Sequencing and Supporting Complex Scientific Inquiry Practices in Instructional Materials for Middle School Students

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Overview

Current national reform documents (American Association for the Advancement of Science, 1993; National Research Council, 1996) and research literature (Krajcik, Blumenfeld, Marx, & Soloway, 2000; Metz, 2000; White & Frederiksen, 1998) argue for the importance of students understanding and engaging in scientific inquiry practices. Science disciplinary practices specify how knowledge is constructed, evaluated, and communicated. *The National Science Education Standards* describe what a scientifically literate students should be able to do and understand about inquiry, "…including asking questions, planning and conducting investigations, using appropriate tools and techniques to gather data, thinking critically and logically about relationships between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments (p. 105, National Research Council, 1996). Practices specify how students should be able to *use* knowledge in meaningful ways, rather than what they should "know" (Lehrer & Schauble, 2006). For example, the practice of scientific explanation includes applying general scientific principles to make sense of data, such as explaining why a predator population decreases when a competitor expands into its territory. While practice involves the performance of scientific work, it relies also on the underlying epistemological understanding or meta-knowledge that articulates why the practice takes the form that it does. For example, being able to construct scientific explanations requires understanding how everyday explanations differ from scientific explanations in the need to go beyond plausibility by being consistent with empirical evidence (Brewer, Chinn, & Samarapungavan, 1998). Learning these practices is essential for students understanding science as a way of knowing and not just a body of facts. However, little careful planning has taken place regarding how to help learners develop these practices over time (Pellegrino, Chudowsky & Glaser, 2001). Learning these practices, like learning any complex idea does not develop instantaneously or as a result of single exposure. Rather learning such complex practices takes time and numerous carefully scaffolded experiences. In this paper, we discuss the development of the learning progressions for five scientific practices: design of investigations, data analysis and interpretation, explanation and argumentation, modeling, and systems thinking.

Despite their importance, scientific practices are challenging for both students and teachers, and they represent a real shift in the activities and norms of classrooms (Duschl, 1990). Actual science practice and science standards can provide guidance as to the broad parameters of the practice that might be targeted for instruction, but do not describe how to make that practice sensible and tractable for learners. The challenge for researchers and teachers is to help students understand these practices. Designing effective instruction requires developing a *learning progression* for the practice, which outlines its essential elements and specifies how it can be developed through successive learning opportunities (Smith, Wiser, Anderson, & Krajcik, in press). One avenue to support student learning is through curriculum design. *The National Science Education Standards* argue "With an appropriate curriculum and adequate instruction, middle-school students can develop the skills of investigation and the understanding that scientific inquiry is guided by knowledge, observations, ideas, and questions" (NRC, 1996, p. 143). The design of instructional materials should include learning progressions that support students developing deeper understandings of scientific inquiry practices that are part of the learning objectives (D. Kuhn, Black, Keselman & Kaplan, 2000). Learning progression can be defined as a sequence of successively more complex ways of thinking about a practice or about content that develop over time. Learning progressions, however, are not developmentally inevitable. There is no single "correct order." Learning progressions should not be thought of as a lock step fashion of developing the practice. As described in the *Atlas of Scientific Literacy* (AAAS, 2001) learning progression show the "rich fabric of mutually supporting ideas and skills" that students need to develop over time. A learning progression characterizes variations of the practice that are appropriate for learners, and a sequence of successively more complex versions of that practice, building from the understandings and practices learners bring to the classroom to a more sophisticated view. Thus, a learning progression for a scientific practice outlines (a) a model of the target practice appropriate for learners, (b) the starting points of learners' intuitive understandings and practices, (c) a sequence of successively more sophisticated understandings and practices, and (d) instructional supports that help learners develop the practice.

A complexity in specifying a learning progression for a practice is that scientific practices unfold along three mutually supporting dimensions. The core dimension is the reasoning involved in developing, testing, and applying scientific ideas. Learning a practice requires learning new disciplinary concepts (such as scientific models) and reasoning strategies (such as evaluating a candidate model's fit with known phenomena). However, engaging in a practice is more than simply learning the steps of a process — scientific practices have an important social element (e.g., Longino, 1990; Nersessian, 2005). For example, science makes progress by testing ideas in the scientific community. Scientists create models to articulate and communicate their understandings, and refine their models through discussion with peers. If our goals are to engage learners in this kind of reasoning in a meaningful way, creating an audience for one's scientific proposals helps create a reason to communicate understandings and respond to critique (Duschl & Osborne, 2002; Kuhn & Reiser, 2005). Thus, in addition to teaching the process of a practice, an important part of helping motivate and make the practice meaningful is to involve students in a social situation where there is an actual need for the practice (e.g., an audience for candidate models). In general, involving learners in the characteristic social interactions that accomplish scientific reasoning tasks can help motivate and make scientific processes meaningful. A third aspect arises due to the importance of using language as a tool while engaging in scientific practice. Science relies on specialized language to clarify aspects of practice, such as distinguishing critiques of a model on the basis of plausibility, generality, or fit with data. Thus, specialized language specialized language is important in helping students perform the activities of scientific practice (Lemke, 1990; Moje, Collazo, Carrillo, & Marx, 2001).

Often science education has proceeded without considering how ideas build upon each other to build rich and integrated understanding of learning. Although standards documents and curriculum materials often delineate learning goals into the elementary, middle and high school levels, they seldom consider explicit connections between ideas and scientific practices, particularly across consecutive grade levels and disciplines. As a result, students experience science as a series of unconnected ideas. The *Atlas of Scientific Literacy* (AAAS, 2001) is one of the first attempts in our nation to show connections between levels of K – 12 education. The *Atlas* shows progressions both within and across K – 2, 3 – 5, 6 – 8, and 9 – 12 grade levels by showing the connections between benchmarks (*Benchmarks for Scientific Literacy,* (AAAS, 1993) that were only once implied. The *Atlas* depicts these connections through a series of maps structured by topics within a discipline that provides a graphical representation of what students should understand across the grade ranges. However, the Atlas has not focused on learning progressions for scientific practices. Moreover, little thought has been put into the field regarding how one practice builds on and depends on another practice.

In this paper, researchers from five universities that work together to systematically design instructional materials that support students in these complex practices discuss the challenges and their ideas of how to carefully sequence the learning of various scientific practices overtime and also how to link the various practices together. Our working hypothesis is that students will be able apply complex scientific practices at a much higher level if such ideas are carefully scaffold over the middle grade years and if teachers link the various practices together. Developing expertise of challenging ideas like the particulate nature of matter or of challenging scientific practices like modeling and argumentation takes a long time and grows slowly over time. Moreover, we need to consider how the development of one practice supports the development of other practices and how to best link the practices. For example, one important connection between the various practices that we are currently exploring is the use of evidence. Evidence is a critical component of the design of investigations. Researchers, be they professional or students, design investigations in order to obtain evidence that provides information to answer their questions. Obtaining evidence is the central purpose underlying data gathering, organization, and analysis of data. In constructing explanations, students need sufficient and appropriate evidence to support their claims. Finally, in model constructions, students need to construct models that best account for various phenomena. In this case, the phenomena serve as the evidence.

The presenters collaborate together in the *Investigating and Questioning our World through Science and Technology* (IQWST) project using a learning goal driven design model to design 6th through 8th middle school materials that align with national standards, situate learning in project-based investigations (Edelson, 2001; Krajcik et al., 2002), and draw upon design principles from current findings in research on learning, literacy, instruction and assessment (Bransford et al., 2000; Pellegrino et al., 2001). Through this design process, we create middle school curriculum materials that help students develop a deep understanding of key learning goals through engaging in inquiry and completing complex task such as constructing scientific explanations and modeling. One of the biggest challenges we face is designing learning progressions so that experiences in one unit can be used to help build a richer and deeper understanding of the practice in later units and in subsequent years. Another major challenge we face is making connections across units, years of school and among the practices themselves. In this paper, we discuss our development of the learning progressions for five scientific practices: design of investigations, data analysis and interpretation, explanation and argumentation, modeling, and systems thinking. Each participant will describe our current learning progression for that scientific practice, which is based on the research literature as well as our own pilot studies. We will give examples from our curriculum materials that illustrate how we are trying to build these scientific practices over time.

Design and Critique of Investigations

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This paper discusses the learning progression that we have begun to develop focusing on the design of investigations. One of the reasons that we have selected the design of investigations to focus on as a specific practice is that designing investigations can help students learn how to approach and solve problems both in science and in everyday life by teaching them how to ask questions and design unconfounded experiments as appropriate. In order to successfully design investigations, students need to access necessary content, frame questions to design experiments around, develop plans for these investigation, and understand the concept of a "fair test". Research has shown students often have difficulty with these different components of designing experiments, such as the identification of controls (variables to manipulate and measure), as well as the creation of necessary procedures to carry out the investigation (Chen & Klahr, 1999; Toth, Klahr & Chen, 2000). While students have difficulty in designing investigations, given the necessary scaffolds and supports they can be successful. For example, students can ask their own questions, and design and carry-out investigation to find the solution to their questions (Krajcik, et al., 1998; Klahr, 2000; Metz, 2000; White & Frederiksen, 2000). The challenge is to identify ways to successfully students as they develop the necessary skills and understanding to carry out investigations and to make meaning from them in terms of the phenomena that they are exploring, arguing for, representing, or modeling (Lehrer, Schauble & Pertosino, 2001). Embedded within these issues is what does it mean to engage in authentic science and the role of investigations in this process (Lee & Songer, 2003; Chinn & Hmello-Silver, 2002).

The IQWST curriculum materials are a series of sequence units that span 6th -8th grade. In doing so, all of the disciplines of middles school science will be addressed. Because of this breadth, we will need to address what varies across the different domains but also what remains constant. The design of the investigation might look quite different but the purpose of the investigation will be similar- developing and testing an understanding about a scientific principle or phenomena.

What is the design of a scientific investigation practice?

All too often one is presented with the scientific method as the process of a scientific investigation. Science is not the linear process often portrayed in the science classroom by this list. However the basic components that are often found on the scientific method list are important components that need to be considered, just not in the rigid and inflexible manner that they are often presented. Often found on this list are development of questions and the design of the basic procedure. In thinking about these two processes, we have question to frame them as question identification and creation, and the investigation design. In both of these "steps", we are including the process of critiquing and revising as key components to developing an understanding about what it means to design an investigation. In addition, it is important to include throughout this process of design, the connection to the phenomena or principle being investigated as well as the reasoning as to why an investigation is being design and carried-out.

Research has identified that there is a connection between the domain specific knowledge and domain general strategies that students use to develop knowledge in each and that there is an interplay between each as the depth of knowledge is developed. Within the context of the authentic science problem context, we are looking to support the development of each by varying the amount of structure, support, practice, strategic, development of the metaknowledge about the practice of designing investigations in the different domains (Kuhn & Dean, 2005).

Why is the design and critique of investigations important?

Designing investigations can help students learn how to approach and solve problems both in science and in everyday life by teaching them how to ask questions and design unconfounded experiments. The design of investigations- regardless of the type of experimentation being designed (i. e. first hand experimental situations, observational, historical or data mining types of investigations) is a key component of science and if we want students to be able to engage in scientific reasoning, students need to understand what investigations are all about and the role of experimentation in science.

Pedagogical approach

Pulling from the prior IQWST work that has focused on the explanation practice, the IQWST materials will use a similar variety of pedagogical strategies to support the design of investigations practice (Kuhn, Kenyon, & Reiser, 2006; Kuhn, & Reiser, April, 2005; McNeill, & Krajcik, in review; McNeil & Kuhn, this session; McNeill, Lizotte, Krajcik, & Marx, 2006). These strategies fall into four categories: motivate, unpack, clarify, and practice. I believe that building off of the prior IQWST work which emphasized developing a more complete understanding of how to support teachers and students in their use of explanations as a scientific practice is a strength of the work that is presented here. By using a framework (McNeill & Kuhn, this session) that has been developed around one practice for instructional consistency, we will be able to make connections more easily between the practices and allow the students to develop a more complete understanding of the scientific processes.

Motivating scientific investigations. When presented as a concrete task for students to complete, scientific investigation can become the rote “scientific method”, it is important that this not happen as this is will not lead to the type of learning that we are looking for as a result of engaging with the IQWST materials. We must help provide a context that helps motivate the practice from the start in a meaningful manner (Simon, 2001) that can be sustained to the end of the investigation. One way of doing this is to design learning environments that sequence activities that create an authentic need for students to engage in the scientific investigation.

In regards to the structure of activities that focus students on developing the practice of investigation, we have currently created a structure to help motivate design and critique of investigations—the scaffolded inquiry sequence. This sequence is based on of work done by Hug and Krajcik (2002) as part of the LeTUS instructional materials development. Modification to this sequence will occur as part of the IQWST development. The Scaffolded Inquiry Sequence (SIS) is a series of investigations situated within a project-based curriculum that creates a meaningful context for learning. In phase one the teacher models for the students how to ask questions, create a hypothesis linked to the question, develop a procedure that addresses the hypothesis, carry out the investigation, gather data, and undertake data analysis and the drawing of conclusions. Throughout this phase, students participate by asking questions, and critiquing what is going on around them. In second phase, the student led the investigation process, ask and create meaningful questions, design and carry out the investigation, gather data, and make conclusions. The students refer back to the previous investigation for any reminders and supports that they might need. The teacher provides support through questions and prompts to support thoughtfulness and reflection. In addition, the feedback that the teacher provides allows the students to revise and modify their investigation.

Unpacking the design of an investigation

Generating questions

Students need to be able to formulate testable (and potentially) answerable questions that can be linked to underlying scientific principle or phenomena that they are motivated to explore/investigate. It is important to remember that not all questions that students ask will led to fruitful investigations. The research literature suggests that students are able to ask a range of questions but that they often struggle with generating questions that can be investigated in meaningful ways (Chin & Kayalvizhi, 2002; Krajcik, et al., 1998; Metz, 2000; White & Frederiksen, 2000; Hofstein, Navon, Kipis, Mamlok-Naaman, 2005). In order to support students in this process, we need to identify ways to motivate students do this and provide the necessary feedback in order to develop this practice.

