

**IQWST Materials: Meeting the Challenges of the 21<sup>st</sup> Century<sup>12</sup>**

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## **1.0 Introduction**

Our current education system is failing to both produce a scientifically literate populace able to understand new scientific advances that affect our lives, and to prepare a workforce for new jobs and professions that have emerged from these advances (Committee on Prospering in the Global Economy of the 21st Century, 2006). Although multifaceted, one underlying cause for this dismal state of affairs is the curriculum materials used in classroom across the United States. Project 2061's (Kesidou & Roseman, 2002) review of middle school curriculum materials concluded that materials failed to take into account students' prior knowledge, lacked coherent explanations of phenomena, failed to support students in developing explanations of phenomena, and that materials covered too many topics superficially with overemphasis on the use of technical vocabulary. Most materials do not provide opportunities for students to use ideas to solve problems. As such, the report concluded that none of the nine middle school programs they examined would help students learn standards. Roseman, Linn, & Koppal (2008) argue that current instructional materials, textbooks and learning technologies often fail to apply what is known about teaching and learning to support effective science learning. Similarly, analyses of state and local district standards have resulted in criticism for shallow coverage of many topics (Schmidt, Wang, & McKnight, 2005). As such, curriculum materials also do not focus on helping learners to develop 21<sup>st</sup> century skills that will allow them to live fruitful lives and obtain jobs in the new workforce. A recent National Academies workshop identified five critical 21<sup>st</sup> century skills: 1) adaptability, 2) complex communication/social skills, 3) non-routine problem solving, 4) self-management/self-development, and 5) systems thinking (National Research Council, 2008).

This manuscript discusses how students develop 21<sup>st</sup> century learning skills through the use of coherent middle school science learning materials. I first describe the middle school science curriculum project, *Investigating and Questioning our World through Science and Technology* (IQWST, pronounced I-Quest) designed to help students meet important learning goals by using what we know about how students learn. Next, I briefly describe the design features of IQWST, including the coherence of the materials, a focus on Big Ideas, the incorporation of project-based science, and the development of scientific practices. I then show how IQWST supports learners in developing 21<sup>st</sup> century skills. Next, I discuss evidence that supports the value of IQWST in prompting student learning of big ideas and scientific practices and describe how this evidence also supports that students learn 21<sup>st</sup> century skills. I end with a general discussion about the importance of more systematic research to support or refute claims made in this manuscript while also arguing for the importance of professional development to ensure fidelity to curriculum materials and new ideas regarding the teaching and learning of science.

## **2.0 The IQWST Story**

The Investigating and Questioning our World through Science and Technology project (Krajcik et al. 2008), sponsored by the National Science Foundation, is a multi-year effort to design, develop, and test the next generation of middle school curriculum materials to enable teachers with diverse knowledge and experiences to teach science effectively to students with a variety of backgrounds and strengths. IQWST is a shared effort among the University of Michigan, Northwestern University, the Weizmann Institute of Science, and Project 2061. IQWST is designed to foster deep and integrated understanding of both science content and scientific practices. IQWST brings together standards-aligned learning goals with project-based

approaches to science pedagogy, incorporating research-based practices to support students' science learning and literacy. In order to support rigorous learning of content standards and engagement in scientific practices, the IQWST design and development team developed a learning-goals driven design process that guides our development and iterative refinement of the curriculum materials (Krajcik, McNeill, & Reiser, 2008). IQWST supports learning core/big ideas in science, both content and practices, over time (Shwartz, Weizman, Fortus, & Krajcik, 2008). For this reason, we refer to the materials as “coherent.” Core ideas from each scientific discipline — physics, chemistry, earth science and biology — are explored each year of middle school, supporting students as they build a sophisticated and systematic understanding of scientific ideas and practices. The materials create contexts that involve students in exploring challenging science content and inquiry practices while engaging them in complex tasks that build their scientific literacy.

### ***2.1 Coherence in IQWST***

The design and development of coherent curriculum materials should support students in developing integrated understandings (Roseman & Linn, 2008). Here, curriculum coherence is defined as the alignment of the specified topics, the depth at which the topic is studied, and the sequencing of the topics within and across the grades (Schmidt, Wang & McKnight, 2005). Because coherent curriculum materials build on each other, such materials should lead to integrated understanding in learners (Linn & Eylon, 2006). By integrated understanding I mean ideas that are connected to each other in such a manner that allows learners to grasp the relationships among the various ideas. Such understanding allows learners to use this relational network to explain and predict phenomena as well as to solve problems in their lives.

IQWST supports middle school students developing integrated understanding of big/core ideas of science through coherent curriculum materials (Shwartz, Weizman, Fortus, Krajcik, Reiser, 2008). The IQWST materials strive to support three forms of coherence: learning goals coherence, intra-unit coherence, and inter-unit-coherence (Shwartz, et al., 2008). Learning goals coherence refers to selecting key learning goals, including science concepts and scientific practices that build on each other over time so that students develop a deeper and more sophisticated understanding of the idea each time the idea is revisited. In designing curriculum materials, creating a coherent set of learning goals is a crucial step in the design process. Learning goals selection is the foundation of designing and developing curriculum materials; if the learning goals do not comprise a coherent set, nothing built upon them will result in students building integrated understandings. IQWST builds learning goals coherence in two ways. The first is by using a small set of powerful ideas – the big ideas of science -- that can be revisited over time. The second is by specifying what we want students to learn in terms of learning performances.

