physical changes</i></p> <ul style="list-style-type: none"> <li>Realize that cutting and grinding into micro level pieces that do not have perceptual properties of the original object does not change the <i>amount</i> and the material type of the object. (Note: we emphasize a general notion of <i>amount of stuff</i> not quite conservation of mass here.)</li> </ul> <p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>Understand that all solid materials can melt, and substance in liquid form is still the same substance.</li> </ul> <p>Key words: grinding, melting</p>	<p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>May be unable to effectively predict conservation of mass during familiar physical changes (e.g., melting) and does not incorporate particle in models of physical change.</li> </ul>	<ul style="list-style-type: none"> <li>Help students understand the conservation of mass during physical changes (e.g., melting) by engaging them in investigations that allow them to measure and record the mass during state change and to analyze data from these investigations.</li> <li>Help students predict conservation of mass during physical changes by engaging them in investigations that allow them to measure and record the mass during state change.</li> <li>Help students develop a particle model for state change by engaging them in more opportunities to construct and revise models. Can also use multiple representations of physical change at the particle level to support student understanding.</li> </ul>
Level 3—Beginning particle model		
<p><i>Reshaping matter—a precursor to physical changes</i></p> <ul style="list-style-type: none"> <li>Realize that mass and volume are conserved when reshaping, cutting, and grinding (e.g., when dividing matter into very small pieces).</li> </ul> <p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>Have the notion that type and number of particles (not distinguishing atoms from molecules) are conserved across some physical changes (e.g., melting, freezing).</li> </ul>	<p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>May be unable to predict effectively conservation of mass during all physical changes.</li> </ul>	<ul style="list-style-type: none"> <li>Help students understand the conservation of mass during physical changes (e.g., boiling and evaporation) by engaging them in investigations that allow them to measure and record the mass during state change and to analyze data from these investigations. May use computer simulations to trace particles.</li> <li>Help students apply a particle model across more cases of physical change by engaging them in more opportunities to construct and revise models.</li> </ul>



Achievement	Gap/challenge	Instructional experience to support progression
<ul style="list-style-type: none"> <li>Therefore, mass is conserved across some physical changes.</li> </ul> <p>Key words: melting, freezing</p>		
Level 4—Unidirectional particle model		
<p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>Have the notion that type and number of particles are conserved across many physical changes consistently (e.g., dissolving, boiling, evaporation) but unidirectional.</li> <li>Therefore, mass is conserved across many physical changes in some directions.</li> </ul> <p>Key words: dissolving, boiling, evaporation</p>	<p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>May be unable to apply conservation of matter to all physical changes bidirectional (e.g., matter is conserved in both evaporation and condensation).</li> </ul>	<ul style="list-style-type: none"> <li>Help students understand that the conservation of mass is bidirectional in evaporation and condensation by engaging them in comparing open versus covered cups experiments. May use computer simulations to represent particle models during evaporation and condensation processes.</li> <li>Help students apply a particle model directionally across all physical changes by engaging them in more opportunities to construct and revise models.</li> </ul>
Level 5—Bidirectional particle model		
<p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>Have the notion that particles are conserved across all physical changes bidirectional (e.g., both evaporation and condensation).</li> <li>Therefore, mass is conserved across all physical changes in all directions.</li> </ul> <p>Key words: physical change; evaporation; condensation.</p>	<p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>May be unable to apply conservation of matter to chemical changes.</li> </ul> <p style="text-align: center;">Energy during change</p> <ul style="list-style-type: none"> <li>May not recognize that some chemical reactions release energy and some absorb thermal energy.</li> </ul>	<ul style="list-style-type: none"> <li>Help students understand that the conservation of mass applies to chemical changes. May use computer simulations to predict and test what chemical components are present before and after certain chemical reactions. Can also use multiple representations of chemical changes to support student understanding.</li> <li>Help students apply a particle model across chemical changes by engaging them in more opportunities to construct and revise models.</li> <li>Help students understand that energy is included in chemical change. May ask students to measure the change in temperature after a chemical reaction and then ask them to construct an explanation by using computer simulations that explore micro level phenomena.</li> </ul>
Level 6—Bidirectional atomic-molecular model		
<p><i>Conservation of material and identity and mass</i></p> <ul style="list-style-type: none"> <li>Have the descriptive notion that the number and type of atoms are conserved during chemical change.</li> <li>Can apply conservation of mass across all physical and chemical changes in all directions.</li> </ul> <p>Key words: physical change, evaporation, condensation</p>	<p><i>Energy during change</i></p> <ul style="list-style-type: none"> <li>May not include mechanistic accounts (e.g., attractive forces within and between molecule) for physical and chemical changes.</li> </ul> <p style="text-align: center;">Energy during change</p> <ul style="list-style-type: none"> <li>Recognize that some chemical reactions release energy and some absorb thermal energy.</li> </ul>	N/A

