Guiding the "Explain":
A Modified Learning Cycle Approach Towards Evidence on the Development of Scientific Explanations

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BioKIDS: An Animated Conversation
On the Development of Complex Reasoning in Science

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Abstract

Scientific literacy involves the ability to read with understanding, determine salient from irrelevant information, explain and predict scientific events, and evaluate and apply evidence and arguments. For many decades, scientists and science educators have worked to develop curricular programs that systematically promote scientific literacy, even as the definition of literacy and the intended audience has evolved with time. Based on current learning theories of how children learn, what do we know about how to best guide students in the development of deep understanding of and reasoning with scientific information? How do we transform digital resources into cognitive tools to support the development of deep understanding of scientific information? This chapter presents a case study of one project's efforts to design learning technologies and curricular activities to support inquiry readiness and complex reasoning around biodiversity and subsequent science topics. Research results support the value in content hints in learning to determine salient from irrelevant data for the construction of scientific claims and evidence. Lessons learned are presented relative to the transformation of the technology from digital resource to cognitive tools and the design of curricular scaffolds.

Introduction

> "All one can do for a learner en route to her forming a view of her own is to aid and abet her on her own voyage. The means for aiding and abetting a learner is sometimes called a "curriculum," and what we have learned is that there is no such thing as *the* curriculum. For in effect, a curriculum is like an animated conversation on a topic that can never be fully defined, although one can set limits upon it. I call it an "animated" conversation not only because it is always lively if it is honest, but also because one uses animation in the broader sense—props, pictures, texts, films, and even "demonstrations". So the process includes conversation plus show-and-tell plus brooding on it all on one's own." (Bruner, 1996; p. 115-116)

The art of developing and utilizing curriculum materials to foster understanding involves, as mentioned above, an active conversation between learners and materials. For decades, scientists and science educators have struggled to develop curriculum materials that support current definitions of scientific literacy. Presently, definitions of scientific literacy include understandings of specific facts and concepts in science as well as several kinds of complex reasoning including determining salient from irrelevant information, explaining and predicting scientific events, reading with understanding, and evaluating and applying evidence and arguments appropriately (National Science Education Standards, 1996). Drawing on current theories of learning (e.g. Bransford, Brown and Cocking, 2000), it seems reasonable to expect that the development of this extensive repertoire of scientific facts and reasoning skills would take many years and multiple exposures as well as a recognition of how to work with early, middle and advanced levels of understanding and reasoning.

Interestingly, while many curricular programs outside the United States have been developed to support sequential building of concepts and reasoning in science (e.g. Japan), American pre-college science curricula rarely take into account the organized and longitudinal development of science concepts or reasoning skills. This reality suggests a conundrum: If learning theories suggest that the development of concepts and reasoning in science takes a long time and repeated exposures to concepts and reasoning skills, why are nearly all American curricular programs in science focused around a single science topic and contain no organized efforts to foster complex reasoning over time or topic? This chapter presents a case of a year-long curricular program designed to systematically foster and evaluate science content development and complex reasoning in science across a year of curricular units. The case describes information on how one research project has addressed the challenge of "aiding and abetting" learners' journeys towards understanding fundamental ideas about science, including articulation of both *what* scientific knowledge should be emphasized and *how* it should be presented to learners.

What Do We Mean by Complex Reasoning in Science?

> "Science literacy means that a person has the ability to describe, explain and predict natural phenomena…Science literacy also implies the capacity to pose and evaluate arguments based on evidence and to apply conclusions from such arguments appropriately." (National Research Council, 1996; p. 22)

As stated in the National Science Education Standards, contemporary thinking about what it means to be a scientifically literate citizen includes more than just an understanding of scientific facts or concepts in the earth, life or physical sciences. Science literacy also includes several types of complex reasoning abilities such as explaining, predicting, posing scientific arguments based on evidence and applying conclusions to new contexts. Contemporary theories of how children learn science discuss the necessity of both a strong foundation of scientific concepts and an understanding of the relationships between facts or concepts, in other words knowledge that represents the interdependence of science concepts and scientific reasoning skills such as explaining or posing arguments based on evidence. Scientists and science educators call the scientific knowledge that includes both concepts and reasoning skills **science inquiry** (National Research Council, 2000). Scientific inquiry represents modes of thinking and the processes of knowledge-building commonly associated with experts in the science disciplines, but often poorly transformed into classroom-based learning by students. A particular focus on fostering scientific inquiry is congruent with research in the cognitive and learning sciences supporting students' questioning and the guided investigation of scientific questions as an essential means of achieving deep content understanding (National Research Council, 1996, 2000; Minstrell and van Zee, 2000; Bransford et al, 2000).

Many science educators and scientists view the development of science inquiry as an essential focus of pre-college science education (e.g. National Research Council, 2000; Minstrell and Van Zee, 2000). While many standards and policy documents also value students' complex reasoning such as the guided investigation of scientific questions (e.g. National Research Council, 1996; 2000), many schools are often caught between fostering inquiry and intense pressure to perform well on high-stakes tests. This tension often results resulting in overzealous efforts towards test-preparation activities at the expense of other time-consuming activities, such as inquiry-fostering activities.

Another enduring challenge of programs that foster students' development of inquiry has been the struggle to focus on articulate reasoning skills within the larger definition of scientific inquiry. To address this challenge directly, this project selected three specific areas of scientific inquiry to focus on in our curricular programs and to constitute our definition of complex reasoning in science. These three specific areas of science inquiry are:

a. The **formulation of scientific explanations** from evidence
b. The **analysis of** various types of **scientific data** (charts, graphs, maps)
c. The **building of hypotheses and predictions** (based on relevant evidence)

These areas were selected to promote our ability to both foster and determine empirical outcomes relative to our success at fostering specific, measurable aspects of scientific inquiry, both within and across curricular units.

Curricular Activity Structures to Promote Scientific Literacy

The design of curricular programs to promote scientific literacy is an enduring challenge for science educators. In the early 1960's, Robert Karplus presented a curricular framework for the learning of science called The Learning Cycle that included both what science knowledge should be learned and how it should be presented,

> "There is a way in which autonomous recognition of relationships by the pupils, i.e. "discovery" can and should be combined with expository introduction of concepts in an efficient program. This will produce

> understanding rather than rote verbalization." (Atkin and Karplus, 1962; p. 45)

The Learning Cycle was one of the first systematic attempts to outline a sequence of how and when certain ideas in science should be introduced to students in order to promote deep conceptual understanding of scientific ideas. Rooted in the learning theories of Piaget, Karplus' Learning Cycle included a sequence of activities that recognized Piagetian concrete and formal reasoning (e.g. Karplus, 1977). Interestingly, Karplus' work also challenged Piagetian stage theory, including Karplus' belief that activities that foster complex reasoning should not "wait until development has occurred spontaneously" (Karplus, 1977; p. 368).

The foundational sequence of the Learning Cycle consists of three instructional phases: *exploration*, *concept introduction/invention*, and *concept application*. In *exploration*, students work with scientific data or materials to ask questions, gather data, and engage with scientific phenomena, often in contexts that are scientifically authentic. In *concept introduction/ invention* a central scientific concept is defined relative to the experiences and questions raised in the *exploration* phase. In *concept application,* students apply the new definition or principle to a new or similar context or situation. The cognitive activity of *concept application* extends the understanding of the principle beyond a single problem context or situation. In subsequent years, additional researchers such as Roger Bybee and others at Biological Sciences Curriculum Study (BSCS) extended the learning cycle to five phases called: *engage, explore, explain, elaborate and evaluate* (Bybee et al., 1989).