Intra-unit coherence refers to the coordination between content learning goals, scientific practices learning goals, curricular activities, and assessments within a unit. Intra-unit coherence allows learners within a unit to build integrated understanding of core/big ideas. IQWST units are guided by a driving question (Krajcik & Blumenfeld, 2006) that sustains, integrates, and drives the activities and investigations of a unit. Driving questions need to match with the learning goals, but they do not specify the learning. IQWST units take 8 – 10 weeks to allow learners to delve into the key ideas and scientific practices of each unit as students explore

responses to the driving question. Each unit in IQWST progresses so that learners develop deeper and more sophisticated understandings of the key ideas.

Inter-unit coherence refers to coordination among units so that learners build a deeper and integrated understanding of core ideas. Inter-unit coherence supports the development of content and scientific practices learning goals across one or several years of instruction. Although each unit has intra-unit coherence, the IQWST design and development team requires that each unit also builds off of and links to both prior and future units, and for ideas to link from one to the other across the units. Thus, students apply scientific practices and concepts across the units promoting a more sophisticated integration of ideas (Roseman et al., 2008; Fortus & Krajcik, submitted) as they work through the units.

Learning-goals, intra- and inter-unit coherence are essential to students' learning of 21<sup>st</sup> century skills. For instance, students will not be able to solve complex problems without having a useable understanding of core ideas. A key attribute of focusing on coherence is that students will know what ideas they understand and when they need to learn more. Knowing what you know and need to know links to the 21<sup>st</sup> century skills of self-development and self-management. Knowing when you need to learn more requires that a learner have a solid foundation of important ideas. Moreover, having a solid foundation of ideas will allow learners to further build their understandings and link to other ideas. The key point behind coherence of a curriculum is that learners will develop integrated understandings that will allow them to take part in various 21<sup>st</sup> century skills.

### ***2.3 A Focus on the Big Ideas of Science***

The National Science Education Standards (National Research Council, 1996) and the Benchmarks for Science Literacy (AAAS, 1993) provide direction on the ideas that children should know and be able to apply in order to be scientifically literate. Our children will grow up in a world where they will need to apply and communicate ideas, make sound decisions based on evidence, and collaborate with others to solve important problems. Yet, most of our schools do not have this focus. We still focus on covering too much content without focusing on developing deep, integrated understanding. We know that coverage of material does not lead to integrated understanding of ideas. The national standards have allowed us to make headway in improving science instruction, but still focus on too many content ideas. Rather than focusing on covering content, our nation needs a long-term developmental approach to learning science that focuses on the ideas we most care about and takes into consideration learners' prior knowledge and how ideas build upon each other. As such, IQWST focuses on helping students develop integrated understanding of the big ideas of science (Wilson, & Berenthal, 2006; Stevens, Sutherland and Krajcik, 2009). We focus on big ideas because they:

1. Help learners to understand a variety of different phenomena within and across science disciplines
2. Provide a framework for thinking about the long-term development of student understanding (Duschl, Schweingruber, & Shouse, 2007)
3. Allow designers to revisit ideas throughout the curriculum so that student understanding becomes progressively more refined, developed and elaborated
4. Include both content and scientific practices (modeling, constructing scientific explanations)
5. Promote intra-unit and inter-unit coherence.

IQWST did not directly set out to meet 21st century skills. The IQWST materials, however, which were thoughtfully created to build an integrated understanding of the Big Ideas including both content and practices, indirectly meet 21<sup>st</sup> century skills identified by the NRC. These include meeting the economy's growing demand for adaptability, complex communications/social skills, and non-routine problem-solving. IQWST, for instance, takes the stance that learning of disciplinary knowledge and the learning of scientific practices needs to occur together. For example, as I will discuss further below, the construction of scientific explanations is an essential practice of IQWST and involves complex communication skills and adaptability as learners need to consider alternative ideas, as well as consider if they have sufficient and necessary evidence to support their explanation.

### ***2.3 Learning Goals-Driven Design Model of IQWST***

IQWST focuses on meeting key learning goals (Krajcik, McNeill & Reiser, 2008) by using a learning-goals driven design process. Our learning-goals-driven design model builds upon and extends the backward design approach presented by Wiggins and McTighe (1998). The learning-goals-driven design model includes three stages: 1) specifying learning goals, 2) developing materials and 3) gathering feedback<sup>3</sup>. We start by selecting big ideas, ideas that have the most powerful explanatory power and that link to standards. Next, IQWST designers unpack the standard so that they develop a deep appreciation for the meaning of the standard. When unpacking, we break apart and expand the various concepts in the standard to elaborate on the intended science content. When IQWST researchers unpack a standard they also consider if the content or practice is suitable for middle school students by considering common student difficulties, prior conceptions that pose challenges, as well as what prior science knowledge students may or may not have. Finally, the unpacking process also entails selecting phenomena that might help the learners understand the materials.

Once the learning goals have been selected and unpacked, we develop learning performances that express the cognitive tasks that students will engage in. The development of learning performances is a critical step as science standards are declarative statements of scientific ideas, and do not specify the type of reasoning we would like to see students engage in with these concepts. An important theme in science reform has been a focus on meaningful understanding, in which the goal of learning is for students to be able to reason with scientific knowledge to understand problems they encounter in their everyday lives. Learning performances allow students to reason with scientific knowledge. In designing learning performances we blend a scientific reasoning and/or practice with particular science ideas to develop a "learning performance." Figure 1 illustrates the process of developing learning performances by crossing a content standard with a scientific practice/reasoning skill. In this case, students use their understanding of chemical reactions to write a scientific explanation about a phenomenon in which they argue that either a chemical reaction did or did not occur, and then justify that claim with appropriate evidence and reasoning.

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<sup>3</sup> In this manuscript, I focus on specifying learning goals. Those interested in the second two phases should see Krajcik, McNeill & Reiser, 2008.