Table 3 presents the LP for constructing scientific explanations. The development of this LP is largely based on an empirical work focused on an LP for evidence-based explanations that account for biodiversity (Songer et al., 2009). Although Songer et al. stressed the importance of integrating content and inquiry reasoning progressions as parallel templates that together constitute a learning progression for a focal topic, we intentionally separate the content and science practice progressions in our current work because there is no convincing empirical evidence that supports the parallel progression of these two dimensions. The development of our LP for constructing scientific explanations is also influenced by the theoretical work of McNeill and Krajcik (2008) and Osborne and Patterson (2011) that characterizes a scientific explanation as a linguistic construct that contains three elements—a claim, evidence, and reasoning—as described in the previous section.

Our LP for constructing explanations shows a progression from simple linguistic structures that include fewer elements, to more sophisticated structures that include more elements and connections among them. Levels 1 and 2 represent very poor explanatory structure that miss major components of the explanatory framework, such as evidence and reasoning. Levels 3 and 4 are intermediate models that present some causal relationships but lack coherence of reasoning with science principles. Levels 5 and 6 include sophisticated coherent models with all components of the explanatory framework, but differ in the extent of sufficient reasoning.

### **Assessment Prototype Development Around the Competency Model and the Learning Progressions**

The CBAL science assessments are being developed based on the science competency model and its related hypothesized LPs. Below we elaborate several essential task features that support such alignment and present examples using a sample formative assessment prototype targeting the core idea of matter. This prototype is meant to measure and improve the teaching and learning of the matter core idea at Grade 6. In this formative assessment prototype, we are also interested in measuring students' ability to engage in the practices of modeling and constructing scientific explanations.

**Table 3*****The Learning Progression for Constructing Scientific Explanations***

Achievement	Gap/challenge	Instructional experience to support progression
<b>Level 1: Nonstructural model</b>		
<ul style="list-style-type: none"> <li>• Student makes no claim or an inaccurate claim.</li> </ul>	<ul style="list-style-type: none"> <li>• Student does not make a claim or makes an inaccurate claim.</li> </ul>	<ul style="list-style-type: none"> <li>• Make it explicit to students about what a good claim is (i.e., an assertion or conclusion that addresses the original question or problem about a phenomenon).</li> <li>• Model and critique strengths and weakness of claims by showing examples.</li> <li>• Provide a rationale for creating claims.</li> <li>• Make use of students' preexisting knowledge about claims.</li> <li>• Provide feedback in response to students' claims.</li> </ul>
<b>Level 2: Noncausal relation model</b>		
<ul style="list-style-type: none"> <li>• Student makes a claim.</li> </ul> <p>Key words: claim</p>	<ul style="list-style-type: none"> <li>• Student does not back up the claim with evidence.</li> </ul>	<ul style="list-style-type: none"> <li>• Help students understand why it is important to include justification to convince others to accept the claims.</li> <li>• Make it explicit to students what is evidence (i.e., the evidence supports the claim using scientific data). Data can come from an investigation that students complete or from another source, such as observations, reading material, or archived data, and needs to be both appropriate and sufficient to support the claim.</li> <li>• Model the justification of claims with examples.</li> <li>• Draw on what students know about evidence or justification in their everyday life and help them understand scientific evidence.</li> <li>• Provide feedback in response to students' justification.</li> </ul>
<b>Level 3: Insufficient causal relation model</b>		
<ul style="list-style-type: none"> <li>• Student makes an accurate claim.</li> <li>• Student backs up the claim with evidence.</li> </ul> <p>Key words: accurate claim, evidence</p>	<ul style="list-style-type: none"> <li>• The evidence is insufficient / inappropriate.</li> </ul>	<ul style="list-style-type: none"> <li>• Make explicit to students what counts as appropriate and sufficient evidence (i.e., by appropriate, we mean data that are relevant to the problem and help support the claim; sufficient refers to providing enough data to convince another individual of the claim). Often providing sufficient evidence requires using multiple pieces of data.</li> <li>• Model the justification of claims with sufficient evidence with examples.</li> <li>• Draw on what students know about evidence or justification in their everyday life and help them understand what counts as good evidence.</li> <li>• Provide feedback in response to students' justifications.</li> </ul>