While the Learning Cycle was introduced for elementary-age students as a part of Science Curriculum Improvement Study (1970-1974), it was later adapted for middle and high school students. In his efforts to systematically incorporate contemporary learning theories of the time in the development of curricular activities to foster complex reasoning in science, Karplus' ideas demonstrate that he was ahead of his time, both in the design of structures that promote the development of complex reasoning in general and in the promotion of complex thinking among younger students, e.g. students in their late elementary or early middle school years that under a strict interpretation of Piagetian stage theory might not be seen as developmentally able to perform complex reasoning.

Several others have outlined visions for the best means to promote deep conceptual understandings of content. Bruner (1996) introduced the idea of a "spiral curriculum" that builds from intuitive to a more structured understanding of concepts through repeated revisiting of the concept with increasing complexity. John Bransford and colleagues articulated a vision of subject-matter competence that drew on contemporary thinking in the cognitive and learning sciences,

> "To develop a competence in an area of learning, students must have both a deep foundation of factual knowledge and a strong conceptual framework…key to expertise is the mastery of concepts that allow for deep understanding of that information, transforming it from a set of facts into usable knowledge." (Bransford, Brown and Cocking, 2000; p. 16)

While the Bransford and colleagues vision emphasized the development of both factual knowledge and a conceptual framework, they were less articulate about a curricular sequence that might systematically support the development of this deep conceptual knowledge.

Learning Theory Underlying the *BioKIDS* Research Project

Constructivism is a learning theory championed by Piaget (e.g. Inhelder and Piaget, 1958), Von Glaserfeld (1998) and others that recognizes learners as active agents involved in the process of acquiring new information. In constructivism, learners bring existing ideas, beliefs and concepts to the learning context, and these ideas and understandings influence their organization and interpretation of new material. Since the introduction of the idea of active learners and constructivism, scholars from a range of disciplines have struggled with the application of constructivism to classroom settings (Bransford et al, 2000). While many explanations for why the application of constructivism to classroom-based research is difficult exist, one explanation is that the theoretical perspective is more successful at characterizing the *relative activity* of learners and knowledge, e.g. interacting in active ways with each other (Piaget, 1978; Vygotsky, 1978), than in articulating *the processes* by which this activity of learners and knowledge occurs.

Without an understanding of the processes by which learning occurs, the translation of theoretical constructs to pedagogical supports or activity structures that might facilitate this learning remains daunting, vague or both.

BioKIDS has as a major goal the support of complex reasoning in science through the exploration of the idea of "inquiry readiness" through several sequential inquiry-fostering curricular units. This term "inquiry readiness" is used to describe an idea that is currently supported by literature (e.g. Bruner, 1996) but, to our knowledge, not yet examined in the ways described here. As Bruner articulates, complex knowledge development can be fostered in younger children assuming appropriate work is done to translate the complex reasoning into appropriate levels of abstractness of complexity, (e.g. "readiness is not only born but made" (1996; p. 119).

One of the priorities of BioKIDS curricular units is the recognition of late elementary and early middle school students as a pivotal population for the development of complex reasoning in science. International assessment results demonstrate that between fourth and eighth grade, American students under perform on high-stakes tests relative to their peers internationally (Linn, Lewis, Tsuchida, and Songer, 2000; **add recent TIMSS results**).

The BioKIDS research project investigates the development of curricular activity structures in science that builds productively on current learning theories. This work contributes to others' research on curricular frameworks and activity structures that foster inquiry understandings in science (Clark and Linn, 2003; White and Fredricksen, 1998; Linn, Lewis, Tsuchida and Songer, 2000), as well as work on the design of educational supports that provide guidance for children and adolescents as they reason about complex scientific phenomena (e.g. Metz, 1995, 2000; Pea, 2004). This work also falls under the broad exploration of research that seeks to understand how learners develop capacity for complex science though the use of innovative educational technologies.

Research on students' development of complex reasoning in biology suggests that fostering complex thinking about living things and animal interactions is not easy. Previous research has shown that children often lack critical thinking skills related to the complexities of animals' lives and their interaction with surrounding environments (Carey, 1985). Furthermore, research has shown that children often display many alternative concepts related to food and energy, predator/prey relationship, and population size (Leach, Driver, Scott and Wood-Robinson, 1992).

On balance, developmental researchers provide evidence that young children understand basic principles of biology and that these understandings provide an opportunity for students to build productively towards advanced reasoning at younger ages. However, while research in cognitive development by individuals such as Kathy Metz (Metz, 2000) demonstrate that young students are highly capable of higher order thinking and complex reasoning in biology, few science programs at the late-elementary age challenge students in this way. Many current activities for elementary students oversimplify concepts, and investigations are limited to observation or classification of animals based on physical characteristics (Barrett & Willard, 1998). Activities seldom go beyond simple isolated facts of individual animals to address relationships between animals and habitats/environments or develop understandings of advanced concepts like adaptation and conservation. Collectively, post-cognitive revolution research suggests that fifth and sixth grade students are capable and ready for complex thinking about, for example, animal relationships and adaptation, but they are rarely provided with the challenge and supports needed to pursue these kind of queries.

In addition, many policy documents discuss the value of fostering scientific inquiry over multiple topics of extended periods of time, but rarely is this research conducted. Clark and Linn's (2003) research on the length of time of curricular units provided empirical evidence that longer interventions result in deeper conceptual understandings of physical science concepts, but this research approach is unusual leading to few studies of this kind. While some research projects are able to provide convincing standards of evidence that inquiry reasoning development has occurred (see for example White and Fredricksen, 1998), many groups cannot demonstrate such evidence, no doubt in part because the duration of intervention and study is often only a few weeks rather than several months or years. Therefore, despite the emphasis in policy documents and standards, few curricular programs or research studies focus on the systematic, appropriate level of the development of reasoning over several weeks, months, years or curricular units.

As implied in Bruner's comment about readiness being both "not only born but made", research on children's knowledge development suggests that the development of complex reasoning requires assistance (e.g. Bransford et al, 2000; add other jls scaffolding papers here), and that more or different kinds of assistance may be necessary at different stages of development or in different contexts, such as real-world settings (e.g. Lee and Songer, 2003**;** Palinscar and Brown, 1984). Research demonstrates that science activities that are grounded in a real-world context can be particularly difficult for novice students, particularly when students are expected to use more extensive repertoire of discipline-based knowledge to determine salient from irrelevant variables (Lee and Songer, 2003). As suggested by Lee and Songer (2003), activity structures can be one effective means of structuring student experiences, managing problem complexity, guiding students to relevant evidence, and supporting the development of learning attempts.

BioKIDS curricular programs were developed to work directly with the challenge of under-performance by 4-8th grade science students towards the first systematic introduction to inquiry thinking experienced by cohorts of science students. BioKIDS curricular units place a high value on the development of inquiry readiness (Songer, 2003) and inquiry reasoning over time. The priority on inquiry readiness arises from the idea that as 10-11 year olds, many American students are unfamiliar with many of the dimensions of complex reasoning in science such as analyzing data or building scientific explanations from evidence.