Only after learning performances are developed will IQWST designers develop the context, assessments, instructional sequence, and learning activities of a unit (see Krajcik, McNeill, & Reiser, 2008). The learning performances serve as the guide to develop learning activities and assessments that align with each other. A focus on learning goals in which unpacking of content standards is followed by the development of learning performances allows designers to develop materials that have aligned instructional materials and assessments (Krajcik, Reiser, McNeill, 2008).

Because of the specificity of learning performances, learning activities and assessment follow directly from them. For instance, the learning performance in Figure 1 would indicate that the unit would engage and assess students in constructing scientific explanations about new substances forming from old substances. Unpacking standards and developing learning performances allow the IQWST materials to achieve closer alignment with curriculum tasks and assessments (Krajcik, McNeill & Reiser, 2008).

Learning performances are key to building coherent curriculum, as they specify how students will make use of content-based standards in cognitive terms. As such, they are central to developing 21<sup>st</sup> century skills. For instance, as the learning performance in Figure 1 states, students will construct a scientific explanation about new substances forming from old substances. In constructing scientific explanations students engage in two key 21<sup>st</sup> century skills – complex communications skills and adaptability. A key aspect that learners need to consider when constructing a scientific explanation is whether they have sufficient and appropriate evidence to support their claims (see section 2.5). Take into consideration appropriate and sufficient evidence helps students develop complex communications skills. Another key aspect in constructing a scientific explanation includes ruling out other possible explanations (see section 2.5). When learners can take other points of view into consideration and see how they do or do not relate to their ideas, they are exhibiting a central aspect of adaptability.

#### **2.4 A project based focus to IQWST**

IQWST materials also apply a project-based approach within each unit. (Krajcik, McNeill & Reiser, 2008). Project-based science (PBS) embeds science learning in the investigation of meaningful real-world phenomena or problems (Blumenfeld & Krajcik, 2006; Edelson, 2001). The exploration of real-world events and occurrences provide students with rich application problems and phenomena that situate the scientific ideas and skills and that can build connections among students' scientific knowledge and their understanding of everyday experiences (Linn & Eylon, 2006). The hallmark of project-based learning is the use of a driving question that integrates and drives the explorations and learning activities of each unit (Krajcik & Blumenfeld, 2006). PBS applies the basic tenant of cognitive apprenticeship in which learners work together and with more knowledgeable others to apply scientific ideas and skills to investigate and solve meaningful problems (Collins, Brown, & Newman, 1989). These approaches involve learners in scientific practices such as argumentation, explanation, scientific modeling, and engineering design (McNeill, Lizotte, Krajcik, & Marx, 2006; Krajcik, McNeil & Reiser, 2008). As such, PBS also helps students develop scientific practices (McNeill & Krajcik, 2008b; Reiser et al., 2001) and understand core scientific ideas as represented by science standards (Geier et al., 2008; Marx et al., 2004; Rivet & Krajcik, 2004).

**Figure 1: Developing Learning Performances**

Content Standard	X	Practice (scientific inquiry standard)	=	Learning performance
When substances interact to form new substances, the elements composing them combine in new ways. In such recombinations, the properties of the new combinations may be very different from those of the old (AAAS, 1990, p.47).		Develop...explanations... using evidence. (NRC, 1996, A: 1/4, 5-8)  Think critically and logically to make the relationships between evidence and explanation. (NRC, 1996, A: 1/5, 5-8)		Students construct scientific explanations stating a claim whether a chemical reaction occurred, evidence in the form of properties, and reasoning that a chemical reaction is a process in which old substances interact to form new substances with different properties than the old substances.

### **2.5 A Focus on Scientific Practices**

Because of our focus on learning performances, IQWST supports students in developing key scientific practices. Scientific practices represent the disciplinary norms and ways of knowing that scientists use as they construct, evaluate, communicate, and reason with scientific knowledge to explain, predict and describe phenomena. In IQWST students apply various scientific ideas to make sense of and explain a variety of phenomena. IQWST supports students in developing several key scientific practices including: constructing scientific explanations and arguments; building and revising models, collecting, analyzing and using data as evidence; finding and evaluating information, designing and conducting investigations, and collaborating with peers in design or debates (Krajcik, Slotta, McNeill, & Reiser, 2008). Building these understandings will not just happen. IQWST supports students in scientific practices by making use of various scaffolds and having students use these practices over time in more sophisticated ways. Each successive use of a practice builds more sophisticated understanding of the practice. We define scaffolds as temporary supports that allow students to take part in complex tasks that they otherwise would not be able to accomplish independently. The purpose of scaffolding is to provide support to extend student competencies according to what students know (Bransford et al., 2000). Quintana and colleagues (2004) and Kali (2006) have suggested several guidelines that developers can use to design scaffolds that support students as they engage in complex tasks.

To support students in constructing scientific practices (McNeill & Krajcik, 2008a, Sutherland, et al. 2006), we broke down this complex task into simpler elements. We designed an instructional framework for scientific explanation that breaks down this complex practice into four components (McNeill et al., 2006; Moje et al., 2004):

1. A claim (similar to Toulmin's claim, 1958) is an assertion or conclusion that answers the original question or problem.
2. Evidence (similar to Toulmin's data) is appropriate and sufficient scientific data that is used to support the claim.
3. Reasoning (a combination of Toulmin's warrant and backing) is a justification that articulates why the data counts as evidence to support the claim by using scientific principles.