Hypothesis and Predictions

With these questions, students then need to be able to create predictions or hypothesis that can be used in the actual design of the investigation. The difference between prediction and hypothesis is one that we are addressing in the IQWST materials. Predictions are more concrete and depict something that will happen based on a reliable scientific theory where as a hypothesis is a tentative statement that proposes a possible explanation to some phenomenon or event. For example, compare the difference between the following two statements: Planarian will grow back to full size after being cut in half vs. if a planarian can regulate its growth, it will grow back to full size after being cut into multiple pieces. In the second statement, a scientific principle is being used to develop the statement- the idea of regulation of body size. In thinking about the design of investigations and the resulting outcomes, the distinction between hypothesis and prediction is one that needs to be addressed.

Actual design of investigations

Students need to be able to formulate scientific procedures that will allow the students to address the question or their hypothesis. In doing so, we want the students to focus on the following questions that we have identified as being areas that students struggle with based on the research literature: what are the variables that need to be addressed, how is the data going to be collected, how will it be analyzed and why the investigation is being carried out at all. Klahr and his colleagues (1999, 2000) have developed the control of variable strategy (CVS) that we will incorporate into the strategies that we use to address this critical component of designing investigations. Work done by Kanari and Millar (2004) has shown that students can carrying out investigations of the relationships between variables that co-varied but not non-covarying variables, this complexity will follow the initial introduction of the need to control variables when carrying out investigations. For instance, Masnick and Klahr (2003) identified that design errors occur in the design stage when some important causal variables not being tested are not controlled, resulting in a confounded experiment. These errors can result from cognitive failures of domain-general knowledge, such as not knowing how to set up an unconfounded experiment, domain-specific knowledge, such as which variables are likely to have an effect. While some of these issues are found only in first hand experiences, others translate into investigations of vicarious phenomena. Because of this, we will want to focus on how to support students as they engage in second hand experiences focused on design of investigations.

Domain specific issues

The research literature has identified distinct domain specific types of investigations that we will need to take into consideration. If students are collecting their own data, they will need to develop a specific type of investigation. This investigation will be designed differently if students access a large data-base or other vicarious types of data. However, issues identified above will still need to be attended to but in a different manner.

Clarifying

As is described in the scaffolded inquiry sequence, teachers and/or the curriculum materials model and critique how to develop testable questions and investigations by providing examples. Students actively participate in critiquing the examples, thereby developing their own expertise in creating the examples. This process leads into the fourth pedagogical strategy, practice.

Practicing investigation

From the research literature and IQWST's own experience in the explanation work, we know that it is important for students to have multiple opportunities to carry out and reflect in meaningful ways about the specific practice being emphasized. We want to allow students to engage in a range of scenarios around designing and carrying out a complete investigation, ideally multiple cycles within a unit. This might range from developing an initial question to carrying out a complete investigation or it might be somewhere in between these two examples. It is also important to consider that the investigation might be one where students collect their own data or it might be a situation where students develop questions around a previously collected data set or vicarious experience. The shift from novice to expert is one that requires multiple opportunities to participate in the specific practice at a range of levels.

Learning Progression for Designing Investigations

The proposed learning progression for designing investigation aims to encourage an in-depth understanding of what it means to "investigate" (the metaknowledge around investigations) as well as the actual practice of (and what it takes to) engaging in investigations. This knowledge will develop over the three middle school years, becoming more and more detailed and complete as students progress through the grades In addition, students will have the opportunity to look across disciplines and begin to understand the similarities and differences of each disciplines approach to investigation, a key issue in carrying out investigations within different disciplines. Students and teachers will emphasize questioning in the sixth grade and how investigations can be developed that address the questions raised. During the seventh grade, students will begin to develop their own investigations that incorporate the questions that they develop that can be linked explicitly to specific scientific principles or phenomena. And in the eighth grade, these ideas will be brought together into full independent investigations that build off of prior investigations (see Table 1 and the examples below).

In the sixth grade, students will be introduced to the idea of questions and designing investigations that can address the specific questions about observable phenomena or discussed scientific principles. Students will be given opportunities to create questions, and/or critique questions using a to-be-identified set of criteria. Connections will be made between the question and the investigations (or data sets that are given to the students) and the scientific principles addressed in the unit. Students will carry out investigations—while there will be some that they design and carry out, the majority will be ones that are designed or highly scaffolded by the teacher. This design of investigations will be scaffolded by teacher and/or text materials as appropriate. Through this scaffolded instruction, it will be possible to address key issues of motivation, question development, control of variables.

In the seventh grade students will continue to develop questions and design investigations that address questions connected to examining/modeling scientific phenomena or principles. Students will be given the opportunity to create questions, critique these and other questions using a set of criteria developed from the 6th grade rubrics (rubrics need to be developed). Connections need to be made by the students between the question and the investigations (or data sets that are given to the students) and the scientific principles addressed in the unit. Students will design and carry out investigations of their own. In designing the investigation, students will need to address:

- Questions and hypothesis: Importance of asking for "why" you think this will happen asking for the "reasoning" component and evidence from prior studies
- Formulate scientific procedures: (based off of the teacher version of 6th grade investigations)
  - Students will design scientific procedures that address the hypothesis
    - Planfulness before and throughout the investigation (Kuhn and Phelps 1982)
  - Students will identify variables to be measured or to held constant.
  - Students will identify what and how data will be collected
- Students need to ask how are you going to analyze it?

In the eighth grade, students will design several related investigations that build on previous results. They will need to address the issues outlined in the seventh grade description but will do this at a greater depth and complexity due to the integrated nature of the investigation. The goal of the 8th grade investigation practice is to integrate the different practices discussed in this session into a more unified, independent investigations. Students will have participated in complete cycles of inquiry in previous units but the 8th grade units will have the greatest independence for the students as they design their final investigation. Throughout the 8th grade, students articulate what model or theory they are investigating and why- this knowledge is the metaknowledge about what an investigation is or how it should have as a goal the test of an idea and to construct an explanation (Zimmerman, 2005).

Table 1: Learning Progression for Design of Investigations*

Instructional Focus	6th Grade	7th Grade	8th Grade
Developing questions/ hypotheses	Development of testable questions from observations	Building off of 6th grade but making explicit connections to prior knowledge and observations Working with differences between predictions and hypotheses	Building off of 7th grade but making explicit connections to and building off of prior results of investigations Use reasoning/theory/claim to consider multiple rival hypotheses and development of investigations to examine the possibilities
Design of Investigations	Design simple investigations that address the importance of CVS Teacher modeling of investigations (control of variables), data record keeping (modeling of note keeping)	Building off of 6th grade, students design investigations that address the importance of CVS as well as covariation of variables/non-covariation of variables Design investigations that result in informative and interpretable results Independent note keeping (scaffolded)	Building off of 7th grade but with increased complexity based content understanding, reasoning More student independence (i.e. less scaffolding) Role of cumulative design and data record keeping
Reason	Students identify a scientific principle or phenomena being studied	Building off of 6th grade with explicit connections between scientific principles, the question and subsequent investigation. Purpose of the investigation is to develop an understanding or testing of a theory (claim or model) Role of experimental error in understanding the investigation	Building off of 7th grade but make explicit connections to the use of reasoning/theory/claim to consider multiple rival hypotheses and development of investigations to examine the possibilities

(*table modeled after the explanation table, this session)

6th grade: What makes a question?

In the sixth grade earth science unit, the focus of the unit is on general weathering concepts (weathering, erosion, and deposition) and as such, key investigations will be focused around these concepts. One example of student investigations that serve to introduce students to developing questions that connect to key concepts, models and investigations is the series of investigations that teacher and students carry out focused on stream tables and the role of water in the formation of landforms. This sequence takes place over multiple lessons. In the first investigation, a teacher demonstration, the teacher introduces stream tables and the conceptual model that a stream table, physical model, represents. The teacher carries out a simple investigation, showing students how to generate questions that can be addressed by manipulating the model and designing investigations that will begin to answer the questions posed. This is in addition to the teacher modeling how to make observations (data collection) that will be used to address the question. The teacher and student engage in a joint critique of the questions and experimental design in order to begin to begin to develop an understanding about this process can evolve with careful revision. Students then engage in a series of activities that address the concepts of erosion and deposition in greater detail, concepts introduced in the previous investigation. With this increased content knowledge, students then ask specific questions about the national parks that they are investigating throughout the unit that they can ask using the stream table. Using these questions, students manipulate the stream table model to begin to investigate how erosion and deposition could have impacted the formation of the particular land form that they are investigating (i.e. Grand Canyon, Rocky Mountain National Park etc).

7th grade: What makes an investigation?

In the seventh grade unit, students design several investigations around living organisms in order to address concepts connected to the circulatory system (investigations focusing on Daphnia) and cell growth and regeneration (investigations focusing on planarian). In both instances, students develop questions after observing the organisms and doing activities that lead up to these ideas on systems and the role of cell division in animal growth. By providing opportunities for observation as well as building on prior activities (where concepts have been introduced), students are given the necessary information to develop questions that can be linked to the learning objectives of the unit. These first opportunities provide knowledge about the content being addressed (or phenomena observed), the actual organism used in the activitiy. Following question generation, students participate in a share and critique of questions by the whole class. After revising the questions, students develop their hypothesis that they are interested in testing. A similar share, critique and revise process is carried out for the hypothesis as was for the development of the questions. Students begin to develop their investigation. In the design of the investigation, students identify variables that they are interested in manipulating. At the same time, students identify variables that they hold constant. Students share and critique their design of investigations, allowing all students in the class to comment on the design. Here students use support questions to help focus the students' attention on key components of the investigation. After students complete the design of the investigation, students plan how they will collect their data, sharing ideas with the rest of the class. Students are then allowed to carry out their investigation and collect their data.

In the planarian investigation, students develop a series of questions that can be connected back to questions about cell division and growth. Students have been introduced to planarians earlier in the unit in a series of simple investigations looking at how organisms respond to stimuli (light and food). In addition to this investigation, students have discussed some of the earlier investigations carried out by scientists describing how planarians can regenerate and the role of this organism in understanding this process. Through these initial investigations, students begin to develop an understanding about the purpose of carrying out these initial investigations as well as the role that their future investigations can have. Students have also examined what cells look like and have learned that organisms can be made up of one to millions of cells, depending on the organism. Using this information, students develop a series of questions about what might impact cell growth. Students can manipulate the size of cut that they make and the rate of regeneration, the use of specific mitotic inhibitors, or different culture conditions (temperature, light, different energy sources among other factors). Students then carry out their investigation and collect their data. In these investigations, students need to decide how to collect reliable and reproducible data. The issue of experimental error is also important in the design and subsequent interpretation of the experiment.

8th grade: Independent inquiry.

In the eighth grade chemistry unit, students will do a range of closed-ended investigations that will examine specific scientific principles. Most of these experiments address ideas relating to photosynthesis: specifically that water and CO_2 are taken up by plants and undergo a chemical reaction, which is facilitated by light, to produce glucose and oxygen. For example, students will grow plants in the presence of light, water, soil, or CO_2 (or in the absence of one of these), minerals and examine plant growth as it varies (or not) in relation to these different variables. Students can develop multiple hypotheses that will address key questions about the role that these different materials play in the growth and development of plants (or not). In addition, students might also control light or CO_2 levels to examine the role that these two factors have in starch production. They may also examine the time at which it takes for a candle to burn in a container with or without a plant. This experiment can address both photosynthesis and respiration concepts. At the end of each closed investigation, students will write down questions about particular ideas or variables that they can test at a later time point. The idea is to provide them with a range of methods, tests, and models that they can then use in their own investigations at the end of the unit.

Implications

As part of the design of investigations in the IQWST sequence of middle school materials, we want to build students understanding and use investigation. We hope that by sequencing across three years in a plan full manner, we can achieve our goals. We anticipate a process of revision ourselves as we continue our development sequence and examination of the proposed learning progressions. We realize that the different practices presented here in this session are all connected. Some of the key connections and overlaps are described below.

Data gathering, organization, and analysis:

In order to participate in the data-gathering phase of inquiry through first hand experiences, one needs to design and carry out an investigation. In designing an investigation, one should already be thinking about what data will be collected and how to organize it best—to answer a posed question, suggested explanation or to test a specific model or idea. Because of these close connections, there is obvious overlap between these practices being developed in all of the IQWST units. However, it is important to remember that data can be given to a student without any design of investigation. Even here, a student should have some idea about how the data was collected (and why the question was asked), making connections to the design of investigation practice possible and crucial.

Modeling

An investigation can be designed to test a specific model. However, the data derived from an investigation can lead to the development of a specific model. If presented with a model, students can begin to develop testable questions that allow them to design investigations to test the model.

Explanation

An explanation can lead to new questions being asked and investigations designed to answer them or it could lead to a different question being asked that further investigations the initial explanation. In doing so, students are engaging in the very nature of science- the issue of tentativeness and the building on prior knowledge is important to consider in developing investigations.

Data Gathering, Organization, and Analysis (DGOA)

David Fortus, Michigan State University and Yael Shwartz, University of Michigan

What is Data Gathering, Organization, and Analysis (DGOA)?

While conducting an investigation is not a linear process, it is convenient, for simplicity's sake, to analyze it as consisting of four discrete steps: a) question identification, b) investigation design, c) data gathering, organization, and analysis (DGOA), and d) explanation construction. This document considers the third of these steps. DGOA overlaps with both investigation design and explanation construction. In investigation design, one considers, amongst others, which data is needed to answer a question and how this data can be obtained. When this data needs to be collected with the aid of instrumentation, the investigator needs to select the appropriate measurement instruments, considering their range, sensitivity, accuracy, repeatability, sampling rate, operating conditions, need for calibration, and price (the list goes on…). We have chosen to deal with these factors under the heading of data gathering, rather than investigation design.