Therefore there is a need for a systematic introduction and sequential building of opportunities for reasoning about complex scientific phenomena as opposed to more traditional or test-driven curricular programs that limit inferring, predicting, or constructing knowledge. BioKIDS curricular units are designed to provide this foundational support for early and systematic, sequential development of higher-order thinking in science.

A final priority of the BioKIDS program is a focus on a specific audience: high-poverty, urban students. Recent appeals for "scientific literacy for all" highlight the importance of providing powerful educational experiences for those students who traditionally have been poorly served by many innovations school programs. Through iterative research on curricular and technology programs for high-poverty urban audiences, this work goes beyond fundamental questions asked by many educational researchers with curricular innovations such as "Will it work?" More specifically, the BioKIDS project ask a more difficult research question—"Will it work in some of the most challenging school environments?" In this work, BioKIDS studies include data collected on cohorts of Detroit Public School students as they build inquiry understandings with several coordinated curricular programs designed and implemented through an approach that challenge urban school norms and the pedagogy of poverty (Haberman, 1991; Songer, Lee and McDonald, 2003).

Collectively, inquiry readiness and constructivist learning theories suggest a systematic development of complex reasoning such as inquiry science over time and topic. Inquiry reasoning in science involves several different kinds of thinking that are often poorly articulated and sometimes confused into a simplistic definition or set of tasks. A program such as BioKIDS that can articulate specific areas of science inquiry (e.g. formulation of explanations, analysis of data and building hypotheses) and that can that systematically examine appropriate means and sequence for building complex reasoning skills may provide an approach to "jump starts" advanced scientific reasoning of capable learners towards a productive foundation for more advanced reasoning in subsequent units and years. Therefore, the goal of inquiry readiness in BioKIDS is to provide a learning-theory driven, curricular-focused, systematic, and guided approach to the particular kinds of complex reasoning in science for students encountering systematic inquiry reasoning for perhaps the first time as 10-11 year old students. This approach builds on the learning approaches of the cognitive and learning sciences (e.g. Bransford et al, 2000) and serves to provide empirical evidence that late elementary and early middle school students are cognitively capable of complex reasoning in science and that when provided with inquiry-fostering activities and appropriate assistance, can begin to develop dimensions of this kinds of thinking performed by older students or scientists.

In summary, The BioKIDS project builds on research in the learning sciences and science education to address research priorities associated with "science for all" and particular dimensions of scientific inquiry for a pivotal population of late elementary and early middle school students from high poverty urban schools. BioKIDS research focuses on cohorts of students' knowledge development over multiple, sequential curricular units specifically designed to recognize the "fits and starts" of the development of complex reasoning throughout an academic year. This work is developed in contrast to studies that evaluate learning relative to a single curricular unit or a short period of time (Songer, 2003).

From Digital Resource to Cognitive Tool

A central component of today's scientific literacy is the appropriate use of technology to support learning goals (Bransford, Brown and Cocking, 2000; National Research Council, 1996). While American schools are experiencing nearly ubiquitous presence of computers and technology (XXXX), much current research documents the underutilization of digital resources by teachers and students (e.g. Cuban, 1993), particularly uses associated with the development of complex reasoning such as inquiry science.

While educational research suggests several ways in which technologies can be used to foster the kinds of complex reasoning in science we desire, (e.g. scaffolds to enhance learning, more opportunities for feedback and revision, building local and global communities; Bransford et al, 2000), many complexities remain relative to our understanding of best means to utilize learning technologies effectively in the higher-order learning of science. Scientists utilize technology for many specific means of support in higher-order thinking including advanced analysis, modeling, and data representation (XXXX). Unfortunately, children's use of technology for science learning is not identical to the uses by scientists, even if some selected features are the same. What is required is the transformation of adult-designed tools into an appropriate version for children, and this translation process is far from simplistic or understood (Songer, 2004). The transformation process requires an examination of the focus audience, cognitive benefits of the resource and learning goals associated with the learning task. Without such an examination and transformation of the digital resource, it is unlikely that the adult-orientated resource can be used productively by pre-college learners.

Recognizing this need to translate rich digital resources into cognitive tools, the BioKIDS group began our work in this area with a search for rich digital resources that had the potential for becoming cognitive tools to foster inquiry reasoning around concepts of biodiversity and ecology. Our search revealed two resources with rich potential: CyberTracker [www.cybertracker.co.za/] and the Animal Diversity Web [animaldiversity.ummz.umich.edu/]. At the beginning, we recognized that each of these resources were resource-wealthy, even if they were not yet translated into effective learning resources for 5th and 6th graders.

As illustrated in Figure 1, CyberTracker is an icon-based interface that runs on a Palm OS handheld computer and was developed by professional African animal trackers to quickly record animal sightings and identification in the field. While the original CyberTracker sequence was designed to track and record African animals, we recognized CyberTracker's potential as a cognitive tool for Michigan-based student data collection of animal data relative to determining the biodiversity of schoolyard zones.

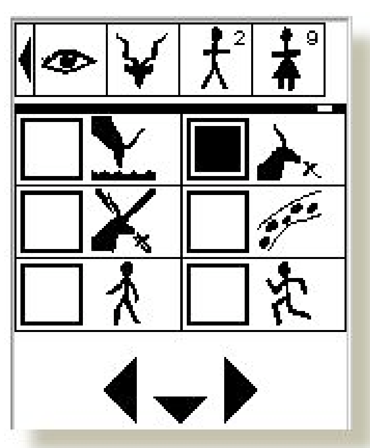


Figure 1: CyberTracker Icon-based Entry for Recording Field-based Data

The second tool, The Animal Diversity Web (ADW), is a database containing information on the natural history, distribution, classification, and conservation biology of animals all over the world. ADW presented rich potential as a cognitive tool in the rich array of species accounts and information for student queries relative to the animals they were observing and studying in their schoolyard zones. Figure 2 displays a sample screen from the Animal Diversity Web.

Once we had selected these learning technologies for transformation into cognitive tools, we began the examination of audience, cognitive benefits of the tool, and learning goals. Concerning audience, we found the icon-based, data entry format of CyberTracker to be a good fit for our audience of young and language diverse audience of urban 5^{th} and 6^{th} graders. Therefore our transformation relative to audience of CyberTracker involved little language adjustment for a younger audience. In contrast, ADW contained a great deal of rich scientific information on animal species but the reading level was far too complex for our target audience. In order for 5^{th} and 6^{th} graders to use species information in ADW, we needed to find a means of translating scientific text into language and presentation formats well-suited to