#### 4. Considering and ruling out alternative explanations.

IQWST also supports students in constructing, revising and communicating models of phenomena. We start to engage students in the model building process in the sixth grade (Shwartz, et al., 2008; Merritt, Shwartz, & Krajcik, 2008). We support students in constructing models by having them consider important criteria related to modeling. In constructing, revising and communicating models students need to apply five criteria:

1. Does the model accurately represent the phenomena?
2. Does the model account for ALL the evidence?
3. Can the model be used to illustrate, explain and predict new phenomena?
4. Is the model organized and labeled?
5. Does the model only include necessary information?
6. Does the model include only the most important components and relationships?

It is important to realize that these ideas are not introduced all at once. We start by introducing the first 3 criteria. As students gain experience with building models and develop understanding of the initial criteria, we introduce them to additional criteria for building modeling. Supporting some criteria initially and then focusing on others later in the curriculum is an example of how we scaffold students in complex practices.

The unique aspect of IQWST is that it introduces students to these practices in sixth grade and then uses and further builds upon these practices throughout the entire 6-8 curriculum. This continual using and building provides a structure for students to develop deeper and more sophisticated understanding of these practices across various domains (Schwartz, et al., 2008). This building and using of practices is an excellent example of inter-unit coherence as various units within and across the years link to and build on previous knowledge and as such promotes deeper and more sophisticated understanding of these practices. In IQWST, students experience constructing explanations, building and revising models, and using evidence throughout the middle grades.

The use of scientific explanations is central to helping students engage in key 21<sup>st</sup> century skills. In constructing models and writing scientific explanations students need to consider if all evidence is used. The research shows that most individuals do not consider all evidence, particularly if the evidence does not support their point of view (Sandoval & Millwood, 2005). IQWST's focus throughout the middle grades will help learners to consider all the evidence. Taking into consideration all evidence is a key aspect of adaptability and complex problem solving. Complex problems will not be solved unless learners use all the information they have available to them. In constructing models, learners also need to present their ideas to others in a clear and concise manner as well as only present the essential relationships, aspects essential to complex communication skills.

### ***3.0 How IQWST helps develop 21<sup>st</sup> Century Skills***

Because of IQWST's focus on 1) coherence, 2) building understanding of big ideas, and 3) using evidence to develop scientific explanations, and to construct and revise models throughout the middle grades, students who experience IQWST will develop important 21<sup>st</sup> century skills essential for scientific literacy. A major goal of IQWST is that students will question the claims

they read in newspapers and on the Web. As such, students who use IQWST will develop important 21<sup>st</sup> century skills, an aspect of non-routine problem solving. Above I discussed how various IQWST features help meet some of the 21<sup>st</sup> century skills. Next, I take a deeper look at how the IQWST curriculum materials help to meet each of these five 21<sup>st</sup>-century skills.

*Adaptability and the IQWST Curriculum:* Adaptability involves the ability and willingness of individuals to cope with uncertain, new, and rapidly changing conditions on the job, including responding effectively to emergencies or crisis situations and learning new tasks, technologies, and procedures. In IQWST we challenge students to build and revise models throughout the middle grades based upon evidence and phenomena. Realizing that models can change when new evidence is presented is an example of adaptability. Middle school students typically see science as “final form” (Duschl, et al., 2007); however, in IQWST, we challenge students to build models and to revise their models when new evidence is presented. For instance, in the sixth-grade unit that focuses on the particle model of matter, students build models of the behavior of gases. They build initial models to explain how an odor might travel across a room and then revise these models based upon experiencing new phenomena that a gas can be expanded and compressed and that a gas can be added and taken away from a rigid container (see Appendix 1, Figure 2).

Throughout IQWST students are expected to justify claims with evidence and reasoning. Teachers and other students will challenge claims that go unsupported. One-word answers are not acceptable. As such, students are challenged to justify their positions by providing evidence and using reasoning. As learners become more sophisticated in constructing explanations, they are also expected to rule out other possible explanations. This can be seen as another form of adaptability as students need to consider if they have sufficient and appropriate evidence to support their claims and if they don't, they need to write new claims that are supported by their evidence. *Appropriate* data needs to be scientifically relevant for supporting the claim. *Sufficient* data addresses whether or not the student has enough data to support his or her claim. (McNeill & Krajcik, 2008b)

*Complex communication skills and the IQWST Curriculum:* Complex communication/social skills require individuals to use skills in processing and interpreting both verbal and non-verbal information from others in order to respond appropriately. According to Levy and Murnane (2004), an individual skilled at communicating is able to select key pieces of a complex idea to express in words, sounds, and images, in order to build shared understanding. Throughout IQWST students must support claims by using evidence and reasoning. Too often, individuals in our society will accept claims made in newspapers, by politicians or on the web without considering the evidence and reasoning that is involved. In IQWST learners not only support claims both verbally and in writing but also evaluate and critique claims made by others. Learners need to know when the data they have is sufficient and appropriate to support an explanation. Because students use evidence and reasoning, writing and verbally presenting scientific explanation can be considered a complex communication skill.

In IQWST students also construct models, present their model to class members, and justify their models using the 5 criteria mentioned above. In particular, learners use evidence to argue that

their model accounts for all the phenomena. As students develop through the curriculum they also have to account that one model might be better than another.

A critical aspect of communicating with others is working in groups. Often, but not always, students construct explanations and build and revise models in groups where they consider evidence and reasoning. Often, groups will present their explanations and models to other students for critique and feedback.

*Non-routine Problem Solving and IQWST:* Non-routine problem-solving necessitates that an individual use expert thinking to examine a broad span of information, recognize patterns, and narrow the information to reach a diagnosis of the problem. Building models that describe and explain related phenomena is complex problem solving, as one model has to account for several related but differing phenomena. For instance, how can the particle model of matter account for phase changes as well as explain why different substances have difference properties. In IQWST, students are challenged to build models that explain a host of related phenomena. In addition, throughout the curriculum, students are challenged to use evidence and reasoning to explain phenomena.