Achievement	Gap/challenge	Instructional experience to support progression
Level 4: Causal relation model		
<ul style="list-style-type: none"> <li>• Student makes an accurate claim.</li> <li>• Student backs up the claim with sufficient and appropriate evidence.</li> </ul> <p>Key words: accurate claim, appropriate and sufficient evidence</p>	<ul style="list-style-type: none"> <li>• Student does not use reasoning to tie the claim and evidence together.</li> </ul>	<ul style="list-style-type: none"> <li>• Help students understand why it is important to include reasoning to convince others to accept the claims.</li> <li>• Make explicit to students what reasoning is (i.e., reasoning links the claim and evidence and shows why the data count as evidence to support the claim).</li> <li>• Model the use of reasoning with examples that tie claims to evidence.</li> <li>• Draw on what students know about reasoning in their everyday life and help them understand scientific reasoning.</li> <li>• Provide feedback in response to students' reasoning.</li> </ul>
Level 5: Insufficient coherence model		
<ul style="list-style-type: none"> <li>• Student makes an accurate claim.</li> <li>• Student backs up the claim with sufficient and appropriate evidence.</li> <li>• Student provides reasoning that links the claim and evidence and includes some, but not appropriate and sufficient, scientific principles.</li> </ul> <p>Key words: accurate claim, appropriate and sufficient evidence, reasoning</p>	<ul style="list-style-type: none"> <li>• Student does not provide appropriate and sufficient scientific principles to link evidence and claims.</li> </ul>	<ul style="list-style-type: none"> <li>• Make required components of a scientific explanation explicit to students.</li> <li>• Make explicit what good reasoning is in science.</li> <li>• Model and critique explanations.</li> <li>• Provide a rationale for creating explanations.</li> <li>• Connect to everyday explanations.</li> <li>• Assess and provide feedback to students.</li> </ul>
Level 6: Sufficient coherence model		
<ul style="list-style-type: none"> <li>• Student constructs scientific explanation consisting of an accurate claim, sufficient and appropriate evidence, and sufficient reasoning including appropriate and sufficient scientific principles to tie the evidence to the claim.</li> </ul> <p>Key words: accurate claim, sufficient and appropriate evidence, sufficient reasoning</p>	N/A	N/A

We have used the hypothesized LP for matter to inform the design of our prototype task. In particular, we have used the LP to identify the mental model of matter that we would expect students to develop at early middle school, which also has implications for the kinds of phenomena that students can adequately explain and model. Our hypothesized LP suggests that students at the early middle school should be developing a particle model (see Table 1). This model includes tiny particles (although not necessarily atoms and molecules) that are in constant motion and that cannot be seen with the human eye. In this model, the type of particles, their motion, and their arrangement determine the macroscopic properties of the material that they make up. With this particle model, students should be able to predict, explain, and model the behavior of solids, liquids, and gases. Without a particle model, the behavior of gases or phenomena involving gases, such as evaporation, boiling, or condensation, cannot be well explained or predicted by students. For this reason, we have targeted phenomena that involve

evaporation and condensation in our prototype task. Many items in the exemplar formative assessment prototype are developed around the LP for the properties and structure of matter and the LP for change and conservation of matter. For example, some multiple-choice item options are aligned with different levels of the LPs to differentiate student understanding. In addition, we have developed items that require students to construct and describe graphic models of matter using a digital modeling tool (see Figure 5). We expect these items to elicit rich evidence of students' initial and developing conceptions of matter addressed in our LP. These models of matter can be scored for presence of particles in student conceptions associated with the nature, arrangement, and behavior of those particles. For instance, we may find that some students' models of matter stay at Level 1 or 2 during the course of the task and reflect only macroconceptions of matter; whereas, other students' models may stay at, or move to, Level 3 during the course of the task and include some particle representations along with some partially incorrect ideas (e.g., incorporating some macroscopic ideas and some missing elements of the behavior and arrangement of particles); and some students' models may stay at, or move to, Level 4 or 5 during the course of the task and represent and describe particle ideas with more accuracies about the behavior and arrangement of particles.