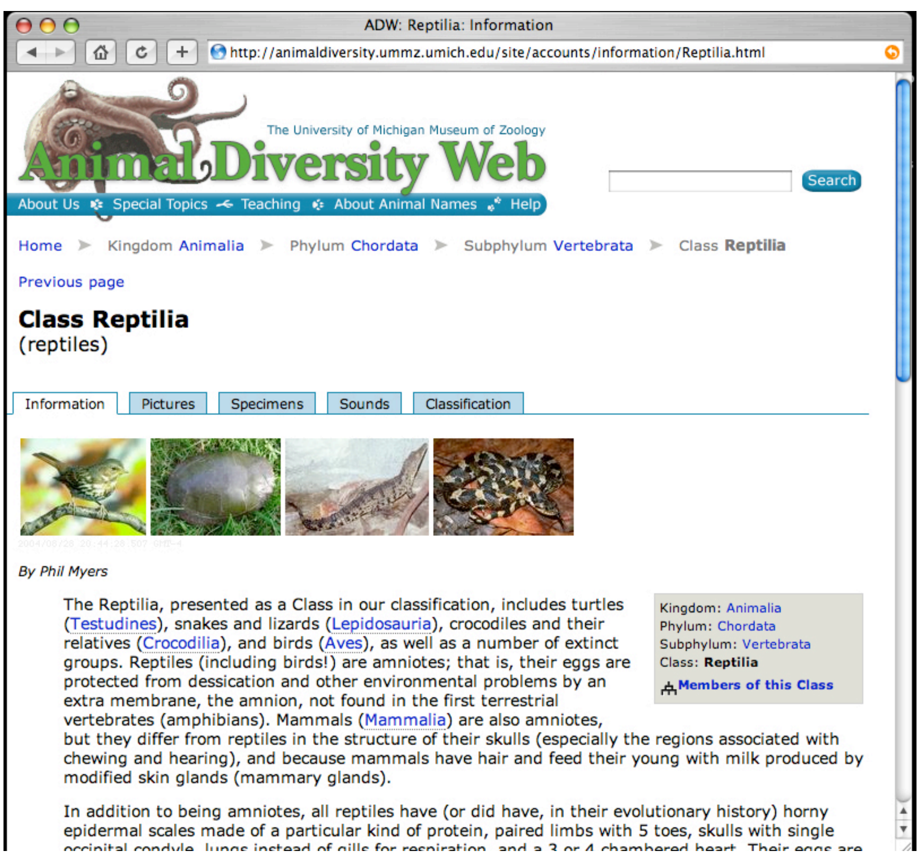


Figure 2: The Animal Diversity Web

middle school children. The result of our translation is the Critter Catalog, a web-based database containing natural history, distribution, classification, and conservation biology information for Michigan-based animals written at a middle-school appropriate reading level. Figure 3 illustrates a screen from the Critter Catalog,

The second transformation step involved an examination of the cognitive benefits of the learning tool relative to our desired learning goals. This process began with a review of the learning goals emphasized in each of our curricular units, and an examination of how each tool might be utilized towards these goals. As mentioned earlier, our curricular units are focused

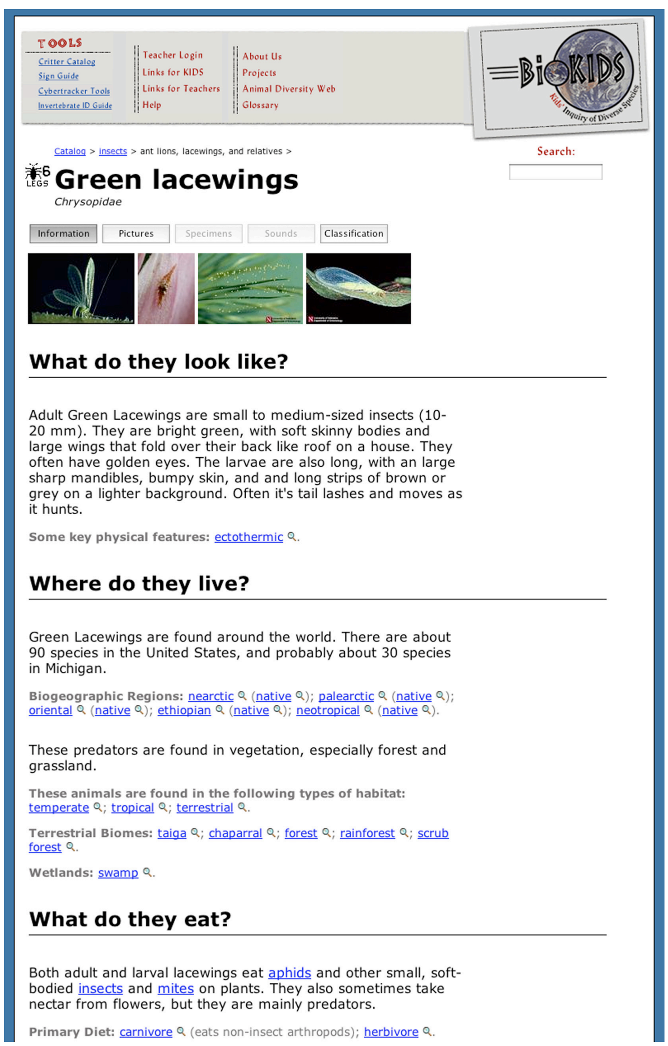


Figure 3: The Critter Catalog

around three dimensions of inquiry reasoning: building explanations from evidence, analyzing data, and making hypotheses and predictions. For each of these goals, the collection and organization of accurate scientific data was essential. Therefore we began the process of rewriting the CyberTracker code to focus on children's accurate data collection of animal data in their Michigan schoolyards. This transformation involved both a reworking of the manner in which animal data entries were organized in animal groups, as well as a streamlined sequence focusing on a small number of types of data focused on our goals (habitats, animal group, animal, number and zone). Figure 4 displays a sample Habitat Summary Sheet of student gathered data on Michigan-based animals.

Similarly, transforming the Animal Diversity Web into the Critter Catalog required an examination of how this tool could foster explanation-building and data analyses. The transformation of the ADW adult-orientated species accounts into a database suitable for use by late elementary students involved many challenges including: a) translating concepts in a way that reduces the amount of text presented without content dilution, b) simplifying organization of species accounts, c) enhancing visual information, and d) substituting familiar species names for scientific names. For more information on the redesign and user-interface evaluation of CyberTracker and the Critter Catalog, see Parr, Jones and Songer, 2004).

Habitat	Animal Group	Animal	How Many?	Location (Zone)
Short grass	6 LEGS Insects	Unknown beetle	13	A
Short grass	6 LEGS Insects	Bee	2	F
Bare ground	Mammals	Norway rat	1	D
Bare ground	Mammals	Rox squirrel	1	F
In the soil	10+ LEGS Myriapods and Crustaceans	Centipede	2	E
Under rock or log	0 LEGS Annelids and Mollusks	Earthworm	1	D
In the air	6 LEGS Insects	Bee	1	A
Single tree	Birds	American robin	1	F

Figure 4: Sample Habitat Summary Table for Michigan-Collected CyberTracker data.

As mentioned in the beginning of this chapter, the development of resources to foster scientific knowledge development involves an active conversation between learners and materials. The conversation to develop digital resources into cognitive tools involves a process of finding and transforming rich digital resources through a series of examinations focused around target audience, cognitive benefits of the tool, and learning goals. Frequently, these examinations and research-based evaluations of learning technologies are not conducted. As a result, it does not seem surprising that many computer resources in schools are underutilized, particularly relative to challenging learning goals such as higher-order reasoning in science.

Building Inquiry Readiness with Curricular Scaffolds

The active conversation between learners and materials in BioKIDS also involved examinations and research-based iterative design of our curricular materials. As with the learning technologies, we desired curricular activities that would take into account the learner and their prior knowledge about both scientific concepts and inquiry reasoning. The curricular materials would build from prior ideas towards inquiry readiness with biodiversity concepts and subsequent content knowledge in sequential curricular units.