As learners progress in the IQWST curriculum, they are presented with situations in which they need to rule out alternative explanations that can explain a phenomenon. Ruling out alternative explanations is an important component of non-routine problem-solving as students have to rule out alternatives. Moreover, providing sufficient and necessary evidence when building an explanation is not routinely done in school, but is the foundation of science and essential when problem solving.

IQWST materials challenge students to apply models and scientific principles to solve problems and explain phenomena. In the 6<sup>th</sup> grade IQWST unit that focuses on the particle nature of matter, students apply the particle models to solve and explain some real world problems. In the 7<sup>th</sup> energy unit, students use principles of energy transformation and transfer to build Rube Goldberg machines. In the 6<sup>th</sup> grade physics unit on light, students use light models that they construct to explain how mirrored sunglasses work.

IQWST also engages students in the design of investigations in which students need to specify dependent, independent, and control variables. The ability to carefully specify and describe variables is an essential component to complex problem solving because often individuals fail to control variables. Failure to control variables leads to assigning causation to a variable when the variable is not the cause.

*Self-management/self-development and the IQWST Curriculum:* Self-management/Self-development includes the ability of individuals to work remotely, in virtual teams; to work autonomously; and to be self-motivating and self-monitoring. One aspect of self-management is the willingness and ability to acquire new information and skills related to work. In IQWST, students evaluate and critique their own models and scientific explanations as well as those created by others. In the 6<sup>th</sup> grade students are give criteria to use to judge the models they build. Students use these criteria throughout the middle grades to evaluate their own models. In essence, these criteria become a thinking tool for model evaluation. In evaluating their models,

learners need to consider if the model they built accurately represents the phenomena or not. If not, then learners need to revise their models so that they do. Deciding if a model can account for all the evidence and explain a host of phenomena is a form of self-monitoring. As students advance in the curriculum, they are to consider if the model only includes necessary information. Again, this is a form of self-management.

When constructing scientific explanations, learners need to consider if they have sufficient and appropriate evidence. This reflection is another form of self-management. Many adults seldom consider if they have sufficient justification for making a decision. This practice helps learners to know when they have enough evidence to support their claims.

IQWST materials also support students in self-management as learners need to adhere to project guidelines and timelines as they take part in various projects. In the 7<sup>th</sup> grade unit on energy, *Why do some things stop and other things keep going?*, students apply the principles of energy transformation and energy transfer to build Rube Goldberg machines. This design project's success depends on managing various components, including managing and gather materials, adhering to a timeline, and meeting criteria for building the Rube Goldberg machine. Students also have to manage potential frustrations towards positive problem solving as initial plans fail and new plans need to be considered (note this aspect also relates to adaptability). In the 8<sup>th</sup> grade chemistry unit, *How do I get the energy to do things?*, students design and implement an experiment investigating one variable related to what plants need to grow. In this investigation, students manage data collection over a five-week period that requires them to monitor their investigations several times a week.

*Systems Thinking and IQWST:* Systems thinking requires that an individual understand how an entire system works, how an action, change, or malfunction in one part of the system affects the rest of the system; adopting a “big picture” perspective on work. During the IQWST curriculum, students explore various systems. For instance, students track the flow of energy in an ecosystem, consider how human body systems affect each another, examine the flow of matter in the rock cycle, and consider the mass and energy changes in closed and open-systems. Because these ideas are done within a year and across years and are linked to each other, students have opportunities to develop systems thinking.

In Table 1, I summarize how the IQWST curriculum helps learners meet various 21<sup>st</sup> century skills. Table 1 also presents evidence for supporting these claims. The next section describes the range of evidence we have in IQWST.

#### ***4.0 Effectiveness of the IQWST Curriculum Materials***

Individual IQWST units have been implemented and tested across numerous sites and over numerous years and have been shown to significantly improve students' learning of content and scientific practices. As mentioned above, IQWST was not designed intentionally to support students in developing 21<sup>st</sup> century skills. As such, we did not specifically assess these skills. However, inferences can be made whether students will develop 21<sup>st</sup> century skills because of our focus on building integrated understandings of big ideas over time and the focus on scientific practices.

**Table 1: 21<sup>st</sup> Century Skills and the IQWST Curriculum**

21 <sup>st</sup> Century Skill	IQWST Curriculum Materials: Learners	Evidence
Adaptability	<ol style="list-style-type: none"> <li>1. Modify and revise models when presented with new evidence.</li> <li>2. Use evidence and reasoning to support claims.</li> </ol>	<ol style="list-style-type: none"> <li>1. Students improve in building and revising models (see Shwartz, et al., 2008; Merritt, et al., 2008, Schwartz &amp; colleges, accepted).</li> <li>2. Students improve in using evidence and reasoning, (see McNeill and colleagues 2006, 2008a &amp; 2008b).</li> </ol>
Complex Communication Skills	<ol style="list-style-type: none"> <li>1. Support claims both verbally and in writing.</li> <li>2. Evaluate and critique claims made by others.</li> <li>3. Use evidence to argue that their model accounts for all the phenomena.</li> <li>4. Work in groups to construct models and explanations.</li> </ol>	<ol style="list-style-type: none"> <li>1. Students improve in supporting claims using evidence (See McNeill &amp; colleagues).</li> <li>2. IQWST engages learning in scientific explanations (See Krajcik &amp; colleagues, 2008).</li> <li>3. IQWST engages learners in accounting for all evidence. (See Merritt &amp; colleagues &amp; Swartz &amp; colleagues).</li> </ol>
Non-Routine Problem Solving	<ol style="list-style-type: none"> <li>1. Building models that describe and explains related phenomena.</li> <li>2. Use evidence and reasoning to explain phenomena.</li> <li>3. Providing sufficient and necessary evidence</li> <li>4. Specify and describe dependent, independent and control variables.</li> <li>5. Apply various models to solve problems.</li> </ol>	<ol style="list-style-type: none"> <li>1. IQWST engages learners in building models that explain a host of phenomena.</li> <li>2. In building explanations throughout IQWST, students use evidence and reasoning to explain phenomena (See McNeill).</li> <li>3. Learners improve in taking into account sufficient and necessary evidence (See McNeill and colleague).</li> </ol>