Likewise, when constructing a scientific explanation, one brings evidence to justify a theory that accounts for the phenomenon being investigated. Evidence is data that has been analyzed and subjected to tests that verify its credibility and that it accurately represents certain characteristics of the investigated phenomenon. We have chosen to deal with the process of analyzing data and verifying its credibility under the heading of data analysis.

Data organization is the process of taking measurement results and organizing them in ways that facilitate their analysis, that allow possible patterns to become apparent.
In general, as will become apparent, much of DGOA involves the knowledge students need to have to be able to deal with and minimize experimental errors.

Why is DGOA Important?

Many studies of science-rich workplaces (Aikenhead, 2004; Chin, Munby, Hutchinson, Taylor, & Clark, 2004; Gott, Duggan, & Johnson, 1999; Lottero-Perdue & Brickhouse, 2002) found that most workers, whose professions require an understanding of the practice of science, do not draw on canonical science content in their work; they all draw on what Gott and Duggan (1996) called "concepts of evidence", that help them answering the following question: When are data good enough to be considered as evidence? For example, after reading a thermometer, a nurse may ask the patient if she held the thermometer under her tongue in order to determine if the reading is a reliable measure of the patient's temperature. These *concepts of evidence* are just those ideas and practices that we have titled DGOA.

Duggan and Gott (2002) showed that these *concepts of evidence* were also critical to a non-science public who were involved with a science-related social issue. Tytler, Duggan, and Gott (2001a, p. 817) stated that "Judgments about evidence are often central in interactions between science and the public." This complements other research into the use of scientific knowledge in everyday science-related problem solving and decision making (Irwin, 1995; Kolstoe, 2000; Michael, 1992; Roth & D´esautels, 2004; Tytler, Duggan, & Gott, 2001b; Wynne, 1991).

On the other hand, research also shows that canonical scientific knowledge is usually not directly useable in science-related everyday situations (Cajas, 1998; Furnham, 1992; Layton, 1991; Layton, Jenkins, Macgill, & Davey, 1993; Roth & D´esautels, 2004; Ryder, 2001;

Solomon, 1984; Tytler, Duggan, & Gott, 2001a; Wynne, 1991). It needs to be deconstructed and then reconstructed according to the idiosyncratic demands of the context before it can become knowledge that is useful for practical, everyday purposes (Chin, Munby, Hutchinson, Taylor, & Clark, 2004; Layton, 1991; Tytler, Duggan, & Gott, 2001a).

Both these conclusions point to the need to increase the attention given to concepts of evidence in school science.

How Do People Decide When Data are Good Enough to be Considered as Evidence?

There are several studies (Chin, Munby, Hutchinson, Taylor, & Clark, 2004; Gott, Duggan, & Johnson, 1999; Lottero-Perdue & Brickhouse, 2002) that investigate how professionals in science-based fields use scientific data. For example, Duggan and Gott (2002) investigated how the employees in five science-based industries drew upon and developed their science knowledge.

Aikenhead (2004) found that nurses were concerned mainly with accuracy when considering data validity. Data became evidence for them after considering the credibility of their data in three ways: a) a datum was corroborated by other data; b) trends in data were perceived; and c) there was a consistency between a datum and other symptoms present in a patient.

Most of these studies point to the fact that people in science-based professions tend to accept data if it does not seem to be anomalous to them. If they perceive it as anomalous, they reject it, or re-measure it. These people are not using data to test their theories; they are using the data in conjunction with theories to explain and understand individual cases. Therefore the existence of anomalous data says nothing about the theory, only about the process of obtaining the data.

This is very different from the work of scientists, who typically use data to verify, test, and elaborate on existing theories and models (Kuhn, 1962) . It is also very different from the way data is typically used in schools, where it has been traditionally used to verify the "correctness" of a theory or to support the process of conceptual change. In both cases, the theory is being investigated, not a phenomenon.

Research on Children and DGOA

Very little research has been done on the ability of children to perform and understand various aspects of DGOA. Most of this research has focused on students' understanding of variability in data due to experimental errors. Thus, most of the recommendations that will be made later in this paper regarding the desired sequencing of learning the aspects of DGOA are based on personal intuition. On the flip side, the following short review helps point out gaps in our knowledge, places where new research is needed.

Sodian, Zaitchik, and Carey (1991) demonstrated even first graders, when presented with a choice between a conclusive and an inconclusive experimental test, can make the correct choice, although they cannot yet design such a conclusive test.

Varelas (1997) found that third and fourth graders' expect some variability in measurements, although why they expected this variability was not always clear. They also exhibit a range of opinions regarding the value of repeated measurements, with some believing the practice informative, and others finding it confusing and a bad idea.

Schauble (1996) found that many children (and some adults) have difficulty in distinguishing variation due to errors in measuring the results and variation due to true differences between the conditions. When in doubt, participants tended to fall back on their prior theories. If they expected a variable to have an effect, they interpreted variability as a true effect. If they did not expect a variable to have an effect, they were more likely to interpret the variability as due to error. Thus, their prior beliefs sometimes led them to make interpretation errors in drawing conclusions.

Similarly, Kanari and Millar (2004) found that 10 year old children can develop basic competence in carrying out investigations of the relationships between variables that clearly co-vary. However, they did not have the same skill with non-covarying variables. This is due to the fact that execution error is more likely to mask non-covarying behavior than co-varying behavior. At this age they have some awareness of execution error but do not know how to incorporate this into their investigations.

Lubben and Millar (1996) found that some high school students still have considerable difficulty understanding data variability, at least in situations where they are given the data but have not performed the measurements themselves.

Petrosino, Lehrer, and Schauble (2002) investigated forth grade students understanding of measurement errors and understandings of measurements as representations of a sample of measures. They had participants use instruments with varying levels of precision and focused discussion on the best ways to summarize the data they collected. Students trained in this way performed significantly above the national average on assessments of how to collect, organize, read, represent, and interpret data.

Masnick and Klahr (2003) found that 2^{nd} and 4^{th} grade students could both propose and recognize potential sources of error before they could design unconfounded experiments.

IQWST DGOA Progression

The following table lists the DGOA learning goals that will be incorporated in IQWST and the grade at which they will be introduced. The same learning goals will be incorporated in later grades as well, but with higher levels of complexity. Each learning goal is actually a combination of a practice and the meta-knowledge associated with the practice. For instance, when deciding whether measurement instruments are needed, one needs to consider the limitations and advantages of our senses, and whether quantitative or qualitative data is needed. When selecting how to organize gathered data, one needs to consider that tables highlight individual measurements but may hide patterns; likewise, graphs and maps highlight patterns but may hide individual measurements. For simplicity, the following table lists only the practices associated with each learning goal, not the meta-knowledge.

In general, the DGOA learning progression follows the following pattern: students are first given opportunities to engage in a practice before discussing the finer details about the way the practice is carried out. Students select which measurement instruments to use and use them before learning that the way the instrument is used has implications for the quality of the data it generates. Students learn to construct various types of graphs before focusing on the pros and cons of the different types of graphs. Students learn how to identify anomalous data before inquiring into the possible sources of the data’s anomality. Students first learn to identify data ranges and only then the importance of indicators of central tendency such as means, modes, and medians. All this is done for single data sets before learning that these measures of central tendencies can be used to compare between multiple data sets.

Learning Goal	6th Grade	7th Grade	8th Grade
DATA GATHERING			
Instrumentation Decide whether instruments are needed	x		
Select appropriate instruments	x		
Proper use of instruments		x	
Units Use of appropriate units	x		
Translate units		x	
Sampling Adequate sample	x		
Recording of data Recording data in an orderly manner	x		
Evaluate data	x		
DATA ORGANIZATION			
Ways of organizing data Select ways to organize data		x	
Tables Read & construct tables	x		
Graphs Select appropriate graph type			x
Read & construct graphs	x		
DATA ANALYSIS			
Relationships between variables Identify patterns	x		
Anomalous data Identify anomalous data		x	
Determine possible sources of aberrance			x
Statistical Thinking Identify data ranges	x		
Estimate & calculate means, modes, & medians		x	
Estimate variance			x
Compare two groups of data		x	
Consider source of variance			x
Interpolation Graphically estimate results of hypothetical measurements			x

Examples from Three IQWST Units

6th Grade Chemistry Unit

Mothballs are placed in a sealed container in the teacher's table at the front of the class. The container is opened and students are told to raise their hands when they can definitely smell the mothballs. Those who have watches are told to record how many seconds passed between the opening of the container and their first smell of naphthalene.

The advantage/disadvantage of using a measurement instrument is discussed. This is actually a situation where the students can determine that their senses are sufficient to detect the smell and that no instrumentation (other than time-keepers) is needed. The teacher is encouraged to talk about our nose as a smell detector. The reading includes a discussion of other detectors developed for gases that people cannot smell.

The students determine whether the collected data is quantitative or qualitative (it is both – the identification of a smell is a qualitative measurement, but the elapsed time until the identification is quantitative).

This creates an opportunity to construct a table and graph of the time it takes to detect smell versus distance from the source. Since students on the same row (or even same table) will detect the smell at different times, the meaning of an arithmetical mean will be discussed. Although specific measurements will be different, a trend can be noticed that the further the distance from the container the longer it takes to detect the smell.

This activity supports the following DGOA learning goals:

- Identify situations where instrumentation is or is not needed to supply the data required by the investigation.
- Select the appropriate measurement instruments for an investigation.
- Determine whether collected data is quantitative or qualitative.
- Construct tables of data.
- Calculate means, modes, and medians from tabulated data.
- Construct graphs of data.
- Identify either a direct or an inverse relationship between two variables.

7th Grade Physics Unit

Working in groups, the students investigate whether two different systems appear to conserve energy: a super-ball bouncing on the floor and a ball-bearing rolling in a transparent vinyl tube bent into a vertical U. For the first system the students measure the maximum height attained by a super-ball on consecutive bounces and graph the results. For the second system the students measure the maximum height attained by the ball-bearing at consecutive extremes of its oscillatory motion and graph the results. Students will need to make multiple measurements to obtain enhance the data's reliability. By comparing the two resulting graphs, the students determine which system appears to be "loosing" energy at a faster rate. They identify the mechanisms for energy "loss" for each system.

This activity supports the following DGOA learning goals:

- Proper use of instruments.
- Determining adequate sample.
- Recording and evaluating data in an orderly manner.
- Constructing tables and graphs.
- Identify patterns in data.
- Identify anomalous data.
- Compare between two groups of data.

8th Grade Chemistry Unit

The 8th grade chemistry unit focuses on chemical reactions in living systems, especially photosynthesis, and the flow of matter and energy in ecosystem. One of the activities in the unit has students engaged in an investigating the various factors that influence the growth of plants (such as light, soil, nutrients, water, etc…). The investigations are conducted in small groups with only little scaffolding.

This investigation will support the learning of the following DGOA learning goals:

- Select appropriate instruments.
- Determine sample size and sampling method.
- Record data in an orderly manner.
- Construct tables.
- Determine appropriate type of graph.
- Construct graph.
- Identify data trends.
- Identify relationships between variables.
- Identify anomalous data.
- Determine possible sources of aberrant data.
- Calculate means and medians.
- Compare groups of data.
- Determine whether data variance is a result of measurement errors or indicative of actual change.

Explanation and Argumentation

Katherine L. McNeill, University of Michigan and Leema Kuhn, Northwestern University

Explanation and argumentation are core aspects of the work of scientists and are essential scientific inquiry practices (Driver, Newton, & Osborne, 2000). Moreover, recent research literature (Duschl, 1990; Sandoval & Reiser, 2004) and reform documents (AAAS, 1990; NRC, 1996) argue that students in science classrooms should engage in practices similar to those of scientists, such as constructing evidence based explanations and engaging in scientific argumentation by defending, critiquing and revising their understandings with their peers. Engaging in these complex practices offers multiple possible benefits to students including motivating their engagement in understanding the science (Engle & Conant, 2002), increasing their understanding of the science content (Zohar & Nemet, 2002), and altering their view of science (Bell & Linn, 2000).

Yet explanation and argumentation rarely occur in science classrooms (D. Kuhn, 1993; Newton, Driver & Osborne 1999). Typical classroom practices often inhibit this type of persuasive discourse. That is, in conventional classroom practices, students are rarely in positions to substantively engage with one another's ideas (Lemke, 1990; Hogan & Corey, 2001). Instead, scientific knowledge is often viewed as authoritative and students' role is to memorize the facts disseminated by the teacher and textbook (Songer & Linn, 1991). This type of authoritative discourse can devalue students' personal mean making and the role of persuasive discourse in classroom science (Tabak & Baumgartner, 2004).

When students do engage in scientific explanation and argumentation, they frequently have difficulty justifying their claims both in talk and in writing. For example, when students engage in persuasive discourse their conversation tends to predominately consist of claims with little justification or support for those claims (Jiménez-Aleixandre, Rodríguez & Duschl, 2000). When confronted with data sets, students struggle to select appropriate data to use evidence (McNeill & Krajcik, in press; Sandoval, 2003) or provide sufficient evidence (Sandoval & Millwood, 2005) in their written explanations. Students also have difficulty providing the backing or reasoning for why they chose their evidence (Bell & Linn, 2000; McNeill, Lizotte, Krajcik &Marx, 2006). Consequently, students need support to successfully engage in the practices of argumentation and explanation.

What is a scientific explanation?