Our early examinations of content and learning goals began with an examination of national (National Research Council, 1996), state (Michigan Curriculum Framework Science Benchmarks, 2000) and district science standards (DPS Science Core Curriculum Outcomes, 2000). For the biodiversity unit, we examined standards relative to the physical characteristics of animals, habitat, adaptation, food web, animal classification, human interaction, and conservation. Although the target audience was late-elementary students, standards at various levels were examined to gain a better understanding of the scope and the sequence of related concepts. Textbooks, published materials, and Internet resources were also examined (Barrett & Willard, 1998; Fletcher, Lawson, and Rawitsher-Kunkel, 1970).

After examination the following learning goals in the areas of scientific content, inquiry and technology were identified for the first curricular unit in biodiversity:

Scientific Content

- Students will learn about the concepts of abundance, richness and biodiversity.
- Students will identify and describe various habitats in the schoolyard.
- Understand the role of microhabitat in supporting different species.
- Students will be able to use their observations and data to describe the abundance and richness of different species in their schoolyard.
- Students will examine the concept of biodiversity in the schoolyard using the data they have collected.

Inquiry

- Promote student inquiry in early years (late elementary) and have students engage in first-hand data collection, exploration, explanation, and synthesis of ideas. (NRC, 2000, pg. 19)

Technology

- Utilize technology as a tool to promote accurate data collection (NRC, 2000, pg. 19), and foster students' content and inquiry understandings.

The next step involved a careful examination of these concepts relative to appropriate sequencing of presentation to promote complex reasoning in science, as suggested by Learning Cycle and other activity structures of Karplus (1977), Bybee (Bybee et al, 1989), Bruner (1996) and others. Table 1 illustrates the curricular sequence and structure for the eight-week biodiversity unit.

Curricular Phase	***Activity***	***Inquiry Goal***	***Selected Examples of Content Goal***	***Role of Technology***
Engage	*Students observe schoolyard as a place for animals (habitats). Students collect habitat data and map the schoolyard.*	*Students engage in a question provided by the teacher, materials, or other source)*	*Students identify and describe various habitats in the schoolyard*	*None*
Explore	*Students explore tools of a field researcher and animal groupings. Students collect animal species and habitat data on one schoolyard zone.*	*Students directed to collect certain data*	*Students view, describe and identify organisms on the basis of observable physical characteristics and structure.*	*Introduction and use of CyberTracker on PDAs for accurate and efficient data collection and organization*
Explain	*Students examine class data to determine the zone with the highest biodiversity (richness and abundance).*	*Students guided in formulating explanations from evidence*	*Students use observations and data to describe the abundance and richness of animals in their schoolyard*	*Students use class data for observation of patterns and analysis. Students graph and analyze PDA-collected data*
Synthesize	*Students use knowledge about specific animals towards activities on food webs and animal interactions.*	*Students guided in formulating explanations from evidence*	*Students explain how physical and behavioral characteristics help a species survive in its environment*	*Students use Critter Catalog to collect animal data. Students transform PDA-collected data into other formats such as tables, graphs or maps*

Table 1: Biodiversity Activity Structure

After each curricular sequence was developed, research was conducted to examine the character and quality of student explanations, data analysis, and hypothesis/predictions. Student think-aloud interviews and pre/posttest learning outcomes guided the redesign of curricular formats in each iterative cycle (see for example Songer, 2005; Lee and Songer, submitted). One research study provided particularly salient information on the role of written prompts in guiding students' explanation-building. Lee and Songer (2003) provided empirical evidence that 5th and 6th graders had particularly high degrees of difficulty in determining salient from irrelevant scientific information when solving problems using authentic data. As a result, we included ten instances of content hints relative to data and evidence questions in the written biodiversity activities. Figure 5 illustrates two questions in the biodiversity curricula in two versions of the curricula: Version B without content hints and Version C with content hints. Content hints are illustrated in bold text.

<table>
<tr><th colspan="2">Question 1</th></tr>
<tr><td>Version B
As a team, decide which one photo you think shows the highest animal biodiversity:
Photo_________

Give two reasons why you chose that photo:</td><td>Version C
Which photo (A, B, or C) shows the highest biodiversity?

Claim: We think photo ____________ shows the highest biodiversity

because…[Data or Evidence
• Which photo has the highest abundance?
• Which photo has the highest richness?
• Which photo has both high abundance AND high richness?}</td></tr>
<tr><td colspan="2">Sample student answers
Partial: "Diversity is like richness and there is more kinds of animals in photo A."

Complete: "It has richness and abundance, the others have just one of the two."</td></tr>
<tr><th colspan="2">Question 2</th></tr>
<tr><td>Version B
Looking at these two bar graphs, discuss as a class which zone has the highest Biodiversity.
Zone _____________has the highest Biodiversity.

Describe what data lead you to this answer.</td><td>Version C
Looking at the two results you obtained from the data analysis, discuss as a class which zone in your schoolyard has the highest biodiversity. Which schoolyard zone has the highest biodiversity?

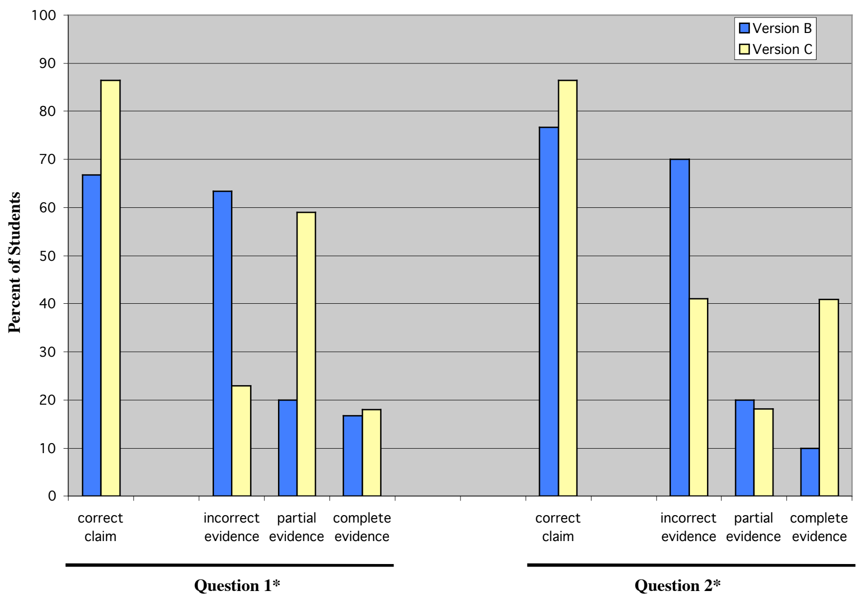
Claim: I think zone ______________ has the highest biodiversity.

because…[Data or Evidence
• How many animals and different kinds of animals were found in this zone compared to other zones?
• Where were animals found in this zone?
• How does this zone support both high abundance and high richness of animals?]</td></tr>
<tr><td colspan="2">Sample student answers
Partial: "They have the most of animals"

Complete: "I chose, because zone C has a high richness and a high abundance"</td></tr>
</table>

Figure 5: Sample Curricular Questions with Content Hints and Student Answers

Mixed-methods data were collected in the form of pre/posttest comparisons, written responses throughout the units, and think-aloud interviews of students' explanation-building. Results demonstrate significant improvements in students' ability to generate scientific claims and explanations when using content hints and prompts supporting the use of explanations (Figure 6) as well as significant differences between control and experimental populations on each of the inquiry reasoning skills of building explanations, analyzing data, and building hypotheses and predictions (Songer, 2005).