Self-management/self-development	<ol style="list-style-type: none"> <li>1. Evaluate and critique their own models and scientific explanations as well as those created by others.</li> <li>2. Use criteria to make judgments</li> <li>3. Consider if they have sufficient and appropriate evidence to support claims</li> <li>4. Self-management to adhere to project guidelines and timelines during various projects.</li> </ol>	<ol style="list-style-type: none"> <li>1. See Merritt &amp; colleagues, McNeill &amp; colleagues, &amp; and Shwartz &amp; colleagues.</li> <li>2. See Merritt &amp; colleagues and Schwartz &amp; colleagues.</li> <li>3. See McNeill &amp; colleagues.</li> </ol>
Systems Thinking	<ol style="list-style-type: none"> <li>1. Consider various systems that track the flow of energy in an ecosystem, consider how human-body systems affect each other, examine the flow of matter in the rock cycle and consider the mass changes in closed and open-systems.</li> </ol>	Although IQWST supports students in system thinking across various units, we have not assessed this idea as it was not a primary learning goal.

We have tested IQWST units in large urban areas, suburban areas, and rural areas. Teachers from public, charter, and private schools in Detroit, MI; Chicago, IL; Evanston, IL; Jacksonville, Florida; Lubbock, TX; Ann Arbor, MI; Tucson, AZ; the District of Columbia, and rural areas of Michigan have implemented IQWST materials. Most are public school teachers from large urban districts. Students from these schools are on free or reduced fee hot lunch programs and are from backgrounds that put them at risk for success in science disciplines.

The IQWST assessment program includes tracking student learning from pre- to post-tests and examining how students perform on writing scientific explanations and on constructing and revising scientific models. The IQWST pre- and post-test design includes low, medium, and high cognitive level items. We collect and analyze classroom artifacts of students' written work and their models. Lastly, in a small subset of schools we videotape students' verbal presentations in which they justify their models or scientific explanations.

We have conducted a number of studies examining students' learning in various units using pre- and post-tests measures as well as the student-written artifacts. These studies all show effect sizes that support the claim that student learn both for science concepts and scientific practices. These studies have been reported in various studies (McNeill, & Krajcik, 2008a; McNeill, et al., 2006; Merritt, Shwartz, & Krajcik, 2008; Shwartz, et al., 2008).

Table 2 below shows results from the enactment of the 2004 – 2005, 7<sup>th</sup> IQWST unit that focuses on helping students learn the nature of chemical reactions, *How can I make new stuff from old stuff?* (herein, *Stuff*). There were a total of 2057 valid pretests and 1838 valid post-tests after data cleaning and recapture. This yielded 1554 matched pre-test/post-test pairs. Attrition amounted to 503 students or 24%. The final scored version of the Stuff test had a maximum possible score of 30 points including 15 multiple choices and 4 (15 maximum score) open-ended questions. All gains were significant at  $p < .001$ . Raw gain was 5.68 points out of 30, or a percentage gain of 19%.

The pre- and post-test consisted of a combination of multiple choice and open-end items. Open-ended items, as well as some of medium cognitive items, blended the use of key content ideas as well as scientific practices. The multiple choice and open-ended items were categorized into one of three cognitive levels (Anderson & Krathwohl, 2001): lower (recalling information; understanding simple and complex information); middle (drawing or understanding simple relationships; applying knowledge to new or different situations; shifting between representations such as verbal to graphic; scientific processes such as identifying hypotheses, procedures, results, or conclusions); and higher (describing or analyzing data from charts and graphs; constructing explanations, building models; drawing conclusions; applying investigation skills; and using concepts to explain phenomena). IQWST ensures content validity by creating items based on a matrix that reflects the relative importance of the learning goals for the unit.

**Table 2: Results from 2004 – 2005 *Stuff* Enactment**

	Pretest Mean (SD)	Posttest Mean (SD)	Gain Mean (SD)	Effect Size
Total Score (30)	7.17 (3.57)	12.78 (6.41)	5.60 (5.14)	1.57***
Multiple Choice (15)	4.84 (2.31)	8.23 (3.59)	3.40 (3.21)	1.47***
Open Ended (15)	2.34 (1.95)	4.55 (3.46)	2.20 (3.01)	1.13***
Level 1 (8)	2.52 (1.47)	4.60 (2.09)	2.07 (2.06)	1.41***
Level 2 (10.75)	3.11 (1.71)	4.86 (2.53)	1.75 (2.38)	1.02***
Level 3 (11.25)	1.55 (1.56)	3.32 (2.76)	1.78 (2.42)	1.13***
<b>Content Clusters</b>				
Substance and Property (8.75)	2.26 (1.68)	4.29 (2.30)	2.03 (2.09)	1.21***
Chemical Reaction (11.625)	3.16 (1.73)	5.28 (2.62)	2.08 (2.50)	1.23***
Conservation of Mass (9.625)	1.75 (1.36)	3.24 (2.32)	1.49 (2.15)	1.10***

\*\*\* p<.001., \*\* p<.0., \* p<.05.