We view explanation and argumentation, as distinct yet overlapping scientific inquiry practices. Explanation is the process of making sense of how or why phenomena occur (Nagel, 1961). An argument is a social discourse (written or oral) activity aimed at justifying or defending a position for an audience (van Eemeren, et al., 1996). We combine the goals of both of these practices to help students create "scientific explanations" in which they defend their understandings of how or why phenomena occur, through persuasive discourse. We chose to combine the two practices in order to align more closely with the learning goals of the national science education standards (AAAS, 1993, NRC, 1996).

Moreover, these practices are closely related. We see argumentation as motivating the explanation in that the goal of convincing one's peers creates a need for students to construct robust explanations. In addition these explanations provide a product around which the argumentation can occur. Thus, we see these practices as different sides of the same problem such that supporting one supports the other. We hope that by capitalizing on this synergy we are creating a more usable reform effort that meets the needs of the classroom teachers with whom we work.

Pedagogical approach

In order to support students in constructing scientific explanations, the IQWST materials use a variety of pedagogical strategies. These strategies fall into four categories: motivate, unpack, clarify, and practice.

Motivating scientific explanations. We have found that we must go beyond giving teachers and students opportunities to practice constructing and defending explanations. When presented as a concrete task for students to complete, scientific explanations can become a rote task in which students write paragraphs without considering why they are doing it or the connections between the elements (Kuhn, L. & Resier, 2005). Thus, we must help provide a context that helps motivate the practice as a whole (constructing and defending scientific explanations) and the components therein. We do this by designing activity structures and problem contexts that create an authentic need for students to engage in the scientific explanation. Our current approach focuses on persuasive discourse or debate; having students critique and argue about one another's explanations, trying to convince one another of their respective knowledge claims. For example, we have currently created two activity structures to help motivate explanation:

1. Argument Jigsaw: Pairs of students construct an explanation. Two pairs then combine, compare explanations and converge on a single explanation on which all four students agree. The goal of this activity is for students with disparate ideas to agree upon a single solution, thereby *creating a need* for students to consider each explanation while determining how they fit together.
2. Whole Class Debate: The groups of four present their final explanations. During the presentations, other students are made responsible for asking the groups questions about their explanations and evidence. By placing students in the role of questioner we are *creating a need* for the students to attend to one another's presentations.

These two activities work together in that the second, the Whole Class Debate, provides a forum for the product of the first, the Argument Jigsaw. Thus, during the Argument Jigsaw students are aware that the product of their work will be presented to and questioned by their classmates. In this way, the Whole Class Debate is designed to *create a need* for the product of the Argument Jigsaw (Kuhn, L., Kenyon & Reiser, 2006). These activity structures and other aspects of the curriculum design are developed to create a motivation for students to construct scientific explanations, using the provided instructional framework.

Unpacking explanation. Beyond motivating this complex practice, we must simplify it and make it more accessible to students. To do this, we developed an instructional framework for scientific explanation (L. Kuhn & Reiser, 2005; McNeill, et al., 2006). This instructional framework builds off of Toulmin's (1958) model of argumentation, containing three components: claim, evidence, and reasoning. The *claim* is a statement or conclusion that answers the original problem. *Evidence* is data that supports the claim. The evidence needs to be both appropriate and sufficient for the claim. The *reasoning* is a justification that shows why the data counts as evidence to support the claim, often students have to back up the link between the evidence and claim by using the appropriate scientific principle. This simplification of Toulmin's model is the result of balancing the design goals of introducing students to the complex practice of constructing and defending claims and creating a pedagogical tool that is both useful and flexible enough to cover a range of scientific disciplines. It is important to note that while we break explanations into these three components for students, our ultimate goal is to help students to create a cohesive explanation in which their answers to all three questions are linked together into a single response.

We have incorporated this instructional framework into our curriculum materials and encourage teachers to use it in their own instructional practices. Beyond identifying these components for the students and teachers, we work to motivate the components by creating activities and problems in which students see the relevance and importance of each component. We then introduce the components to the students and discuss what they mean and why they are important. During the IQWST units, we provide written curricular scaffolds to help students develop an understanding of the components (McNeill et al., 2006) and teachers use the framework to help clarify and provide feedback on students' explanations (McNeill & Krajcik, in review).

Clarifying explanation. In order to clarify for students how the general framework applies to different contexts, we both model the use of the practice and provide students with feedback on their own work. Both the curriculum materials and the teacher model explanations by providing examples and critiquing the strengths and weaknesses of those examples. For example, a teacher might project a written explanation on an overhead and discuss with the class the strengths and weaknesses of the example explanation. Furthermore, we encourage teachers to provide students with formative feedback on their explanations and provide specific suggestions for improvement. In addition, we support teachers as they assess and respond to their students' written explanations by providing rubrics. These rubrics include the 3 components of an explanation – claim evidence and reasoning – as well as specific details about how these components should be filled in the specific problem context.

Practicing explanation. Finally, we feel it is important for students to have multiple opportunities to practice constructing explanations. In order to develop proficiency, students need to practice this learning goal across units and time. Furthermore, while we view scientific explanation as an important learning goal across all of the different discipline areas in IQWST (i.e. earth science, biology, chemistry, and physics), we also acknowledge that each domain has a different set of criteria for defining "good" evidence and reasoning. Consequently, it is important for students to engage in this practice across multiple domains such that they have an opportunity to develop more flexible and usable knowledge around this scientific inquiry practice.

Learning Progression for Constructing and Defending Scientific Explanations

One goal of the IQWST middle school curriculum is to help students develop increasing expertise with constructing, defending and evaluating scientific explanations, over the three years. We are developing a 3-year learning progression, or instructional sequence, through which students will work as they develop their increasing expertise.

This learning progression for scientific explanation focuses on different aspects of the practice at different points in time, such that each year has a specific focus. By giving each year a specific focus, we are limiting the amount of new information to which students are introduced, at any one point in time. Furthermore, since each year of instruction includes units in all four domains (e.g. earth science, biology, chemistry, and physics) this also allows students to see how that focus plays out in different content areas and contexts.

This learning progression is designed around the instructional framework of claim, evidence, and reasoning. For the first two years students will focus on understanding the complexity and necessity of individual elements (e.g. they will do evidence in the 6^{th} grade and reasoning in the 7^{th}). Each grade level includes any complexity introduced in the previous year, but also includes added complexity for each component. The table below provides a summary of the different focuses in 6^{th}, 7^{th}, and 8^{th} grade. We then go on to describe each grade focus in more detail and provide a concrete example from the current developmental work that is going on in the IQWST units.

Table 1: Learning Progression for Scientific Explanation

Grade	**6^{th} Grade**	**7^{th} Grade**	**8^{th} Grade**
Instructional Focus	Data and Evidence	Reasoning	Complex Problems
Claim	Simple claims, gradually moving to more complex claims requiring more than one piece of supportive evidence	May have multiple steps, each of which needs support	Multiple claims – data sets may support multiple claims and need to determine the claim that best fits the data
Evidence	Differentiate between opinion, observation, inference, and evidence Sufficient and appropriate evidence Variation in data and experimental error Multiple interpretations of data	Same as 6^{th} grade with increased complexity based on reasoning	Use evidence to consider counter explanations and rebuttals
Reasoning	A scientific principle	Importance of scientific principles to justify why data counts as evidence to support a claim	Use multiple scientific principles Use reasoning to consider counter explanations and rebuttals

6^{th} grade: Data and evidence. During 6^{th} grade, we introduce scientific explanations and the instructional framework of claim, evidence, and reasoning. Although we introduce students to all three components, our instructional focus is on helping students develop an understanding of data and evidence. We want to help students understand the difference between data and evidence and develop a concept of "good" evidence to support a claim. In other words, that data becomes evidence when it is used to answer a specific problem or support a particular claim. There are multiple characteristics of data that we want students to consider when they determine whether it can be used as evidence and the quality of that evidence, including differentiating between opinion, observation, inference and evidence, considering both the appropriateness and sufficiency of that data and evaluating the variation in data in terms of patterns, natural variation and experimental error.

For example, the 6th grade earth science unit, *How does water shape our world?*, focuses on different processes that shape the earth' surface such as weathering, erosion, and deposition (Rivet, Ingber, Finn, Rossi, Lee & Jona, 2006). Students conduct investigations and then write scientific explanations to answer the question: How has water shaped landforms in different national parks (e.g. the Grand Canyon, Isle Royale, the Badlands, etc.)? Students use a variety of data sources to answer this question including photographs, maps with surface water, and descriptions of the national parks. Currently, the unit is being piloted so we do not have actual examples from students. Our goal is to help 6th grade student write scientific explanations like the following example that answers the question: How has water shaped the Grand Canyon? The italics in the example highlight the different data that is being used as evidence.

> The Grand Canyon was shaped by water that weathered and eroded away the rocks. Weathering is when earth materials are broken down into small bits of sediment. Erosion is when sediment is moved on the earth's surface. Water moving can cause weathering and erosion. *Both the map and photographs show that the Colorado River is at the bottom of the Grand Canyon. The photograph during the hard rain shows that the water is moving fast and that the water is brown. The photographs during the rain also show brown water running down the walls of the canyon. The description of the Grand Canyon said that the soil is very hard and there are few plants to hold it in place.* That is why I think the brown water means that the rain and river are breaking down the rocks in the Grand Canyon and washing them away. So water made the Grand Canyon.

One particular focus in this unit is on helping students differentiate between observation and inference. For example, the above hypothetical example provides specific observations from a map, photographs, and a description of the Grand Canyon, to support the inference in the last sentence about the brown water. We think that this type of distinction between observation and inference will be difficult for students. We expect that some students will not provide the specific observations, but rather they will jump to the inference. Consequently, in the 6th grade we focus on helping students understand the importance of including actual observations as evidence in support of their inferences.

7th grade: Reasoning. During the 7th grade, we extend the 6th grade understanding of explanations by focusing on the characteristics and importance of reasoning. This begins by helping the students experience the necessity of scientific principles and theories, as they select data to be evidence to support a claim. The curriculum materials explicitly focus on how a student might select one piece of data over another because of scientific principles and how the principle can show why their data counts as evidence to support their claim. We also introduce the notion that it is important to explicitly discuss that scientific principle in your scientific explanation, because you cannot assume that your audience has the same assumptions or understandings.

For example, one of the 7th grade IQWST units, *How Can I Make New Stuff from Old Stuff?* (McNeill et al., 2004), focuses on three key chemistry concepts: substances and properties, chemical reactions and conservation of mass. In one of the lessons, students investigate whether a chemical reaction occurs between vinegar and a copper penny. Before students begin the investigation, they are asked, "What data will you need to determine whether a chemical reaction occurred?" This question prompts them to consider the scientific principle they have already learned around chemical reactions – that when a chemical reaction is when two or more substances interact to form new substances, which have different properties (e.g. melting point, density, solubility, color and hardness). This frames students' investigation and data analysis, and they also return to this idea at the end of the lesson when they construct their scientific explanations.

At the end of the investigation students write a scientific explanation about whether a chemical reaction occurred. Below is an example from one student from the 2004-2005 school year that illustrates a student using scientific principles in their reasoning to show why their data counts as evidence for their scientific explanation. The example has the student's original spelling, grammar and punctuation, but we added the italics to highlight the student's reasoning.

> There was a chemical reaction when we combined the copper penny and vinegar. The properties color, hardness, solubility, density, and melting point. The penny is a chocolate copper and the substance on the penny is a dark aqua green. The hardness of the penny is hard (not breakable) and the substance on the penny is powdery. The penny is not soluble and the substance on the penny is. The density of a penny is 8.96 g/cm^3 and the density of the substance is 1.88 g/cm^3. The melting point of the penny is 1084°C and the substance on it is 115°C. *Properties being different means a new substance was formed means a chemical reaction happened. Because a way to tell if a chemical reaction is to see if the properties changed, a new substance has to be formed, so properties have to be different.* Therefor a chemical reaction happened when a copper penny and vinager.

Often students tacitly use their understandings of the science principles in their explanations and do not clearly articulate them for their audience. They may think of their audience as their teacher and assume that he or she already knows what a chemical reaction and knows why the student chose to use some data as evidence, such as density and melting point in this example, but not other data such as mass or volume. During the 7th grade in IQWST, we specifically focus on helping students articulate these science principles in their writing and understand why it is important to clearly specify that link between their claim and evidence.

8th grade: Complex problems. In the 8th grade, the students engage in more complex investigations that require them to make sense of large, often conflicting, data sets, thus, their explanations become increasingly complex. During this year, the curriculum materials have students work with complex data, for which there is no clear claim, thereby requiring a more sophisticated understanding of the science, data analysis and investigative processes. This creates opportunities for a greater focus on alternative and competing explanations and rebuttals. The classroom activities focus on supporting students as they learn to engage in this persuasive discourse and debate the strength of counter explanations. This focus supports the idea that science is not a static set of facts, but rather explanations about phenomena change over time as scientists gather new evidence, refine scientific principles and convince their peers of their revised knowledge claims.

One example of this type of complex problem occurs in the 8th grade biology unit that is currently being developed. This unit focuses on key biology ideas related to natural selection. In the culminating investigation, students analyze a database of information about the Galapagos finches from the mid 1970's. In 1976 most of the Galapagos Finches died, but a few survived. Students are trying to explain why so many of the birds died and why some were able to survive. Answering this question requires that students combine multiple types of evidence (both qualitative and quantitative), which have the potential of supporting multiple claims. Because of the complexity of the data set, students often do not agree on what claim best fits the data, which provides opportunities for argument including consideration of counter explanations and rebuttals. This argumentation then motivates students to return to the database and gather more evidence, supporting their various explanations as to what happened to the finches.

The transcript below is from one group of students who engaged in this investigation during the 2004-2005 school year. This discussion illustrates the type of persuasive discourse we hope to encourage both in talk and writing during the IQWST units.