In addition, we have used our hypothesized LP for constructing scientific explanations to guide the design of the task. For example, our LP suggests that if students do not have sufficient knowledge about the structure of a good explanation, they may not be able to express what they know in an efficient way. Therefore, we provide a structure for students to enter the critical parts of a scientific explanation (i.e., their claim, evidence, and reasoning), in order to help them articulate their reasoning and, thus, help them externalize their mental model.

In addition, we will use the LP for constructing scientific explanations to guide the scoring of students' written scientific explanations collected from the task. The LP will allow us to anticipate and categorize the quality of students' explanations as we collect them and assign them to particular levels in the LP. For example, in students' written explanations, we expect a number of students to state a claim in their written explanations, but provide insufficient evidence (Level 3) or provide inappropriate and insufficient scientific principles (Level 4). In the following sections, we present several task features in the exemplar formative assessment protocol. In addition, we elaborate on the importance of including these features in our task design by connecting them with existing research in the learning sciences.

## Scenario-Based Assessment

Consistent with one of the key design principles underlying CBAL, we will create a reasonably realistic scenario for each assessment prototype. The literature in problem-based learning (PBL) research posits that engaging students in solving a real-world problem promotes knowledge acquisition, problem-solving skills, and motivation through authentic learning tasks (Hmelo & Lin, 2000). Thus, PBL, in turn, provides opportunities to measure the integrated application of both conceptual knowledge and science practices. In the scenario context, a driving question will be proposed in a conversational context that sets the goal for the whole task. In this exemplar formative task, students are asked to come up with an answer to the driving question: *How can you get pure water to drink out of ocean water?* We embedded the driving question in a context where three middle school students and their teacher (Ms. Jessie) are on a school trip at an ocean beach and are having the following conversation:

Ms. Jessie: Hi, I am Ms. Jessie. Wow! What a wonderful day to spend with my students on a class field trip at an ocean beach!

Tania: Hi, I am Tania. Ms. Jessie, I'm thirsty. I wish we could just drink the water in the ocean. There's so much of it.

Jack: Hi, I am Jack. Too bad that we can't drink the ocean water. Can you imagine how much stuff there is in it? You can get really sick if you drink the ocean water.

Ms. Jessie: You're actually talking about a really important topic that affects many people and animals all around the world—getting enough pure water to drink every day.

Locus: Hi, I am Locus. That's what my dad told me. If scientists could only figure out a cheap and simple way to clean up ocean water to drink, a lot of people's lives would be so much better and healthier.

Ms. Jessie: Great! This is an excellent research idea. Why don't we, as a small group, carry out an investigation and try to find a solution? The problem we need to solve is this: *How can you get pure water out of ocean water?*

We select this driving question because it is situated in a meaningful context for students and, therefore, should require and promote sense-making during the problem-solving process. In addition, it is a complex, open-ended problem that requires students to engage actively in analyzing and refining the problem an explaining, hypothesizing, representing, designing, and conducting investigations to test and revise hypotheses. Therefore, this scenario can provide many opportunities to measure both students' conceptual understanding and their ability to apply science practices to solve problems. After the scenario is presented, the conversations among the student characters continue to help students refine the driving question into more manageable and testable questions, such as the following: What is in the pure water and the ocean water? How is pure water different from ocean water? To purify the ocean water, what should be left in and taken out? What process can help get the pure water back? Then various activities are designed to help students to respond to those refined questions.

### **Simulation-Based Assessment**

Another feature of all CBAL science tasks is that we use simulations as opportunities to collect evidence of what students know and can do in science. By allowing students to interact with representations of phenomena, simulations provide an effective way for students to explore phenomena, or unseen mechanisms underlying phenomena, that would otherwise be impractical or difficult for students to observe in a typical assessment context. This expanded range of explorable content, in turn, allows assessments to measure students' knowledge of content and science practices that are important to be tested, but which are not well assessed in traditional paper-and-pencil assessments. In addition, simulations allow us to create log data of students' actions when working through a scientific investigation. Recent studies have shown that simulations can generate evidence of students' achievement levels and measures of their science practices (Bennett, Persky, Weiss, & Jenkins, 2007; Quellmalz & Pellegrino, 2009). As Quellmalz, Timms, Silberglitt, and Buckley (2012) stated: "Because simulations are interactive, students can demonstrate their abilities to apply the active inquiry practices of science by designing investigations, conducting iterative trials, predicting, observing, and explaining findings, and critiquing the investigation of others" (p. 364).