The results in Table 2 (and other published studies) demonstrate significant learning gains for learners from a variety of school districts who have teachers with diverse backgrounds. These results support the intra-unit coherence of IQWST materials. Unfortunately, we did not assess 21<sup>st</sup> century skills, but we have strong evidence that IQWST supports students in building understanding of big ideas, both in terms of content and scientific practices. As much as people are convinced that constructing scientific explanations, building and revising models, designing investigations, and building products promote 21<sup>st</sup> century skills, IQWST assessments provide evidence that students learn 21<sup>st</sup> century skills.

We are currently conducting a national field test trial where we are examining student learning across the units within a year and across years. In this work we are tracking students across three years of using the IQWST materials and are examining student learning using a matched comparison group. The IQWST national field test design follows a cohort of students for three years and requires a whole-school design. Students in IQWST and a matched comparison group take a benchmark-aligned assessment at the beginning of 6<sup>th</sup> grade and the end of the 6<sup>th</sup>, 7<sup>th</sup> and

8<sup>th</sup> grades. The *benchmarks-aligned assessment* is an externally created, distal measure that includes a representative sample of middle grades science content and is only given to IQWST students. IQWST-aligned assessments, the proximal measures, are also externally created. This measure is an external but proximal measure of the curriculum's effectiveness. The proximal assessments are aligned with the IQWST units. They assess only the content addressed in the curriculum and may use some of the same representations and contexts included in the units. Only IQWST students take the proximal measure. The distal measure is aligned to national standards in science education. The assessment samples content is found in the *National Science Education Standards* and the *Benchmarks for Science Literacy*, whether or not the content is found in the IQWST curriculum. IQWST students take pre- and post-tests for each unit, a near measure developed by the IQWST team. Although we have finished one year of the national field trial, it is too early to present results. However, tentative findings indicate that IQWST and comparison students scored similarly on the end-of-year benchmark-aligned test. This finding is not surprising given that the assessment measures a full three-year middle school science education. Both the IQWST students and the comparison group have only experienced one year of science learning but received a test that sampled all the middle school standards. As IQWST students experience more of the material, we expect them to perform significantly higher than the comparison group.

#### ***4.1 How effective is the IQWST curriculum in developing 21<sup>st</sup> century skills?***

McNeill and colleagues have fairly strong and repeatable evidence that students improve in constructing scientific explanation across a unit (McNeill et al., 2006; McNeill & Krajcik, 2008a, 2008b, Krajcik, McNeill & Reiser, 2008; Merritt, Shwartz, & Krajcik, 2008). Students improve in all components of constructing a scientific explanation; however, less progress is seen in the reasoning component. One possible explanation for seeing less progress in reasoning is that the reasoning component is the most complex aspect of writing scientific explanations. In writing their scientific explanations, students will often not explain why they chose certain data or explain a key scientific practice. Learners have difficulty articulating what scientific principle is needed to show that the evidence they selected supports the claim. This is not surprising, as students need to coordinate the use of new scientific ideas to support their position. As students gain experience in using various scientific ideas, their use of reasoning should improve. This suggests that articulating scientific principles is challenging for students and indirectly shows challenges in developing complex communications skills.

We also have evidence that students improve in constructing and critiquing models (Shwartz, et al., 2008; Merritt, Shwartz & Krajcik, 2008, Schwartz, et al., accepted). Appendix 1, Figure 2 illustrates a student's growth in constructing models of how an odor (gaseous state) moves from a source to a detector (nose). This embedded assessment activity comes from the 6th grade IQWST unit, "*How can I smell things from across the room?*" (herein *Smell*) in which students develop models of the particle nature of matter (Merritt, Shwartz & Krajcik, 2008). In this embedded assessment activity the classroom teacher opens a jar that contained an odor while students have their eyes closed and asks students to raise their hands and open their eyes when they smell an odor. The teacher then directs the students to imagine that they have a very powerful microscope that allows them to see the odor up really, really close. What would you see? Figure 2 shows a learner developing a more sophisticated model of the particle nature of matter as the unit progresses. This evidence provides indirect support for students developing

non-routine problem solving and adaptability. Because the IQWST units result in growth in students' construction of scientific explanations and the construction and revision of models, IQWST provides indirect evidence that learners develop 21<sup>st</sup> century skills of adaptability, complex communications/social skills, non-routine problem solving, and self-management/self-development.

#### ***4.2 How do IQWST's design principles account for the improvement in student learning?***

We have tentative evidence that IQWST improves students' understanding of the big ideas of science (both content and practices). What can account for student growth? The careful focus IQWST developers have placed on unpacking standards, creating learning performances and building coherence both within and across units partially accounts for the results. The unique aspect of IQWST is that it introduces students to various core science content and scientific practices in sixth grade and then further builds upon these core ideas and practices throughout the middle grades (Krajcik, McNeill & Reiser, 2008; Fortus & Krajcik, submitted). For instance, the particle nature of matter is first introduced in the 6<sup>th</sup> grade and this idea is refined and further developed in the 7<sup>th</sup> and 8<sup>th</sup> grades. As argued above, having an integrated understanding of core ideas is essential in knowing what you know and being able to self-develop when problem-solving.