> Janelle: What I notice is that your claim and our claim is opposite. Because we said it is from the drought and you said it is from harsh rain. And our evidence is that we actually have measurements that says the rainfall decreased.
>
> Toby: Yeah. [nodding his head]
>
> Janelle: But, do you actually have numbers that says the rainfall increased? Because you can't say it increased without numbers.
>
> Toby: Yeah.
>
> Janelle: Ok, let's see it.
>
> Toby: So, the rainfall in 1973 seemed pretty devastating to kill all the finches in the wet season [voice is louder as if presenting].
>
> Janelle: But here is the thing, the rainfall is pretty balanced.
>
> Toby: No, I mean it is not going to keep going up, because in 1979, none of the finches really died in the wet season.
>
> Janelle: I don't think the rainfall kills the plants. I don't think it drowns them at all.
>
> *Conversation continues with students debating their evidence and inferences.*

In this conversation, we see Janelle realizing that their claims are opposite. This is the first step to engaging in persuasive discourse – the students realize they do not agree. She then highlights evidence as the way in which they can decide between their competing claims. Given the challenges mentioned at the beginning of this paper (e.g. that students have a difficult time working with evidence when explaining phenomenon), this is an exciting move. Finally, we see the students engage in interpreting their data, figuring out why their claims are different and which more accurately represents the data. This illustrates how students can engage in persuasive discourse where they consider different claims and debate the relative merit of those claims.

Concluding Comments

Through all three years, students will be working with all three components and will be engaging in argumentative discourse around their explanations using their increasingly complex understandings of how to evaluate explanations to ground their discussions and decisions. By the end of 8th grade, we hope to start problematizing the framework and discussing with students the limitations of thinking about scientific explanations as consisting of three components. Bringing in the idea of rebuttals and counter explanations introduces an added complexity that goes beyond the claim, evidence, and reasoning framework. By initially simplifying this scientific inquiry practice and adding complexity over time using a structured, coordinated and thought out instructional sequence, we hope to help students' develop a flexible expertise around scientific explanations.

Scientific Modeling

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Introduction

We focus our work on the practice of scientific modeling because of its centrality in both science and science learning. Views of science have shifted from a focus on hypothesis testing and experimentation to an understanding of science as building and refining explanatory models (Lehrer & Schauble, in press; Stewart, Cartier, & Passmore, 2005). Furthermore, science instruction focused around modeling can help learners develop deep understanding of subject matter and the nature of science (Lehrer & Schauble, 2000; Schwarz & White, 2005). Despite its importance, students typically do not develop an understanding of modeling (Carey & Smith, 1993), and many teachers lack strategies for supporting their students in the practice (Justi & Gilbert, 2002).

It is the goal our work within the IQWST, a project-based curriculum development project spanning 6th, 7th and 8th grade, to support the development of scientific modeling within curriculum materials. As a result, this paper sets out to define and outline learning goals and learning progressions related to the practice and underlying conceptual understanding of modeling within the context of the IQWST curriculum materials. This paper also provides examples IQWST units to illustrate these modeling learning goals and progressions.

Definition of models and modeling within context of inquiry and other IQWST practices

We define a scientific model as a simplified set of rules, representations and relationships that embody portions of scientific theories and principles and that allow someone to generate explanations and predictions for natural phenomena. A scientific model may be a physical object, an equation, a graph, a drawing, a computer program, a paragraph, or even a mental image; however, it must embody scientific theory and allow someone to make explanations or predictions. A representation by itself is not considered a scientific model if it does not embody scientific theory and does not explain or help make predictions about phenomena. For a good example of a scientific model consider the Bohr model of the atom, which specified that electrons could only be in certain orbits around the nucleus. This model defines relationships between subatomic particles such as electrons and protons, and can be represented by using a simplified representation were electrons are shown as tiny dots moving in certain orbits about a larger central atomic nucleus that contains protons. This model also allows one to make specific predictions about the interactions between different atoms and also allowed scientists to explain a number of other phenomena such as the specific emission spectrum of certain elements, which corresponded to discrete jumps between the allowed orbits.

Models can be further broadly classified into two types: internal models and expressed models. Internal models refer to the individual's internal representation of the explanatory mechanism and/or predictive patterns and laws that underlie particular natural phenomena (see figure 1). An example of such a model include one's mental conception of matter as consisting of moving particles with empty space in between those particles. This model can explain a range of phenomena involving matter, such as phase change and diffusion of different substances, and can be used to make predictions about the behavior of matter. Expressed models can be thought of as the external representations of an internal model. For example, to explain how phase change occurs for a particular substance one could draw or build an external representation of matter using ball-and-stick diagrams of atoms and molecule or develop animations of matter using moving dots to represent particles in motion. A drawing or physical object that depicts the Bohr atomic model would be included in this category of expressed models.

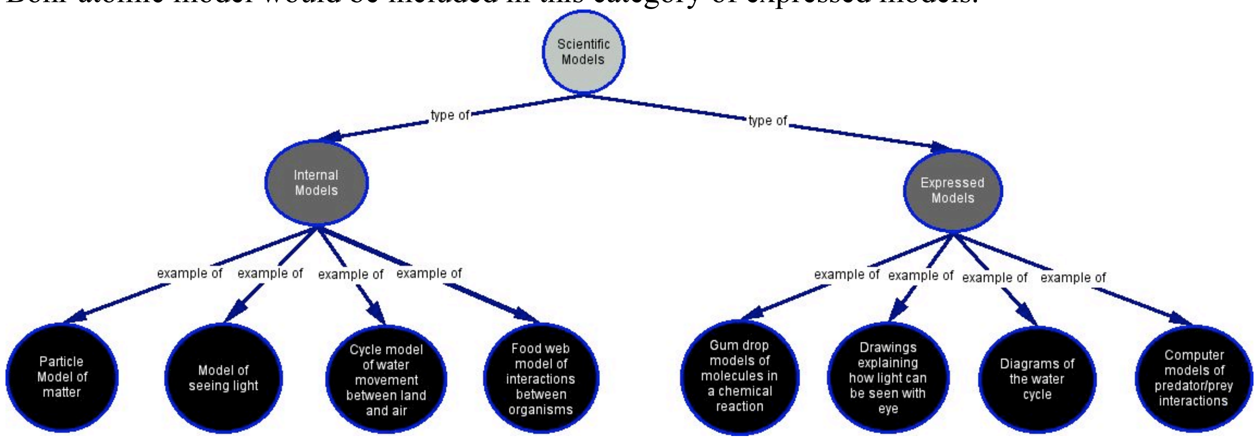

Figure 1: Diagram representing the broad classification of models into internal and external models and examples of models in each category. The examples of models in the figure are found in various IQWST units.

We also define the practice of scientific modeling as consisting of several core practices: *constructing, using, evaluating, and revising models*. For example, constructing a model is often accompanied by using the model to explain natural phenomena and inform the design of investigations to test the model's predictions. This leads to evaluating and revising models in light of findings (see figure 2). An example of this process is the construction of the Bohr atomic model. An earlier researcher, Ernest Rutherford, proposed the model of the atom in which all the electrons of an atom simply just orbited the atom in a dense cloud (Holton and Brush, 2004; Ezhela et al., 1996), however, other scientists noticed there were inconsistencies between this model and the reality. For example, a consequence of this model would be that electrons would quickly spin away from the nucleus which is inconsistent with the longevity of many atoms. Bohr revised the model to suggest that electrons orbited the nucleus in discrete shells with specific energy levels (Holton and Brush, 2004; Ezhela et al., 1996). This had the advantage of explaining why atoms could be stable and also other atomic phenomena such as the distinct photo emission spectra of certain elements. Others such as Frank and Hertz conducted investigations that then tested Bohr's proposed orbital model that atoms have electrons at discrete energy levels by measuring the amount of energy that atoms could absorb and found that they did so in discrete amounts (Ezhela et al., 1996). This experiment confirmed Bohr's model. Additional experimental and theoretical work suggested further revisions to Bohr's model until the model became the modern quantum mechanics model of the atom.

We recognize that modeling is often connected with other aspects of scientific inquiry, such as constructing explanations, designing investigations, and interpreting or generating data**.** For example, models can be used to guide investigations, to interpret data, to construct explanations or to test other models (see figure 2). This interconnected nature of the different scientific practices is also evident in the example of the evolution of the Bohr model of the atom presented above. What Bohr proposed prompted others to conduct specific experiments that could both test the model and explain additional natural phenomena. These scientists then constructed explanations based on this empirical and theoretical work.

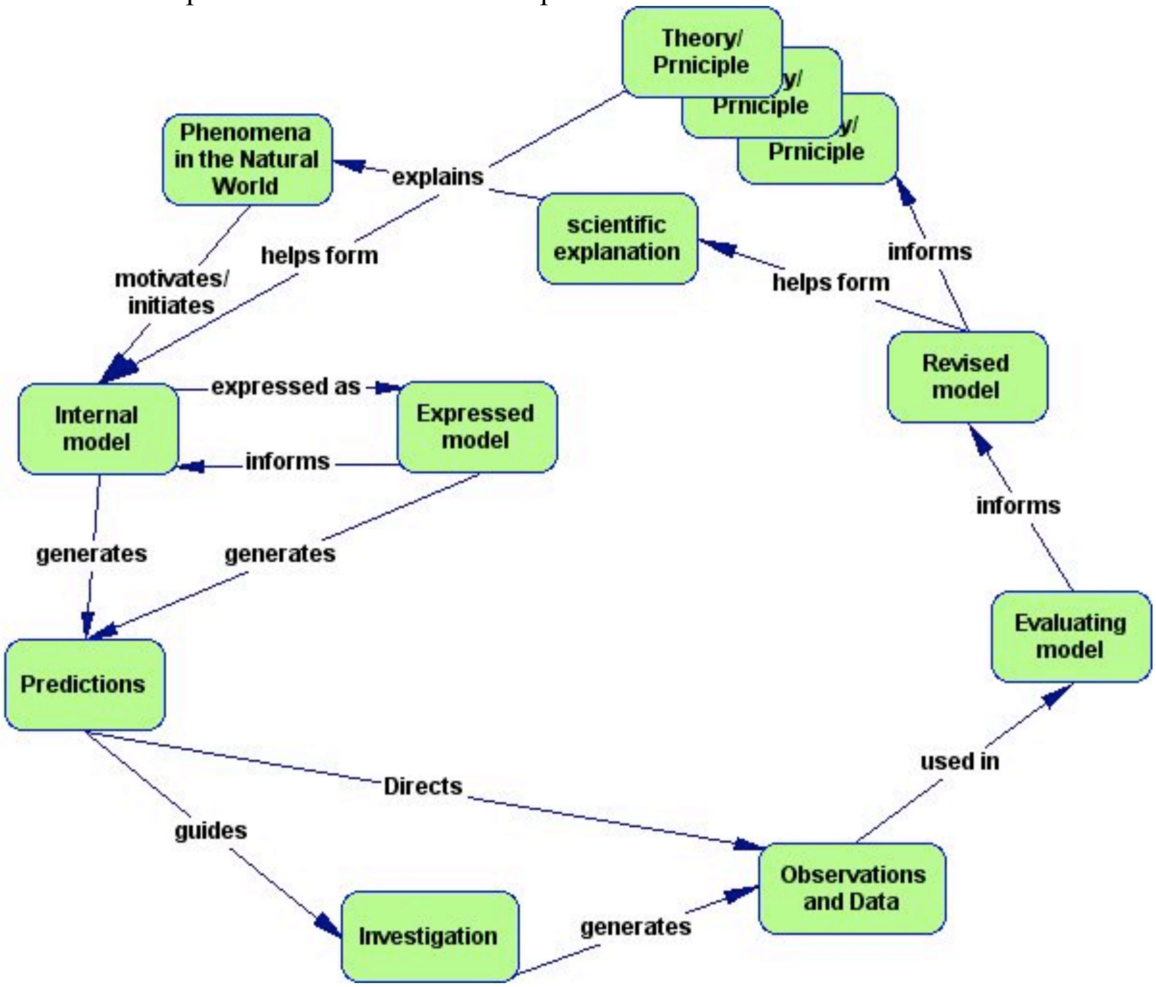

Figure 2: Representation of the different practices of modeling (construction, evaluation, revision, and use) and how these practices relate to other practices such as conducting investigations, collecting data, and constructing explanations, as well other constructs of science such as phenomena and theories. We also note while there is essentially one progression represented in this diagram, one could start at or move to a number of different places in this modeling cycle and that arrow heads could go in both directions. Thus we acknowledge the use of models in the process of scientific inquiry could be more complicated than what is presented here, but the point here is that models are not a separate aspect of inquiry in science.

Learning Goals for Modeling

Learning goals for students around modeling help us to design instructional supports, formative and summative assessments, and clarify expected learning progressions and thus are critical to curriculum design and study. In this section we outline the learning goals for understandings and abilities around modeling. The framework we used for designing learning goals for modeling builds on our prior work involving learners in modeling tasks embedded within project-based inquiry (Krajcik & Reiser, 2006; Zhang, Krajcik, & Liu, in press), studies of instructional supports for the knowledge that underlies modeling (Schwarz & White, 2005), and on theoretical analyses of models and the nature of science (AAAS, 2001). We also draw on analyses of students' learning of modeling in the literature (e.g., Grosslight et al., 1991; Treagust, Chittleborough, & Mamiala, 2002).

A core aspect of this framework is the necessity of identifying two related learning goals for modeling — (1) the practice itself, and (2) the understanding of modeling that underlies the practice, termed *metamodeling knowledge* (Schwarz & White, 2005) (see figure 3). Involving learners in the practice requires that they understand the rationale for norms that govern the practice (e.g., models need to be evaluated against empirical evidence) to motivate the practice and make learners' engagement meaningful, rather than simply going through a rote sequence of steps. For example, constructing models is potentially meaningless unless it is understood that the purpose of constructing the models is to be able to predict and explain a set of phenomena (Schwarz & White, 2005; Snir, Smith, & Raz, 2003). In the sections that follow, we first outline the aspects of the practice itself, and next describe the elements of metamodeling knowledge necessary for meaningful engagement with the practice. We then describe a learning progression that characterizes different degrees of sophistication, organized into a trajectory of learning through the middle school grades.