*Statistically significant (p > 0.05)

Figure 6: Student responses on scientific claim/evidence. N = 30, 22.

Student Use of Curricular Scaffolds

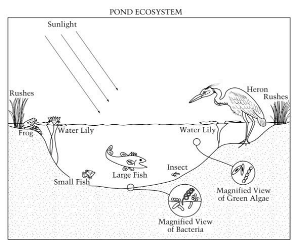
Having determined the importance of scaffolding in supporting student construction of explanations, we then turned to specific student responses for greater in-depth examination. For this study, we focused specifically on students' responses on hypothesis or prediction questions. Making scientific hypotheses and predictions can be considered a subset of making scientific explanations. Like explanations, hypotheses and predictions must utilize supporting evidence and reasoning to be considered scientifically legitimate. Hypotheses and predictions can essentially be considered explanations that occur prior events or experiments, rather than afterwards. Our goal for this study was to characterize the nature of students' hypotheses and predictions as they learned across the three curricula, to identify what might or might not promote of sense of agency in students.

This study analyzed the hypothesis or prediction responses of twelve students selected at random from our original sample of 2351. Six students were male, and six were female. These students were spread across three different teachers at two different schools within the district. After selection, the respective teachers identified three of the students are high performing, six as average achievers, and three as relatively low performing students, based on classroom performance. All students are had participated in three inquiry-oriented science curricula: a biodiversity curriculum, and weather curriculum, and a simple machines curriculum. Each of the curricula was approximately eight weeks in length. The biodiversity curriculum was enacted in the fall term, from September through November. Students then engaged in a traditional curriculum on light and sound. The weather curriculum was enacted from February to mid-April, and the simple machines curriculum was enacted from mid-April until the end of the school year in June. Though each curriculum focused on different science content, all the programs were designed to foster scientific thinking and reasoning. In each curriculum, students collected and analyzed data related to the content area. Scaffolds were provided to help students formulate explanations of scientific questions and concepts using their observations and measurements as evidence.

One primary data source for this study was selected student responses from the pre- and post-tests administered for each of the three curricula. A total of fifteen items, five items from each assessment, were selected for analysis. The focus of these assessment items was for students to demonstrate the ability to make hypotheses or predictions that are justified by evidence either provided by their assessment item or from their own content knowledge background. The fifteen items ranged in complexity. Six items were multiple-choice items, where students were asked to select the most scientifically appropriate hypothesis or prediction from the choices provided. Nine items were open-ended, where students were expected to make their own hypothesis or prediction and provide supporting evidence and reasoning.

Our other primary data source was student interviews. Interviews were administered at the conclusion of the simple machines enactment. During the interview, students were asked to respond to twelve items from the three curricular assessments using a think-aloud procedure. The purpose of these interviews was twofold. First, to further probe student reasoning on test item responses. Second, to obtain reasoning from students for the several test items that were multiple-choice. Each interview took approximately 30 minutes. All student interviews were digitally recorded and transcribed. Excerpts from interviews are used in this paper to support interpretation assessment item analysis. We also collected student notebook responses for all work done during the enactment of the three curricula as a secondary data source.

We analyzed assessment items, interview responses, and student notebooks using the same set of codes and coding rubric. To identify each response and identify patterns of responses in the students, we performed a first pass at coding for each interview item response using a grounded theory approach (Strauss & Corbin, 1990). Each response was coded at two levels. First, a code was used to identify responses supported by evidence (table 2). Once responses were identified, a second set of codes was used to characterize the nature of the supporting evidence, if provided (table 3). Overall, for each response we noted the presence of a claim, the presence of supporting evidence, the type of evidence utilized, and overall accuracy of the hypothesis or prediction.

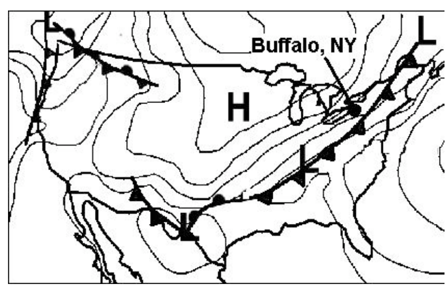
<table>
<tr><th>Code</th><th>Description</th><th>Sample assessment item</th><th>Sample response</th></tr>
<tr><td>4</td><td>Internally consistent</td><td rowspan="5">The picture below shows a pond ecosystem. Use this picture and what you know about the things in it to answer the questions in this section.


If all of the small fish in the pond system died one year from a disease that killed only the small fish, what would happen to the algae in the pond? Explain</td><td>The algae in the pond get more and more. The little fish used eat the algae and since they dead, they nothing to stop the algae from growing</td></tr>
<tr><td>3</td><td>Internally inconsistent</td><td>The algae will all die. When the little fish are gone, they'll be nothing to eat the algae, so the algae will be gone.</td></tr>
<tr><td>2</td><td>Unsupported correct</td><td>The algae will get big and multiple</td></tr>
<tr><td>1</td><td>Unsupported incorrect</td><td>The algae will all be gone</td></tr>
<tr><td>0</td><td>No response</td><td></td></tr>
</table>

Table 2. Coding key used to identify evidence-supported responses

<table>
<tr><th>Code</th><th>Description</th><th>Sample response</th><th></th></tr>
<tr><td>1</td><td>Scientifically plausible</td><td rowspan="2">Omar and Norma are planning to go on a picnic today. They look out of the window and see some high, thin clouds. Choose an answer and complete the sentence below to explain your answer.

I think it <u>will rain | will not rain</u> because…</td><td>I think that it will not rain because the clouds Omar sees are thin, high clouds. If it's going to rain, the clouds be thick and dark. These clouds are not rain clouds.</td></tr>
<tr><td>2</td><td>Scientifically implausible</td><td>I think it will rain because high, thin clouds bring rain</td></tr>
<tr><td>3</td><td>Appropriate evidence used</td><td rowspan="3">The pressure map below was constructed on March 2^{nd}, 2003. On this date, Buffalo, NY, had heavy snow with overcast skies. The temperature was 0 °C, and the pressure was 1008 mb at 1 PM.



Based on the map above, predict pressure in Buffalo, NY, on March 3^{rd} at 1:00 PM. Give one reason that supports your prediction.</td><td>I think the air pressure will be high because the H means high pressure and it moving toward the city</td></tr>
<tr><td>4</td><td>Inappropriate evidence used</td><td>The air pressure will increase because the map shows a cold front coming toward Detroit</td></tr>
<tr><td>5</td><td>Extraneous evidence used</td><td>The air pressure will go down because there's an ice storm coming, and when the weather is worse and that means the pressure dropped</td></tr>
</table>

Table 3. Coding key for characterization of evidence used to support responses

Results

Figure 7 shows the percentage of assessment responses where students provided evidence in support of their hypothesis or prediction. This does not include multiple choice questions, where no opportunity to provide evidence was allowed. This also does not represent whether the claim or evidence was scientifically appropriate, only if students utilized evidence of any kind to support their hypothesis or prediction.