In this exemplar formative assessment prototype, the screenshot in Figure 2 displays an interactive simulation designed for students to manipulate and test predictions about the relationship between the number of particles and density of matter. Students can design multiple

experimental trials and explain why they think the experiments can test the provided prediction. For each trial, students will set up variables. After the students finish setting up the variables, a log data table will automatically record their setup variable values along with the values of the total volume, mass, and density of the liquid. Thus, students will be able to review a log of their interactions with the simulation tool and the outcome of their manipulation. The logged information will also be available for students later when they are asked to analyze the data and present evidence-based reasoning about whether the experiments support or refute the prediction. The simulation provides exploration opportunities for students to generate hypotheses about the relationship between mass, volume, and density in a pure material (water) and a mixture (filtered water). Then students can design experiments to test their hypotheses. By observing the particle interactions in the simulation, and analyzing the data patterns from the log data, students can collect evidence to support or reject their hypotheses.

CBAL Question 17 of 54 40:32

Now you will use the simulation to test the prediction that: **The density of pure water and the filtered water can be different even if they have the same volume.**

**Variables**

Amount of water particles (0 to 100)

Amount of salt particles (0 to 80)

RESET

Water Particle (blue dot)

Salt Particle (yellow dot)

**Simulation Log Data**

Trial	Amount of Water Particles	Amount of Salt Particles	Total Mass (g)	Total Volume (mL)	Density (g/mL)
1 X					
2 X					
3 X					
4 X					

How many trials do you plan to run on the simulation?

Please put down the setting of each variable for each trial. Explain your choice.

Figure 2. Screenshot of the formative assessment simulation prototype.



## Scaffolded Formative Assessment

Students benefit from *scaffolds* as they often construct knowledge in supported environments. Vygotsky's (1978) "zone of a proximal development" model posits that the optimal task difficulty at which students should work for purposes of new learning is the one at which they can be successful, given appropriate instructional scaffolds. Process scaffolds can cue important components of inquiry (Duschl et al., 2007). Our tasks will employ such scaffolds to provide an environment for students to work within their zones of proximal development. There are three characteristics of designed scaffolds in our formative assessment prototypes. First, scaffolding provides clear directions to explain what students must do to meet the expectations for a certain activity, thereby, reducing confusion and uncertainty. Second, scaffolding keeps purpose and motivation in the forefront by revealing to students why they are doing the activity. In scenario-based assessment, it is important to keep the *big problem* in focus. Third, scaffolding keeps students on task by providing a pathway and outlining the steps involved. This scaffolding requires the progression of activities to be liberating yet controlling at the same time.

The screenshots in Figures 3 through 5 present an example of how we scaffold students to draw an initial model of ocean water, by providing explicit instruction on the key points of scientific models (Figure 3) and giving an example of a scientific model (Figure 4). Furthermore, as illustrated in Figure 5, we provide clear directions about what the student is supposed to model. In order to activate students' prior knowledge and scaffold their thinking for the culminating performance, we provide prompts, such as what things need to be in the model and what things need not be in the model. Such scaffolds are important, since the epistemology of models receives little attention in normative and consensus views of the nature of science (Gobert & Pallant, 2004; Schwarz & White, 2005), in particular, using models to explain a natural phenomenon and using evidence to revise a model that fails to explain a phenomenon. In our task, we provide multiple opportunities for students to revisit their initial models and revise them after engaging in multiple activities.