Modeling Practice

As previously mentioned, scientific modeling includes multiple practices that work together, namely constructing, using, evaluating, and revising models to explain and predict phenomena. We use the term phenomena to stand for objects, events, and processes that are being modeled. Thus, these four practices — *constructing*, *using*, *evaluating*, and *revising models* — comprise the progress variables for the modeling practice construct. The following is an articulation of these learning goals including examples from our planned materials development.

Constructing models: Students will construct models consistent with prior evidence and theories to explain or predict phenomena. For example, middle school students will construct a physical model of how light propagates and interacts with matter to describe how humans see an object. Similarly, elementary students will construct a diagram to represent how water's changes of state are related to one another in a solar still in order to understand the earth's water cycle.

Using models: Students will use models to explain or predict phenomena. For example, middle school students will use a particle model of matter to explain why gasses expand and how new substances can be formed from substances with very different properties.

Evaluating models: Students will compare and evaluate the ability of different models to accurately represent and account for patterns in phenomena, and to predict new phenomena. They will evaluate how well the models meet their intended purpose. For example, middle school students will compare multiple models of light propagation and decide which features are most useful in accurately representing and accounting for patterns in light phenomena.

Revising models: Students will revise models to increase their explanatory and predictive power (e.g., taking into account additional evidence or aspects of a phenomenon). For example, middle school students will revise their models of the particulate nature of matter as they learn how matter can be rearranged in chemical reactions.

Our pedagogical approach situates students' engagement with scientific practices in meaningful problems. Hence students' experience with modeling will be embedded within the broader context of investigating, understanding, and explaining phenomena (Lehrer & Schauble, 2000; Schwarz & White, 2005). Scientific modeling will play a variety of roles in students' investigations. These include creating and using models to understand and apply scientific ideas; to illustrate and defend ideas; and to evaluate theoretical interpretations of data. Furthermore, students' experience with modeling practice will involve the aspects of practice identified earlier — scientific reasoning, embedded in social interaction that creates a need for the practice, using scientific discourse. Thus students will be involved not only in constructing models and "turning them in" to teachers, but will use models to communicate with and to persuade their peers.

Meta-modeling Knowledge

To meaningfully engage in the practice requires developing the conceptual or epistemological knowledge that underlies the practice. Such *metamodeling knowledge* includes understanding the purpose of scientific models, their nature, and criteria for evaluating them (Schwarz & White, 2005). As articulated earlier, we focus on how the underlying knowledge can help guide the practice. Thus we identify epistemological understandings as learning goals that can help students plan and evaluate their investigations (Kenyon & Reiser, 2005; McNeill, Lizotte, Krajcik, & Marx, 2006; Sandoval, 2005). Knowing the forms and purposes of models and criteria for evaluating them can help guide learners in more successful and reflective use of models in scientific reasoning (Schwarz & White, 2005; Snir et al., 2003). For example, knowing that models can be used to help think about and answer a scientific problem can help someone use that model in their own reasoning (Smith, Snir, & Raz, 2002). Knowing that models are not direct copies of object can help learners understand that they should not interpret all aspects of a model literally in mapping the model to the real phenomenon (e.g. understanding that the scale size between planets is inaccurate in most canonical solar system models) (Schwarz, 2002).
We represent metamodeling knowledge in four aspects: knowledge about the *purpose of models*, the *nature of models*, the *evaluation of models*, and the *revision of models* (see figure 3). Although these aspects have some overlap, they tease apart four critical aspects of metamodeling knowledge that guide the practice.

Purpose of models: Students should know that scientists construct models to explain or predict natural phenomena. Models are helpful in thinking about processes that are difficult or dangerous to observe or too abstract to easily understand. Students should also know that constructing and using models can help clarify and advance scientific understanding.

Nature of models: This learning goal has three aspects. First, students should know that a model is a simplified representation of a phenomenon in the real world, and that different models may represent the same phenomenon. Second, students should know a range of types of models, including physical (e.g., a scale model of an airplane in a wind tunnel, used to investigate wing shapes); conceptual (e.g., molecules of a gas are analogous to tiny elastic balls bouncing off one another); and mathematical/computational (e.g., interacting predator and prey species in a computer simulation). Third, students should know that models are not exact replicas of objects, events, or processes, and as such have characteristics not shared with what is represented.

Evaluation criteria for models: Students should know that models are based on previous evidence and theories. Models must be evaluated based on how consistent they are with evidence about relevant phenomena, and how consistent they are with other models and theories.

Revision of models: Students should know that models can be revised if they fail to explain or predict phenomena in the world accurately and consistently**.**

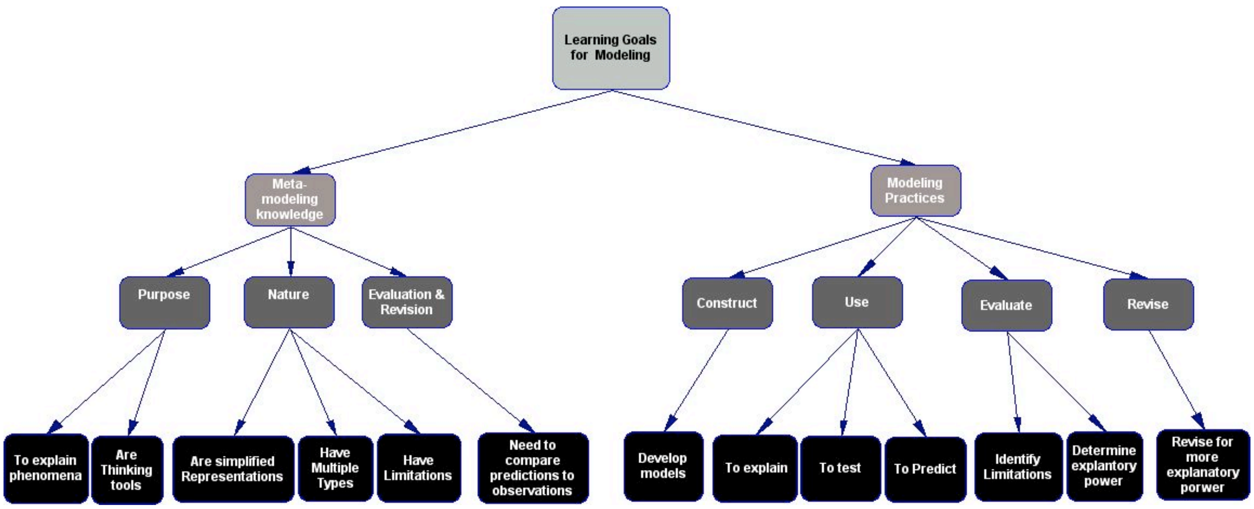

Figure 3: Representation of the different types of modeling knowledge of that will be supported in the IQWST instructional materials.

Learning Progressions

Prior research indicates that middle school students can evaluate and revise models (Schwarz & White, 2005; Stratford et al., 1998). Our learning progression works backward from these targets, to identify progressions of understanding and practices that we argue are feasible given studies of elementary students with instruction focused on epistemological understandings and scientific practice (e.g., Lehrer & Schauble, 2004; Smith et al., 2000).

Based on the prior work, we plan to engage middle school students in the core modeling practices of constructing, using, evaluating, and revising models. What changes within the learning progression as we move from across years are various kinds of complexity: (1) increasingly complex scientific content in the models; (2) increasing complexity of the particular example of the practice, such as moving from using models to explain familiar phenomena (6th grade) to using models to make predictions about unfamiliar phenomena (7th grade); (3) decreasing teacher and instructional materials scaffolding, such as working with clearly indicated evaluation criteria earlier in the sequence, to being responsible for evaluating models and using those criteria by 7th grade. This progression represents only the starting point of the proposed project; we will evaluate it in empirical work and refine it based on our studies. By eighth grade we also hope that students will not only be able to participate in these modeling practice but also use models in conjunction with the other scientific practices addressed in IQWST, such as constructing explanations, and conducting investigations.

In this learning progression we are hope to move students from naïve understandings of models where models are seen as scaled replicas of the target that do not change unless the reality changes to more expert understanding where models can be abstract and do not have to look like the real thing, and be revised based on knew knowledge acquired or evaluations of model (Grosslight et al, 1991). We also want learners to move from simple notions of just playing with models or creating models that imitate objects to creating and using models to think through ideas, reason and explain with ideas, and persuade others of ideas

	6th grade	7th grade	8th grade
Modeling Practices			
Construct	Students construct models that are consistent with sets of familiar phenomena.	Same as 6th grade and in wider range of contexts.	Same as in 7th grade and in still wider range of contexts.
Use	Students use models to explain familiar phenomena	Same as in 6th grade and in wider range of contexts and also to predict new phenomena.	Use models to guide investigations, help interpret data, make predictions, and ask questions (in combination with other practices)
Evaluate	Students identify obvious strengths and limitations of models, and begin to consider whether particular phenomena can be accounted for by particular models.	Students identify features of models that are inconsistent with particular phenomena, suggest other phenomena that could be used to test models, and compare the ability of different models to explain and predict.	Evaluate as in 7th grade but students are also able to abandon models in favor of alternative models if consistently fail to explain phenomena in the world
Revision	Students begin revising models to better account for a set of phenomena.	Student revision of models now begins to take account of both their explanatory and predictive power.	Same as in 7th grade and take into account consistency with scientific theories and principles.
Metamodeling Knowledge			
Purpose	Students should know that models are useful for thinking about phenomena that are difficult to observe directly (e.g., phenomena occur on too small a scale or are too complex) and that scientists construct and use models to explain sets of phenomena.	Same as in 6th grade and within multiple contexts. Students should know that models are important for predicting phenomena.	Same at in 7th grade but students should know models can also be helpful for guiding investigations, interpreting data, and asking questions.
Nature: Models as repre-sentations	Students should know that models can represent processes that are too complex or occur on too small a scale to observe directly.	Students should know that models can represent processes that happen on too small or large a scale to observe or that cannot be manipulated.	Same as 7th grade and within other contexts.

Nature: Types of Models	Students should know that a variety of models, such as physical objects, diagrams, and simulations, can be used to represent phenomena in the real world, and that different models can be used to represent the same thing.	Students should know that a variety of models, such as physical objects, diagrams, graphs, equations and simulations can be used to represent phenomena in the real world, and that different models can be used to represent the same thing.	Same as in 7th grade and also include conceptual models
Nature: Limitations of Models	Students should know that models may sometimes mislead, by suggesting characteristics that are not shared with what is being modeled.	Same as 6th grade and with additional models and limitations.	Same as 7th grade and with additional models and limitations.
Evaluation and revision of models	Students should know that models can be evaluated and revised by comparing the model's predictions to actual observations in the real world.	Same as 6th grade.	Same as 7th grade and understand that models can be revised to account for new knowledge or understandings.

Pedagogical approach.
Our pedagogical approach to supporting the practice modeling focuses on 1) motivating the practice, 2) pushing students to reflect on their own practice of modeling through classroom discussion that explicitly focusing discussion on key meta-modeling knowledge relating to models and modeling, 3) providing prompts that remind students to consider key meta-knowledge or practices relating to models, and 4) providing multiples opportunities and contexts through which students can construct models, use model, and discuss models.

To motivate students, we provide interesting or personally relevant phenomena for which students can construct models to explain or predict, as opposed to simple description. For example, in our 6th grade physics, our driving question is "how do we see objects?" and in the our 6th grade chemistry unit it is "how can I smell things from across the room?" A range of vivid visual or sensory phenomena are experienced for which students need to develop models to explain or predict. To push students to reflect on their practice, we have students create, evaluate, revise, and use their own models. Classroom discussion explicitly focuses on how these models are evaluated, how they have been revised, what limitations they have, and how they were used to help students think about and understand the phenomena, and how they compare to other types of models. To scaffold students understanding of models, we provide instructional prompts for teachers in teacher materials and for student in student materials, aimed at reminding students to think about what is being represented by the models, the limitations of the models, and how their models have been revised. Finally, we are engaging students in multiple contexts involving models across multiple years. Students will experience modeling 6th grade, 7th grade, and 8th grade in physics, chemistry, earth science, and biology. Moreover students will experience a number of different types of models, both internal and expressed (See figure 1).

Examples of how the modeling learning goals are supported in IQWST materials:

Some units in IQWST have more emphasis on modeling than others, but a number of units planned will have some activities devoted to modeling. Below we provide two units in 6th grade that focus on models heavily and another unit in 8th grade that intends to focus on modeling a more complex manner by combining the practice with other practices.

Example 1: 6th grade Physics

The 6th grade IQWST physics unit addresses several benchmarks focused on the nature of seeing and light (including interaction of light with matter, and color)[1]. The unit's driving question is "Seeing the light; when can I believe my eyes?" and the unit begins with an anchoring phenomenon of a message written in red and green letters. The message is first illuminated with green light (making it impossible to see the red letters), and then with red light (making it impossible to see the green letters.) Students can only read the hidden message when it is displayed with white light. The question posed to students is "why?"

In order to answer this question, the first of four learning sets in the unit begins with ideas about the nature of light and seeing. The second learning set addresses how light interacts with matter (reflection, absorption, and scattering.) The third learning set addresses color and light, and the last learning set addresses non-visible light.

Once the anchoring phenomenon is established, students conduct some preliminary investigations about basic aspects for how we see. Then they construct physical models for how we see that initially incorporate 4 aspects (a light source, an object, and eye, and a path for light to travel between the light source, the object, and the eye.) See an example model below.