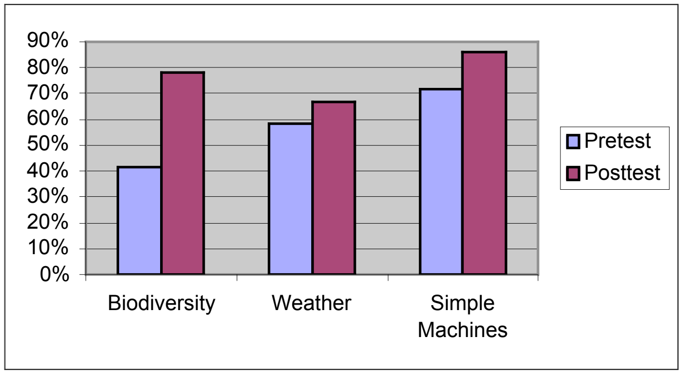


Figure 7. Percentage of evidence-supported responses in three unit tests

Figure 8 shows the percentage gains in student use of scientifically appropriate evidence in making hypotheses and predictions in the three assessments. In scientifically appropriate responses, students have made a scientifically accurate hypothesis or prediction, and supported with factually accurate evidence.

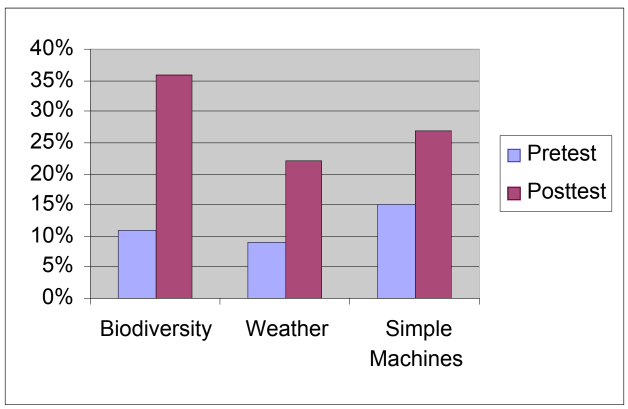


Figure 8. Percentage of scientifically correct responses across three unit tests

In figure 9, we show the comparison of consistent responses from pre- and post-test for each of the three assessments. In consistent responses, students provide evidence the supports the hypothesis or prediction claim they make. Unlike scientifically appropriate responses, that evidence may not be factually accurate. However, if it were, the reasoning students draw between their claim and evidence is logical. For example, if students have the erroneous belief that algae consume small fish in a food chain, they might use that fact as evidence that algae population will decrease if all small fish are killed. This response would be scientifically inaccurate, yet internally consistent.

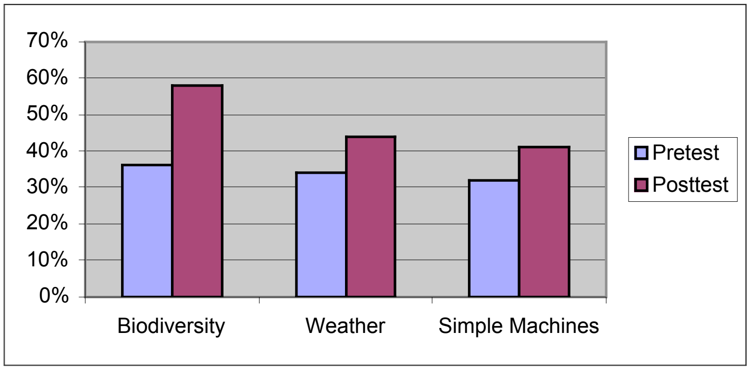


Figure 9. Percentage of consistent responses across three unit tests

In figure 10, we compare students' identification of the scientifically appropriate claim to claims that are supported internally consistent evidence and reasoning, regardless of whether or not they are scientifically accurate hypotheses/predications, this time with addition of multiple-choice items. Student reasoning behind multiple-choice items was established in interviews.

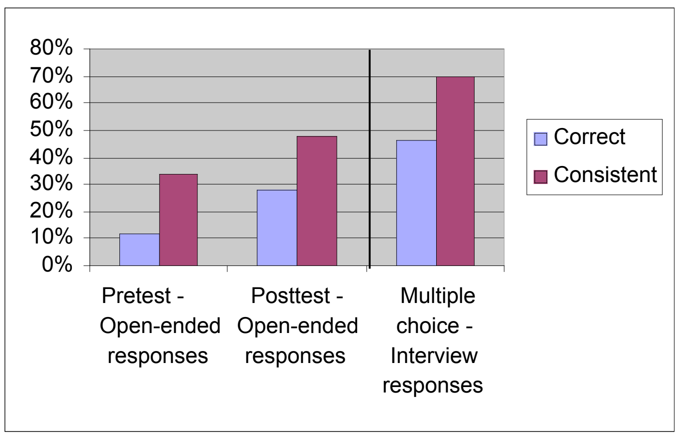


Figure 10. Percentage correct vs. consistent responses for all units

The data show that in each of the curricular assessments student use of evidence in support of their claims has noticeably increased from pre-test to post-test. Due the small number of students in our sample, these results are not statistically significant, but they do show a trend of improvement. In addition, utilization of evidence has generally increased across the three curricula as well. In each of the pre-tests, evidence use has consistently increased, from 41.7% in the biodiversity curriculum, to 58.3% and 71.4% in the weather and simple machine curricula. The improvement from pre to post was not as large in the weather curriculum, but this may be attributable to the fact that the enactment of the weather unit was not as complete as for the biodiversity unit. In some cases, students' lack of content knowledge may mean that they were not aware of the kinds of evidence that could be utilized for making their hypotheses and predictions.

The trend of the results in figure 7 suggests that over the course of the three curricula students are more accustomed to providing evidence-supported responses. By the end of the third curriculum, students are providing evidence for nearly all test items. These results suggest that scaffolding present in the curriculum may support students' recognition of the need to provide supporting evidence when making scientific claims.

In figure 8, we see the greatest gains between pre- and post-test in the first curriculum. Students increased their percentage responses with identification of appropriate evidence from 11% to 36% in the biodiversity curriculum, a 24 point improvement. In the weather curriculum, students gained only 13 points over the initial 9%, and in the simple machines curriculum, there was only an 11 point increase. Similarly in figure 9, the data show that in the first curriculum, consistent responses increased by 22% from pre- to post-test. However, in the second and third curriculum, consistent responses increased by only 10% and 9% respectively.

These differences across curriculum may be attributable to differences in enactment. The curriculum with the greatest gains (biodiversity) also had the most complete enactment, with 98% of the curriculum activities completed. Teachers were only able to partially enact both the weather curriculum and the simple machines curriculum, completing 68% and 66% of curriculum activities respectively.

More importantly, in figures 8 and 9 we can compare the percentage of evidence-supported responses that are correct versus the percentage that are consistent. When students do not have the specific content knowledge to make an educated hypothesis or prediction, their responses may vary from wild and irrational speculation to a reasoned guess. Scaffolds in our three curricula are designed to teach students that all scientific claims must be supported by relevant evidence.

Across the three curricula, noticeably more responses are consistent than correct. For example, in the biodiversity unit, we see that almost 60% of responses are consistent, whereas only 36% of the responses are actually scientifically correct. The aggregate of this data, along with the same data for multiple-choice responses is presented in figure 10. Students were more noticeably more able to use relevant evidence in support of their hypothesis or predication than they were to identify a scientifically accurate or plausible hypothesis or predication. Figure 10 shows that while only 12% and 34% of responses in open-ended pre- and post-test items had scientifically correct claims respectively, 28% and 48% of the claims used internally consistent supporting evidence. Similarly, on the post-test only 46% of the responses were scientifically correct, but in interviews students were able to provide internally consistent evidence and reasoning for their responses 70% of the time. The data suggest that students demonstrated reasoning skills even in absence of content knowledge. It may be that the scaffolding supports students in their reasoning ability, even if it is not sufficient to support their content-specific understanding.