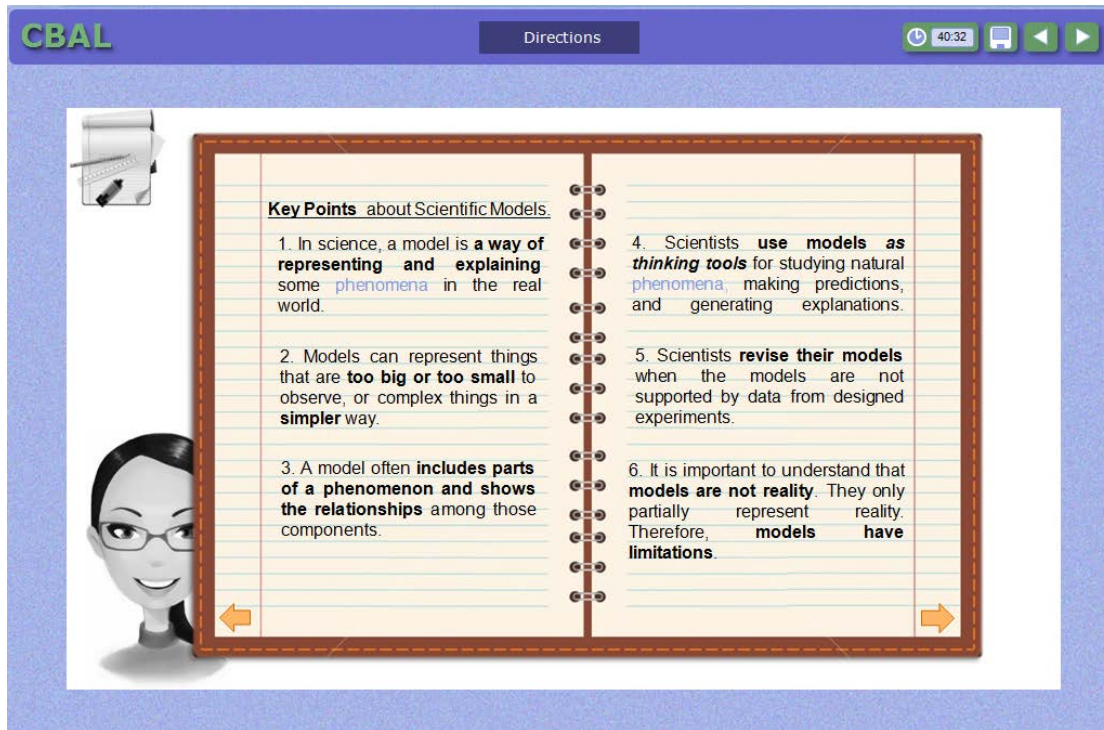


Figure 3. Screenshot of the prototype—key points of modeling.