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[1] Those benchmarks include:

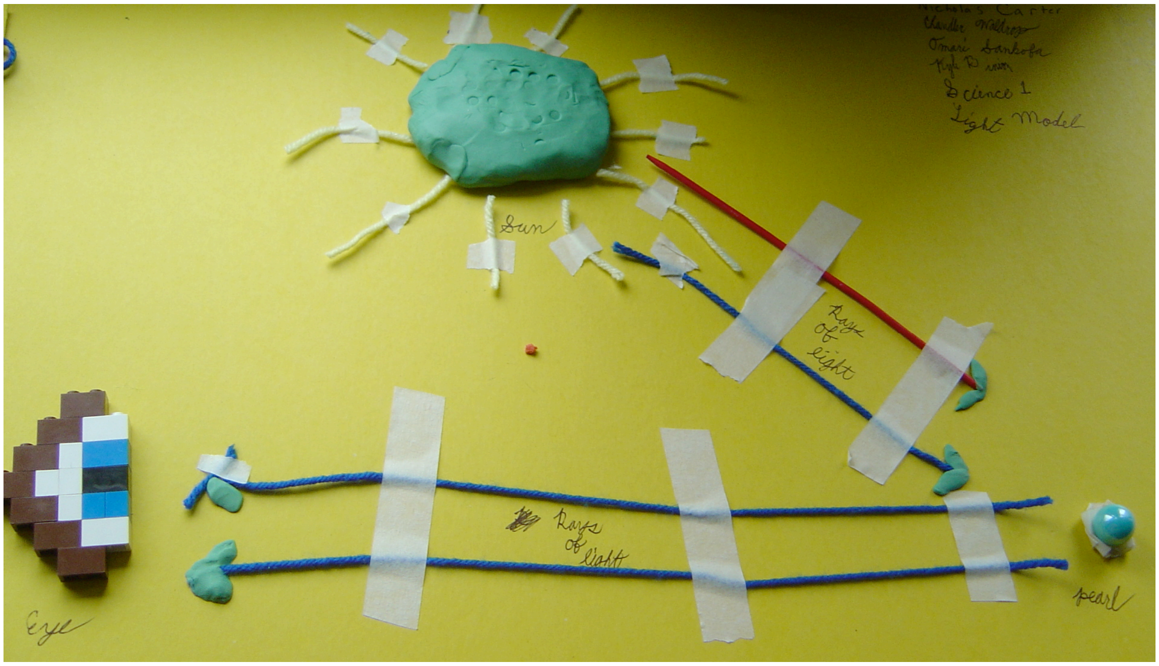
AAAS 6-8: 4F/2: Something can be "seen" when light waves emitted or reflected by it enter the eye – just as something can be "heard" when sound waves from it enter the ear.

NSES 5-8: Transfer of Energy/3: Light interacts with matter by transmission (including refraction), absorption, or scattering (including reflection). To see an object, light from that object – emitted or scattered from it – must enter the eye.

AAAS 6-8: 4F/1: Light from the sun is made up of a mixture of many different colors of light, even though to the eye the light looks almost white. Other things that give off or reflect light have a different mix of colors.

AAAS 6-8: 4F/5: Human eyes respond to only a narrow range of wavelengths of electromagnetic waves – visible light. Differences in wavelength are perceived as differences in color.

AAAS 3-5: 3A/2: Technology enables scientists and others to observe things that are too small or too far away to be seen without them and to study the motion of objects that are moving rapidly or are hardly moving at all.



Students read a little bit about modeling, listen to their teacher about the purpose and nature of modeling, think about the strengths and weaknesses of their own model, compare and contrast all of their physical models, and think about the advantages and disadvantages of different models. The teacher helps students construct a consensus model of light from all of their physical models. This two-dimensional model of light is then used and revised throughout the rest of the unit.

In the first learning set, for example, students use their consensus model to explain how shadows work. In the second learning set, the students revise their model to account for how light interacts with different kinds of matter (transmission, absorption, and reflection). In the third learning set, students revise the model to account for different colors/wavelengths of light. At the end of learning set three, students also apply their model to explain the anchoring phenomenon. In learning set four, the model is again revised when it is applied to light outside the visible spectrum (infrared and ultraviolet).

As a result, the light unit currently addresses the prior scientific modeling learning goals:

- Students construct models that are consistent with set of familiar phenomena
- Students use models to explain sets of familiar phenomena
- Students identify obvious strengths and limitations of models
- Students revise models to better account for a set of phenomena
- Students learn how models are used to explain set of phenomena
- Students learn that models can never be exact in every detail
- Students learn that models can be evaluated and revised

Example 2: 6th grade chemistry

The 6th grade IQWST chemistry unit focuses on benchmarks which address ideas about the structure of matter[2]. These benchmarks basically refer to the conceptual scientific model for

[2] These benchmarks include 4D- M1 and 4D-M3:

matter: matter is comprised of particles (atoms or molecules) and these particles are in constant motion, with more motion at higher temperatures and different rates of motion for a given substance in different states of matter. The unit essentially requires students to develop conceptual models of matter that explain the behavior of matter.

The driving question for the unit is "How can I smell things from across the room?" and requires students to explain how an odor such as ammonia or vinegar can be smelled from a distance. Students experience this phenomena in the first lesson of the unit and are asked to construct models of how they can smell odor from a distance. Students are asked to draw picture of this phenomena and provide written explanations to accompany their drawings. These drawings and explanations are the students' expressed models (see Figure 4 for examples of students models). In addition, to the phenomena of smell, students are asked to draw models that explain other real world phenomena through out the rest of the unit. Some examples of these other phenomena that students are asked to observe include: the ability of air be added to existing air in a confined container, the ability of air can be removed from a container while the remaining air expands and fills the container, the ability of a strip of pH paper to change color when held above the surface of a solution of ammonia, and the ability of a spot of colored dye to move faster in hot water in comparison to cold water. As students develop models to explain all of these phenomena they asked to compare models and revise their models to account for the observed phenomena and gradually develop their internal models of matter. In the end we hope that the students can then revise their original models for how odor can be detected from across the room to one more aligned with the accepted scientific thinking.

4D-M1: All matter is made up of atoms, which are far too small to see directly through a microscope. The atoms of any element are alike but are different from atoms of other elements. Atoms may stick together in well-defined molecules or may be packed together in large arrays. Different arrangements of atoms into groups compose all substances

4D-M3: Atoms and molecules are perpetually in motion. In solids, the atoms are closely locked in position and can only vibrate. In liquids, the atoms or molecules have higher energy, are more loosely connected, and can slide past one another; some molecules may get enough energy to escape into a gas. In gases, the atoms or molecules have still more energy and are free of one another except during occasional collisions. Increased temperature means greater average energy of motion, so most substances expand when heated

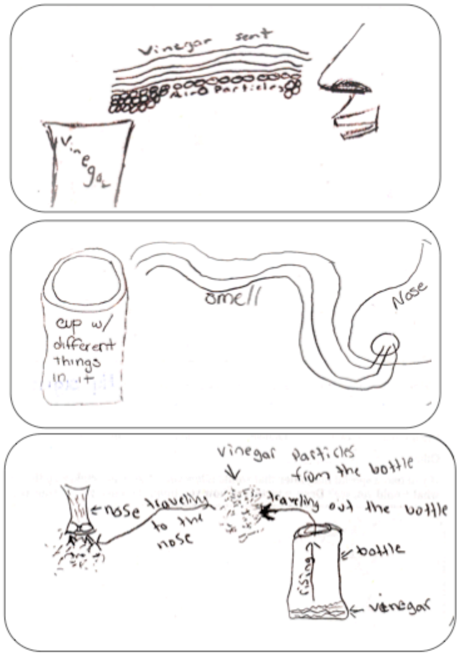


Figure 4. Shown are three models drawn by students in the 6th grade chemistry unit. Students are asked to draw their models of how they can smell a substance located in a cup (e.g. vinegar) from their seats. Different students drew different models. For example, some students drew models reflecting a continuous model where there is no distinct particles but rather streams of material (middle model), some students drew a mixed particulate model where a combination of particles and continuous matter are present (top model), and some students drew a particle model of matter which we hope students would develop near the end of the unit (bottom model).

During this unit, students are constructing models and using these models to explain phenomena. At different points in the unit, students are also asked to identify what their models are explaining and what is being represented in their models, to revise their models, to identify the limitation of their models, and to critique and evaluate their models of matter based on how well they explain the phenomena. In addition, explicit discussions of about the nature of models occur at the beginning, middle, and end of the unit and focus on models as representations, multiple models, model limitations, and model change. As a result of the student activities around modeling matter and discussion of model, the following learning goals are addressed in this 6th grade chemistry unit.

- Students construct models that are consistent with set of familiar phenomena
- Students use models to explain sets of familiar phenomena
- Students identify obvious strengths and limitations of models
- Students revise models to better account for a set of phenomena
- Students learn how models are used to explain set of phenomena
- Students learn that models can never be exact in every detail
- Students learn that models can be evaluated and revised

Example 8th grade:

The following is the proposed use of models for an 8th grade chemistry unit focusing on the chemistry unit behind photosynthesis and respiration[3]. Students will first construct models of how they think food, water, carbon dioxide, water and light relate to plants drawing on what ever prior ideas or knowledge students have about plants. Students will then experience a range of phenomena such as plants requiring water and carbon dioxide to live, plants taking up carbon dioxide, plants making carbohydrates, plants releasing oxygen gas and students will be prompted to construct models that account for these phenomena in plants. Students will be guided to develop diagrams to revise their initial models that represent photosynthesis. This model should be revised to show that plants take in carbon dioxide in the air through leaves and water in the soil through roots and use light to facilitate the chemical reaction between carbon dioxide and water to create glucose, which is stored in the plants, and oxygen gas, which is released back into the air. Students will then use this model of photosynthesis to ask a question and make a prediction concerning the factors involved in photosynthesis and design an investigation to test this hypothesis. For example a student may conduct a closed-ended investigation to find out that carbon dioxide is required by plants to make glucose. The student might then use the model of photosynthesis to predict that increasing light intensity would increase glucose production in plants. The student would then be encouraged to test this prediction by designing an open-ended investigation. Perhaps the student would design an investigation where light intensity is varied and starch production measured. The student would then be encouraged to interpret experimental data based on how well it compares to predictions from the model. Discussions in class will occur around how the models were used in this unit, how they helped students in their investigations, and how they helped students interpret data. Students will discuss how this model is similar or different from the other types of models they have used in the past. Students will also discuss how the drawing of photosynthesis reflects a mental model of photosynthesis.

In this way, the 8th grade unit addresses these learning goals related to modeling:

- Students learn how models are used to explain or predict sets of phenomena
- Students learn that models can never be exact in every detail
- Students able to revise or abandon models in favor of alternative models if consistently fail to explain phenomena in the world
- Should know models can also be helpful for guiding investigations, interpreting data, and asking questions.
- Students should know that a variety of models exist such as diagrams and conceptual models.

[3] Benchmarks for this unit include:

AAAS 6-8: 5E/1:Food provides the fuel and the building material for all organisms. Plants use the energy in light to make sugars out of carbon dioxide and water. The food can be used immediately or stored for later use....

AAAS 6-8:5E/2:Over a long time, matter is transferred from one organisms to another repeatedly and between organisms and their physical environment. As in all material systems, the total amount of matter remains constant, even though its form and location change.

AAAS 6-8:5E/3: Energy can change from one form to another in living things. Animals get energy from oxidizing their food, releasing some of its energy as heat. Almost all Food energy comes originally from sunlight.

AAAS 6-8: 6C/3: To burn food for the release of energy stored in it, oxygen must be supplied to cells, and carbon dioxide removed. Lungs take in oxygen for the combustion of food and they eliminate the carbon dioxide produced….

Concluding remarks

The IQWST project provides a unique opportunity to develop rich understanding of models and modeling that others have not been able to do because it enables curriculum designers to focus instruction round modeling over three years and across different content domains. Others suggest that students need to experience multiple types of models in different contexts in order to really understand models (Schwarz & White, 2005), and this IQWST curriculum project can provide this experience. In addition, this is also a unique opportunity to study how well students can to engage in the practice of modeling and how much they can understand about models and perhaps how to come to understand other factors that will impact student learning of modeling throughout the years such as teacher knowledge and teacher instructional practice.

Systems Thinking

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Introduction

Many scientific processes, in particular biological and earth processes, operate as dynamic systems. Systems thinking is a skill students can use to translate real-world problems into a more coherent understanding of the underlying science concepts (Assaraf & Orion, 2005). Understanding how dynamic systems work is often crucial to scientific analysis (Hmelo, Holton, & Kolodner, 2000). For example, in learning about the earth's water systems, students can develop an understanding of the important role of water systems in the global ecosystems. The ability to utilize systems thinking is also called for in national standards. The *Benchmarks for Science Literacy* (AAAS, 1993) describes systems thinking as an essential component of higher-order thinking, and the *National Science Education Standards* (National Research Council, 1996) consider the idea of systems as providing a framework which students can use to explore complex phenomena and situations, such as the four major interacting components of the earth system.

For this scientific inquiry practice, we are interested in helping students develop fluency with systems thinking. Systems thinking refers to more than just recognizing systems or describing their function. Rather, systems thinking is the ability to use an understanding of what systems are and how they work to explain, analyze, and predict complex and dynamic phenomena in a variety of different contexts. As described by AAAS (1993), "The main goal of having students learn about systems is not to have them talk about systems in abstract terms, but to enhance their ability (and inclination) to attend to various aspects of particular systems in attempting to understand or deal with the whole system" (11A Introduction).

We know it is exceptionally difficult for students to learn about systems (Assaraf & Orion, 2005; Hmelo et al., 2000), yet little research has been conducted to explore ways of supporting students' development of systems thinking across multiple units and grades (Kali, Orion, & Eylon, 2003). In order to address these challenges, we propose a developmental sequence across multiple middle school science units to support students in organizing and applying their understandings and ways of thinking around systems. The sequence includes opportunities to explore dynamic aspects of individual systems (such as reservoirs and evaporation in the water cycle), comparisons of common features across systems including both aspects such as stocks and flows, as well as concepts such as the non-linearity of material movement within systems. We feel this process will help to foster more holistic understandings and ways of thinking about dynamic systems overall.