A challenge for the designers is making sure to link back to make connections to students' previous experiences. This is not easy work and requires the designers to make multiple passes through the materials. This idea of building through a year and across years is not characteristic of curriculum in the US. Intra-unit and inter-unit coherence does not allow the IQWST materials to "cover" as many ideas as more traditional textbooks do and most state standards expect. Building and linking ideas across time takes time; however, such learning can result in students being able to apply, use, and build on these ideas. This is the scientific question, however, that IQWST is asking: Does spending time on linking and building on core ideas and scientific practices lead to deeper and more integrated understanding? Because of IQWST's focus on practices and use of ideas across time, students who experience IQWST should develop important 21<sup>st</sup> century skills; however, this hypothesis also needs direct evidence.

IQWST has other design features such as the creation of meaning contexts in which students experience phenomena, explore answers to a driving question, and ask their own related questions, experiencing multiple representations of phenomena, and students collaborating together (Krajcik, Slotta, McNeill, & Reiser, 2008). IQWST has also developed student reading materials that build upon, expand on and re-represent ideas present in class using considerate text (Sutherland, 2008). These additional design features are aligned with what is known about promoting learning (Bransford, Brown, and Cocking, 1999; Duschl, Schweingruber, & Shouse, 2007). These research-based features can also account for the findings. As of yet, we have not tried to separate out the effects of these various design features.

#### ***5.0 Meeting the Challenge of the 21<sup>st</sup> Century***

As the United States becomes more based on a global economy in which information freely flows across the world, our children will need to apply and communicate ideas, make sound decisions based on evidence, and collaborate with others to solve problems. These activities all require a deep and interconnected understanding of the fundamental ideas underlying these

problems. Unfortunately, curriculum materials and instructional practices used in the United States are not helping our children develop the knowledge and skills necessary to compete in the 21<sup>st</sup> century. IQWST, through its learning goals driven design process, intra-unit and inter-unit coherence, and design features has created materials to address this problem and help middle grade learners develop the understanding of the big ideas of science and key skills to prepare them for the 21<sup>st</sup> century. Based on the IQWST experience, coherent curriculum with embedded key design principles should support students in learning the big ideas of science and because of the focus on scientific practices, also support learners in developing 21<sup>st</sup> century skills. IQWST's coherent curriculum materials have the potential to produce a populace that is scientific literate and is prepared for new jobs and work skills of the 21<sup>st</sup> century. This assumption, however, needs empirical support. The IQWST national field test design will provide some data to support or refute this hypothesis. The IQWST materials, however, need to be tested using a more careful experimental design in which teachers are randomly assigned to using the IQWST materials or some other materials, and then teachers using the IQWST materials must be tracked to see if they are implementing the unit according to the designers' intent. The IQWST materials need to be tested to verify that the intense development work the designer underwent to create coherent materials actually make a difference and lead to a more integrated understanding. But to do so requires that teachers use the materials as intended. We know that teacher implementation of materials make a difference in student learning (O, Donnell, 2008; McNeill & Krajcik, 2008); hence, we need to track teachers' implementations. Such an effort will require intense professional develop to help teachers use the materials as intended.

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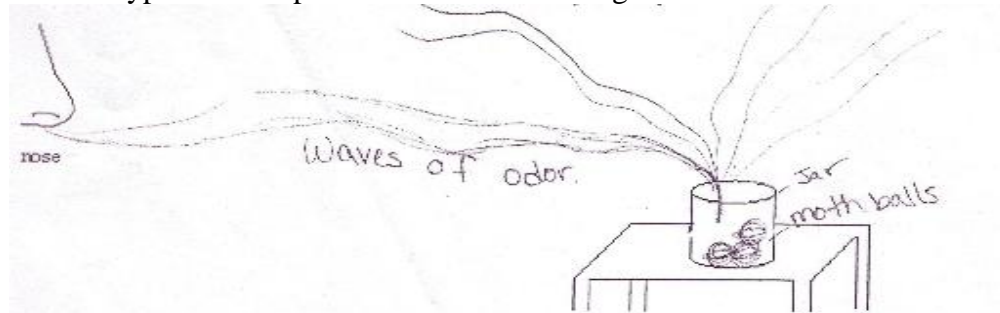
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## Appendix 1, Figure 2: Progression of Student Models through a Unit

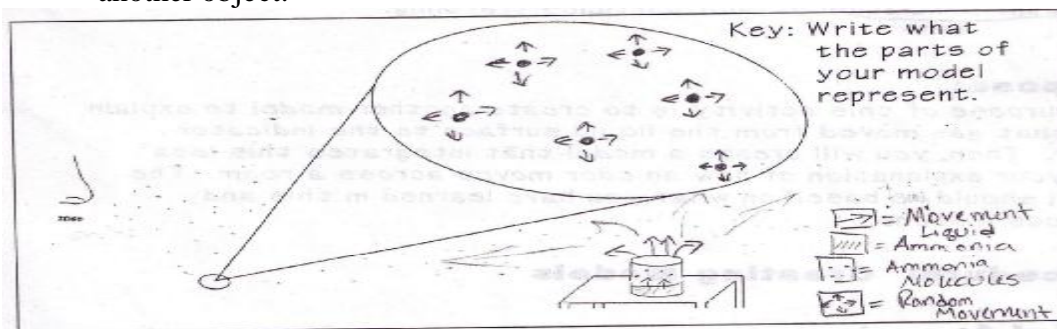
### Students initial models

- 45% of students created continuous models
- Typical description: The odor is coming out of the source



### Lesson 5 student models

- 52.3% of students created a particle nature of matter model
- 70.5% of models include movement
- Typical description: Molecules in the liquid come off the surface of the liquid and become a gas. They move around and change direction when they come in contact with another object.



### Lesson 15 student models

- 75% of students create a particle model, 25% a mixed model
- 68% of students include odor particles that are moving in straight lines until they collide into each other; 32% include both odor and air
- 55% of students' written portion of models explains movement of particles; 25% include incorrect mechanism