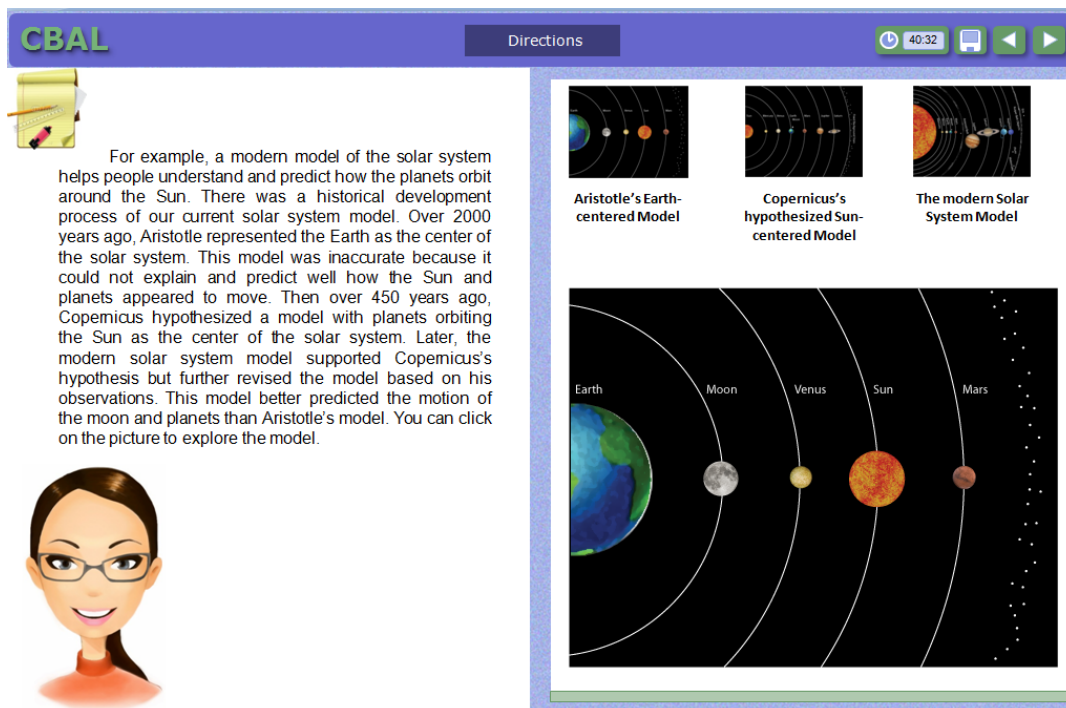
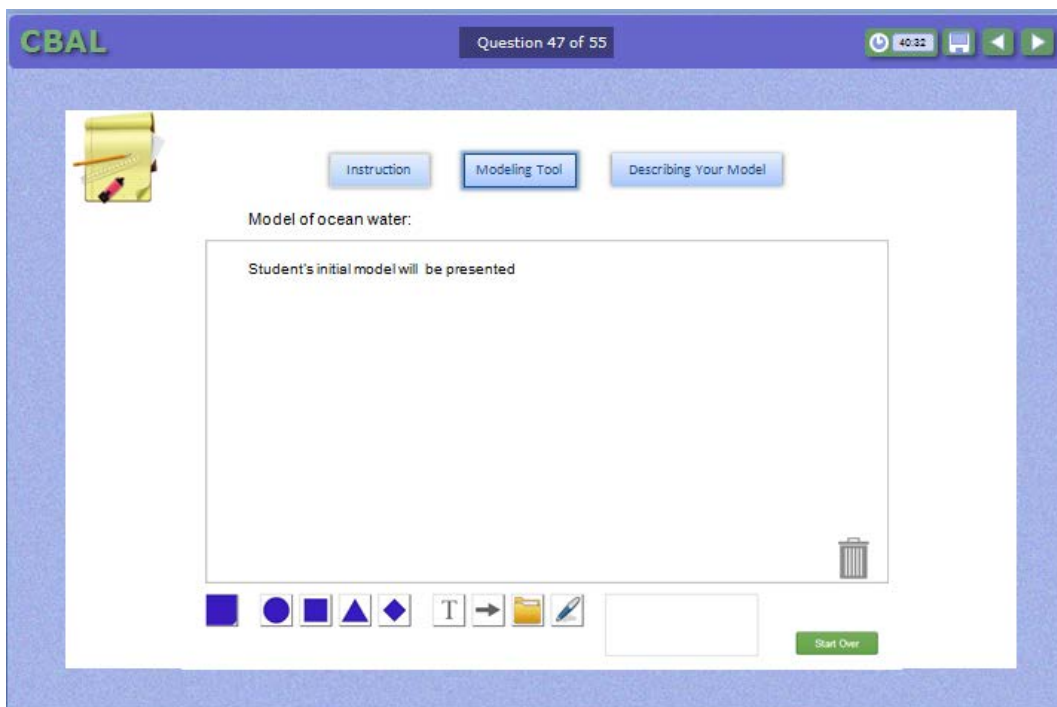


Figure 4. Screenshot of the prototype—an example of modeling.



**Figure 5. Screenshot of the prototype—drawing a model.**

## Conclusions

In this report, we present a middle school science competency model, three of its related learning progressions, and a formative assessment prototype developed under the guidance of the competency model and the learning progression. In this competency model and learning progressions, we attempt to describe how students represent knowledge and develop competence in the subject domain (Pellegrino et al., 2001). The competency model and learning progressions begin with an understanding of the domain knowledge, science practices, and crosscutting concepts promoted by the NGSS (2013). In addition, we included epistemic beliefs and motivation, which are identified by the literature in science education and learning sciences as important influences. The hypothesized LPs allow us to design assessments that can, in principle, provide useful and understandable information to teachers, parents, and policy makers to guide their decision making. To illustrate how our competency model can be used to inform assessment development, we also present a sample formative assessment prototype. Through this example, we introduce several design features of the task that are consistent with our competency model and the research on how to support the teaching of science (such as the use of a rich problem-based scenario, the use of scaffolds, and the use of interactive simulations).

In the immediate future, we will apply our model of cognition to develop a set of formative and summative prototype assessment tasks and develop professional development materials to facilitate the implementation of the prototype assessments. The task development process will be iterative in nature and will involve the use of cognitive labs with students to test and refine the tasks and our model of cognition. Then we will conduct pilot studies to explore the construct validity of the prototype assessments, as well as the validity of the LPs. In addition to traditional psychometric approaches (e.g., multidimensional item-response models) to validation, we will also conduct cognitive psychological analyses, for example, analyzing what students do as they respond to the assessment task and what they say about task demands (Snow & Lohman, 1989).

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