What Is the Practice of Systems Thinking?

Assaraf and Orion (2005) describe systems thinking as a school of thought that focuses on recognizing the interconnections between parts of a system and synthesizing them into a unified view of the whole. They also suggests that the ability of students to perceive coherent systems depends on both scientific knowledge and cognitive ability. Thus we view the practice of systems thinking as consisting of a combination of both an understanding of what systems *are* (what they consist of and how they operate) as well as an ability to appropriately apply this understanding to explain new situations and phenomena. The goal is for students to be able to recognize patters and interrelationships, and learn how to structure those interrelationships into more effective, efficient ways of thinking about new situations and phenomena (Assaraf & Orion, 2005).

Many definitions and descriptions of dynamic systems abound in the literature. Hmelo et al. (2000) define a dynamic system as a coherent whole consisting of parts whose functions interact and influence each other. Kali et al. (2003) and Assaraf and Orion (2005) both define a system as an entity that functions as a whole through the interaction of its parts. Thus understanding systems involves considering the causal interactions and functional relationships between parts of the system and with other systems (Hmelo et al., 2000). Common features of dynamic systems across these descriptions include the following: the properties and function of the entire system may appear quite different from the properties and behaviors of individual elements (Assaraf & Orion, 2005; Hmelo et al., 2000; D. A. Penner, 2000); interactions between components take place continuously; systems maintain stability via feedback through cause-and-effect feedback loops connecting parts of the system (Assaraf & Orion, 2005); and systems operate over a range of time and distance scales. Building from these descriptions, we have identified a set of eight characteristics of dynamic systems critical to understanding how systems operate.

1. Systems include multiple interacting parts, which consist of stocks (reservoirs) and flows (movement between reservoirs)
2. Understanding the whole system consists of more than the just understanding each of the parts – it requires a holistic view of the system as an entity itself and how it operates
3. Material that moves through a system can change form, sometimes into forms that are not visible, but the material does not leave or "disappear" from the system
4. Movement through the system can take place via multiple different processes
5. Movement though the system is not necessarily linear/cyclical, but rather dynamic
6. Systems have both temporal and spatial characteristics
7. Interactions between parts of a system operate continuously and dynamically
8. Disturbances to one part of the system may cause changes throughout the whole system

We believe that these understandings are a necessary component to systems thinking, because they encompass the "essence" of what systems are and how they operate. Without this level of understanding, students will not be able to comprehend any situation as a dynamic system.

In addition to these understandings about systems, students also need to develop abilities to appropriately utilize and apply these understandings to explain new situations and phenomena. One essential component of higher-order thinking is the ability to think about a whole in terms of its parts and, alternatively, about parts in terms of how they relate to one another and to the whole (AAAS, 1993; Kali et al., 2003). Thus scientific idea of a system implies detailed attention to inputs and outputs and interactions among the system components (AAAS, 1993). Assaruf & Orion (2005) consider the ability to perceive a system in context of its interrelationship with other systems. Such ways of thinking have been summarized by Kali et al (2003) in four dimensions of systems thinking: "thinking in models" (models that represent systems), "closed loop thinking" (non-linear thinking), "dynamic thinking" (retrospective view and foreseeing future trends), and "steering the system" (ability to make informative actions in a system).

Challenges to Developing Systems Thinking

Researchers are still unclear as to how people develop systems thinking (Penner, 2000). However, they have identified several challenges that students face in developing the practice of student thinking. One of these challenges is that students often perceive a system as unrelated parts or pieces of information, and lack the dynamic, cyclic, and systemic perception of the system (Assaraf & Orion, 2005). Research has shown that systems are often taught as stagnant steps or a connection of linear processes, and students do not often have the opportunity to engage with the *dynamic* aspects of systems or develop fluency with system thinking skills. Most students are introduced to systems in overly simplified static forms, and these early conceptions form schema that can be difficult to overcome with later instruction (Hmelo et al., 2000). For example, in a study of students learning about earth systems, Kali et al. (2003) found that most students were unable to link the various components of the water and rock cycles together in a coherent network. Based on this work, they defined a continuum of characteristics of students' system thinking, which range from low systems thinking (a completely static view of a system) to increasing awareness of materials transformation to high systems thinking (an understanding of the cyclic and dynamic nature of the system).

In IQWST we attempt to address these challenges by designing a learning progression that builds students' capacity and fluency with systems thinking, as well as identifying a set of pedagogical strategies to cut across the learning trajectory that characterize our approach to supporting students in developing this practice.

Pedagogical Approach

The traditional methods to teaching dynamic systems has been to introduce the structural elements of the system through a series of related definitions. But such an approach does not often lead to the understanding that *what* they are learning is indeed a system (Hmelo et al., 2000). From the literature we have identified three strategies that appear to help students develop systems thinking, and which we use as the basis for our approach in the IQWST curriculum materials.

Increasing complexity. In light of the known challenges facing learners in developing systems thinking, one of the key supports we utilize in our design is to begin with simple systems and increase complexity slowly over time (AAAS, 1993; D. A. Penner, 2000). By beginning with simple systems, students can develop an understanding of a system's underlying components and characteristics without being overwhelmed with its complexity. This process has been found to helps students focus their attention on the links between micro-level interactions and macro-level patterns within and across systems (Penner, 2000). We also begin with systems that are relevant to students and contextualized to both the content understanding and their everyday experiences. This provides students with more cognitive resources on which to draw to come to understand systems (Rivet & Krajcik, in press).

Designing, building, and revising models. Research has shown that iteratively designing and refining models of specific systems helps students develop understandings of those systems. For example, Penner, Giles, Lehrer & Schauble (1997) demonstrated that deep understanding of a natural mechanical system could be accomplished by elementary students by iteratively constructing better and better models of that system. We know that similar to other ideas, learning about systems in some situations may not transfer well to other situations. Therefore systems should be encountered through a variety of approaches, including designing and troubleshooting models of systems (AAAS, 1993). In the IQWST units, students are provided with multiple opportunities and a variety of supports to engage with models and other representations of systems.

Maintain focus on dynamic aspects of systems. As described earlier, one challenge that students face in developing systems thinking is that they first learn about systems as individual elements and simple relationships. This can foster an understanding of systems as static entities that can be difficult to alter, even with additional instruction. Thus we recognize that it is critical to keep students focused on the behavior of the system and the function of the parts within the system, in order for students not to just develop a static view of the system as just parts with only a liner relationship between them (Hmelo et al., 2000). We attempt to accomplish this goal by maintaining a dual focus on both the micro-level aspects of the system (the parts and relationships between the parts) and the macro-level patterns of the whole system and interactions between systems from the very beginning. Through focused discussion, critique, and practice, we emphasize the dynamic aspects as critical characteristics to recognizing, defining, and evaluating different types of systems.

Learning Progression for Developing Systems Thinking

One goal of the IQWST middle school curriculum is to foster students' ability and fluency in this way of thinking in various contexts and around various types of systems over the three years of the program. We are developing a three year learning progression through which students will work as they develop their increasing expertise. This learning progression for systems thinking focus on different aspects of the practice at different points in time, such that each year has a specific focus. This allows students to develop understanding of one aspect and build their expertise across units and grades. Additionally, since each grade spans four content areas, students have the opportunity to utilize and apply their developing fluency with systems thinking across different subject disciplines and contexts.

The learning progression for systems thinking is framed around the three aspects of understanding systems: the parts, the relationship between the parts, and the system as a whole. For the first year students focus primarily on understanding what a system is and how it functions. In the second year students focus on the holistic characteristics of the system and how different systems interact. In the third year, the focus is on the implications of disturbances to the system. Each grade level includes the conceptual development and complexity of the previous year, but also includes added complexity and dimensions for each component. Table 1 provides a summary of the foci for 6^{th}, 7^{th}, and 8^{th} grade. Each grade focus is described in more detail below, illustrated with examples from the current IQWST units in development.

Table 1: Learning Progression for Systems Thinking

	6th	**7th**	**8th**
Instructional focus	*What affects what?*	The whole is greater than the sum of the parts	Disturbing the system
Parts of system	Distinguish the parts of the system	Consider the relative scale of the parts in relation to each other and to the whole	Add, subtract, & alter parts
Connection between parts	Describe the relationships between the parts	Describe feedback loops and ripple effects	Recognize equilibrium & imbalance
System as a whole	Recognize that together these parts make a system, with characteristics unique from the parts	Recognize how system characteristics change with perspective/scale	Thinking temporally: retrospection and prediction

6th grade: What affects what? In the 6th grade the focus is on understanding what a system is – what the parts are, how the parts interact, and how the characteristics of the system as a whole are different from the individual parts. For example, the 6th grade earth science unit, *How does water shape our world?*, focuses on major earth processes including the water cycle, the rock cycle, and weathering, erosion, and deposition. To learn about the water cycle, students first explore the different water reservoirs (e.g., oceans, lakes, glaciers, atmosphere) and their characteristics, including size, location, and residence time, then how water moves between reservoirs (e.g., evaporation, precipitation, infiltration, flow). Only at this point are students introduced to the water cycle as a conceptual framework. Students then participate in a "water cycle game", where they take on the role of a water molecule and physically move from table to table to represent movement between reservoirs. Their movement is dictated by rolling dice at each table, and for each movement they note the process that was used to get them to their new location. There is also the possibility that they will stay in the same reservoir for multiple rounds, and that possibility is dependent on the size and residence time of the actual reservoir. At the end of the game, students map their own path through the water cycle and compare it to those of their peers. Through discussion and iterative modeling, students determine that there is not one single path that all water follows through this cycle but rather could follow one of many various paths. Additionally, they identify that even though a single droplet of water may stay in one reservoir for an extended period of time, overall water in the cycle is constantly moving.

Through this and other activities, students learn about the general characteristics of systems and how they operate. We recognize that developing this understanding of systems is challenging. Thus to support students, we focus on are relatively simple systems at this level, and provide multiple opportunities for students to design, construct, and revisit models of these systems. In the water cycle example described above, student participation in the game creates a type of dynamic model in the classroom which students can observe. By also diagramming and sharing their movement through the game in a pictorial representation, students have a chance to deepen their understandings of systems through constructing and revisiting this model.

7th grade: The whole is greater than the sum of the parts. In the 7th grade, the practice of systems thinking shifts to focus more on the characteristics of the system as a whole, and consider how the whole system is greater than the sum of its parts. Students continue to identify the parts of a system and relationships between them, as they did in 6th grade. However they now also consider issues of scale in relation to how systems operate. They also focus on cause- and effect relationships, feedback loops, and ripple effects through a system.

The 7th grade chemistry unit, *How do I make new stuff from old stuff*, provides a good example of students' engagement with these ideas. In this unit students focus on chemical change and chemical reactions. In one activity, students explore the reaction of Alka-Seltzer and water in both an open system and close system environments. Students both observe the macro-level phenomenal of this reaction, and then model the same reaction in both the open and closed system conditions at an atomic level. In the first phase, students combine the two reactants in an open container and observe that there is a "loss" of mass. They use their models to demonstrate that there are left over atoms from this reaction that were not accounted for in the observations. To account for those atoms, given that matter cannot be created or destroyed, students determine that they need to repeat the experiment within a close container. With this set-up, students observe that a chemical reaction does take place and new substances are formed (salt and carbon dioxide gas), but that no mass is lost in the process. This corresponds to the atomic models they create of this reaction in a closed system. Reflecting on this experiment, students identify the different parts of the two systems they explored and discuss how even in the "open" system the gas did not "disappear". Rather, it became part of the larger atmospheric reservoir of gasses. Thus the notion of systems thinking supports students in understanding important scientific concepts, such as the conservation of matter.

8th grade: Disturbing the system. In the 8th grade units, students build on their understanding of systems and increasing fluency with systems thinking to explore what happens when there are disturbances made to the system. Such disturbances may include adding, subtracting, or changing the parts of the system, or altering the connections between the parts of the system in some way. Utilizing their familiarity with cause-and-effect relationships and feedback loops developed in the 7th grade units, students focus on how systems maintain equilibrium and respond to imbalances. This focus creates the need for students to develop a temporal perspective on systems – analyzing them retrospectively to consider their characteristics and how they functioned before the disturbance, and predicting the impact of the disturbance on future behavior of the system.

In the 8th grade biology unit of IQWST, *What will survive?*, students engage with such disturbances to systems by exploring concepts around natural selection. The key activity of the unit is the study of the finches in the Galapagos Islands. Students analyze data regarding the characteristics of finches and how the population of finches on the island has changed over time. Through this exploration of the data, they address questions such as, "why did the finch population change?" and "why did some finch die and others survive?". To address these questions, students need to consider other aspects of the biological system and how both parts of the system and the system overall changed over time. Consideration of the fauna, environmental changes, and predator-prey relationships all play into students' developing explanations of the data and addressing their research questions. The activity concludes with students' predictions as to the impacts of future changes to the system may be, and reflecting on how a single perturbation to a part of the system (in this case, the change of fauna) has extended rippling effects across the entire system over time and space.

Conclusions

Across the three years of middle school science, students will be engaged with various examples of dynamic systems as related to science ideas in each of the four major disciplines (physics, chemistry, biology and earth science). By the end of 8^{th} grade, we hope that students will not only learn about these systems within the content domains, but develop a more holistic view of systems and a fluency with systems thinking that allows them to look across these disciplines and make connections between scientific concepts and phenomena. As an inquiry practice, we believe that systems thinking can further students' ability to explain phenomena, ask questions, and make predictions in a variety of contexts. By supporting the development of these skills through a learning progression across middle school, we hope that students will develop capacity and fluency with systems thinking that will further their understanding of science and the world around us.

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