Conclusions

A goal of inquiry readiness within a foundational science unit as the first of several sequential curricular units guided the systematic transformation of digital resources into cognitive tools and the development of activity sequences, structures, and hints to foster complex reasoning skills in science. Mixed-methods research guided the iterative refinement of resources, sequences, and learning goals.

Revisiting the larger goal of scientific literacy for all forces a reexamination of reasoning skills involved in scientific literacy, as well as examinations of both the *what* and *how* to achieve these goals. As outlined by Bruner (1996), we recognize that there is not any one curriculum that is ultimately best for learning particular content, but the development and implementation of curriculum in classroom contexts should be an animated conversation to critically and empirically examine the *what* and *hows* to foster the development of scientific explanations, data analysis, and hypotheses generation. Part of this animated conversation is the explicit examination and transformation of resources into cognitive tools focused specifically on the learning goals at hand.

An additional area of development essential to this work is the development of robust assessment systems to accompany the transformed cognitive tools. As documented by assessment experts (e.g. Pellegrino, 2001), many of the most popular assessment instruments are based on outmoded models of learning and are not a good match to the learning goals and objectives of programs focused on higher-order thinking. Therefore, in order to conduct sound educational research on the effectiveness of curricular programs over time, new thinking about assessment systems is needed, as well as empirical evaluations of assessment instruments to ensure instruments are be reliable and valid determinants of beginning, middle, and advanced levels of complex reasoning. Our work to develop and evaluate comprehensive assessment systems to complement sequential curricular units is discussed in Songer (2005) and ongoing.

References

Atkin, J.M., Karplus, R. (1962). Discovery or Invention?, *Science Teacher 25, 45.*

Barrett, K. & Willard, C. (1998). Schoolyard Ecology Teacher's Guide. UC Berkeley Lawrence Hall of Science's Great Explorations in Math and Science Program.

Bransford, J., Brown, A. L., & Cocking, R. R. (2000) How people learn: Brain, mind, experience and school. National Academy Press, Washington, D.C.

Bybee, R., Buchwald, C., Crissman, S., Heil,D., Kuebis, P, Matsumoto, C., McInerney, J. (1989). Science and Technology Education for the Elementary Years: Frameworks for Curriculum and Instruction, The National Center for Improving Science Education.

Bruner, J. (1996) The Culture of Education. Harvard: Cambridge: Massachusetts.

Carey, S. (1985). Conceptual Change in Childhood. MIT Press, Cambridge Massachusetts.

Clark, D. & Linn, M.C. (2003) Designing for Knowledge Integration: The Impact of Instructional Time. *The Journal of the Learning Sciences, 12(4), 451-493*

Cuban, L. (2001). Oversold and Overused: Computers in the Classroom. Cambridge, MA, Harvard University Press.

DPS Science Core Curriculum Outcomes (2000) http://www.detroit.k12.mi.us/index.shtml

Fletcher, S., Lawson, C.A., Rawitscher-Kunkel, E. (1970). Organisms, Teacher's Guide. Science Curriculum Improvement Study. Rand McNally & Co.

Haberman, M. (1991). The Pedagogy of Poverty Versus Good Teaching. *Phi Delta Kappan(December): 290-294.*

Inhelder, B., & Piaget, J. (1958) The Growth of Logical Thinking From Childhood To Adolescence. Basic Books, Inc.

Karplus, R. (1977). Science teaching and the development of reasoning. *Journal of Research in Science Education 14(2): 169-175.*

Leach, J., Driver, R., Scott, P., & Wood-Robinson, C. (1992). Progression in understanding of ecological concepts by pupils ages 5 to 16. Leeds, UK: The University of Leeds.

Lee, H.-S., & Songer, N.B. (submitted) Expanding an understanding of Scaffolding Theory Using an Inquiry-Fostering Science Program. *The Journal of the Learning Sciences. October, 2004.*

Lee, H.S., and Songer. N.B. (2003) Making Authentic Science Accessible to Students. *International Journal of Science Education. 25(1).1-26*

Linn, M.C., Lewis, C., Tsuchida, I., and Songer, N.B. (2000) Beyond Fourth Grade Science: Why do US and Japanese students diverge? *Educational Researcher 29(3), 4-14.*

Metz, K. (1995). Reassessment of Developmental Constraiints on Children's Science Instruction. *Review of Educational Research 65(1): 93-127.*

Metz, K. (2000). Young children's inquiry in biology: Building the knowledge bases to empower independent inquiry. In J. Minstrell and E. van Zee (Eds.) Inquiring into inquiry learning and teaching in science (pp. 371-404). Washington, D.C: AAAS

Michigan Curriculum Framework Science Benchmarks (2000) http://www.michigan.gov/mde/0,1607,7-140-28753_28760---,00.html

Minstrell, J., & van Zee, E. H. (2000). Inquiring into inquiry learning and teaching in science. Washington, D.C., American Association for Advancement of Science.

National Research Council (1996). National Science Education Standards. Washington, DC: National Academy Press.

National Research Council (2000). Inquiry and the National Science Education Standards: A Guide for Teaching and Learning. Washington, DC: National Academy Press.

Parr, C., Jones, T., and Songer, N.B. (2004) Evaluation of a Handheld Data Collection Interface for Science. *Journal of Science Education and Technology. 13(2). 233-242*

Pea, R.D. (2004) The Social and Technological Dimensions of Scaffolding and Related Theoretical Colncepts for Learning, Education, and Human Activity. *The Journal of the Learning Sciences, 13(3), 423-451.*

Pellegrino, J., Chudowsky, N., Glaser, R. (2001). Knowing what students know: The science and design of educational assessment. Washington, D.C., National Academy Press.

Songer, N.B. (2005) Persistence of Inquiry: Evidence of Complex Reasoning Among Inner City Middle School Students. Paper presented at the American Educational Research Association (AERA) annual meeting.

Songer, N.B. (2004) Evidence of Complex Reasoning in Technology and Science: Notes From Inner City Detroit, Michigan, USA. IPSI-2004 Pescara Conference, Italy.

Songer, N.B. (2003) Coordination of the Development and Evaluation of Complex Reasoning in Science. Paper presented at the American Educational Research Association (AERA) Annual Meeting, Chicago, IL. Session 22.089 April 21, 2003.

Songer, N. B., Lee, H., & McDonald, S. (2003), Research Towards an Expanded Understanding of Inquiry Science Beyond One Idealized Standard, *Science Education. 87(4), 490-516*

Von Glaserfeld, E. (1998). Cognition, Construction of Knowledge and Teaching. Constructivism in Science Education. In M.R. Matthews (Ed.). The Netherlands, Kluwer: 11-30.

Vygotsky, L.S. (1978). Mind in Society. Cambridge: Harvard University Press.

White, B.Y. & Frederiksen, J.R. (1998). Inquiry, Modeling, and Metacognition: Making Science Accessible to All Students, *Cognition and Instruction, 16(1), 3-118.*