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New Perspective–New Practice

by **Sherian Foster**

Curriculum as Web of Inquiry

*Richard Lehrer, Leona Schauble, and collaborating teachers and researchers, in their Modeling in Mathematics and Science (MIMS) project, take a fundamentally different approach. They view curriculum as a web of inquiry—**purposeful** inquiry designed by the teacher and comprising everything that students do and learn, the complete classroom ecology related to student understanding in a domain.*

Customary Perspective – Curriculum as Prescribed Course of Study

Typically, mathematics and science curricula treat topics as isolated entities with little attempt made to connect them. A week of study of photosynthesis might follow a week of study of the sun, but connections, when they are made, are either superficial or come from teacher initiative and knowledge, not from the K–12 textbooks. Even thematic units tend to rely on context to connect topics, with little deliberate integration of disciplinary content or cognitive work across the various subject areas that come into play.

This organization of study makes it convenient to consign topics, rather arbitrarily, to grade levels. Partly as a result, coverage is generally valued over understanding, and adherence to predetermined time units for studying a topic (seldom longer than a week or two) becomes as important a way of measuring successful teaching as student scores on standardized tests. Textbook questions, often used as models to teacher-designed tests, tend to call for one-word, fill-in-the-blank, or, at best, short-answer responses that match the answers (often also even the exact wording) in the textbook. Those memorized responses are easy to grade—and easy to "learn." Students have no time (and no need) to think in depth, to explain their reasoning, to understand each other's thinking, or to raise new questions. All too often the questions students do raise are given short shrift because of the necessity to remain on schedule, or because they seem peripheral to the topics at hand. Even in the later grades, students are seldom encouraged to engage in *doing* and *using* science and mathematics to investigate and solve problems as

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scientists and mathematicians do, or even as nonscientists do at home or on the job.

This traditional, prescribed curriculum also leaves little room for teachers to engage in and deepen their own understanding of science and mathematics and of the rich interrelationships across those (or other) subject areas. Particularly when the course of study in a classroom is dictated by a textbook, teachers are asked to make few substantive decisions. Their decision making tends, instead, to revolve around classroom management rather than around student thinking and understanding. So-called "teacher–proof" curricula actually *require* the teacher to do little or no thinking about the ideas they are teaching. Because teacher involvement in the development of curriculum is so undervalued, their participation, even when they are involved, is generally limited to finding new contexts to serve as the backdrop or medium of instruction. Determining *what* content will be pursued and to what depth is too often seen as beyond the scope of even the most experienced teachers.

In the MIMS approach, teachers are much more than activity monitors and grade keepers–they are designers. Teachers must ensure that students engage with ***worthwhile*** *content and that they learn and understand that content with accuracy and depth.*

New Perspective—Curriculum as Web of Inquiry in a Content Domain

Richard Lehrer, Leona Schauble, and collaborating teachers and researchers, in their Modeling in Mathematics and Science (MIMS) project, take a fundamentally different approach. They view curriculum as a web of inquiry—*purposeful* inquiry designed by the teacher and comprising everything that students do and learn, the complete classroom ecology related to student understanding in a domain.

Teachers not only plan discrete activities and give quizzes and tests, but also plan, evaluate, build, and continuously reshape exactly what is studied and how, with specific attention to student thinking and the development of deep understanding.

A web of inquiry in a domain involves many complex connections to previous knowledge and extends those connections in ways that build new student knowledge. Webs of inquiry begin with questions that come from the teacher, or arise out of students' curiosity. Content is not left to chance or to students' whims, as critics sometimes accuse, but is driven by inquiry guided by the teachers' knowledge of the mathematics or science to be taught. Because teachers determine which broad concepts are to be studied (e.g., change over time, decomposition) and design chains of inquiry to do so, they must have a clear understanding of the important central concepts of science and mathematics, of the connections across mathematics and science, and of the skills students need to extend or apply their knowledge. *Specific* content (e.g., tomato rot) and *specific* tasks (e.g., using compost columns, studying bread mold) may be determined, in part, by students' questions and curiosity as they participate in the *process* of inquiry.

Adopting this perspective of curriculum means that important central concepts of mathematics and science become the focus and substance of prolonged study: They can no longer simply be consigned to a particular grade level. More attention is paid to what students study (and how) *over much longer periods of time*. For example, students' early experience characterizing variation in growth and development (in plants, perhaps) may be drawn on in a later grade when they search for explanations for variation based on principles of evolution. Understanding and this kind of content knowledge do not simply happen because content has been presented or "delivered" clearly. If student understanding is to be as full and complete as possible, deliberate attention must be given to making strong connections across students' webs of inquiry, including strong connections across mathematics and science. Care must also be taken to design webs of inquiry such that student understanding deepens and becomes more mature, complex, interconnected, and formal over time.

In the web of inquiry approach used in the MIMS project, teachers are much more than activity monitors and grade keepers: They are designers. Teachers must ensure that students engage with *worthwhile* content and that they learn and understand that content with accuracy and depth. They must see that the tasks students carry out have *purpose* in terms of their web of inquiry. As illustrated in the classroom example and the comments that follow in the next sections, teachers daily make a myriad of *substantive* decisions that shape students' web of inquiry over extended periods of time.

Students are more than human file cabinets. In web-of-inquiry classrooms, they participate in mathematical and scientific inquiry. Guided by teachers' questions, students move from informal to formal ideas in a domain, from *wondering about* to *doing* mathematics and science. They formulate precise questions and conjectures, design ways to test those conjectures, make careful observations, gather data, represent and make sense of data, draw conclusions based on their data, and formulate new questions and hypotheses based on what they have learned. Students in these classrooms learn and use science and mathematics in ways that scientists and mathematicians do in the real world. The result is increased student interest, ownership of their work, and deeper understanding of content.

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Important central concepts of mathematics and science become the focus and substance of prolonged study; they can no longer be consigned to a particular grade level and never seen again. It does mean that more attention must be paid to what students study (and how) ***over much longer periods of time.***

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Overview

MIMS Web of Inquiry

Although modeling is central to the practice of mathematics and science, students often do not learn to use modeling until the upper grades. Furthermore, important central ideas of mathematics essential to constructing and using models—geometry of space, measurement, uncertainty and probability, data and statistics, and growth—are not typically emphasized (and often not included) in school mathematics.

But suppose students, beginning in first grade, studied these areas of mathematics in a classroom that deliberately cultivated students' use of modeling to mathematize the world around them, to solve problems, and to test conjectures. How would this affect their thinking in and learning of mathematics? Suppose these students then brought the knowledge and understanding they had gained from this strong modeling approach to mathematics to bear in an inquiry-based study of central ideas in science? These questions and others guided the research done by Richard Lehrer and Leona Schauble through teacher–researcher collaboratives in Modeling in Mathematics and Science (MIMS) project (funded by the National Science Foundation, the James S. McDonnell Foundation, and the the National Center for Improving Student Learning and Achievement in Mathematics and Science).

The major thrust of this work has been the use of modeling to study the important central ideas in mathematics and science and the identification of principles for designing classrooms that foster mathematical modeling and purposeful inquiry.

Although much of the MIMS work has been in mathematics, the classroom example that follows this article focuses on science learning. Comments follow, first on the classroom example itself, then on the project as a whole from a teacher who has participated in the MIMS project since its inception, from her principal, and from a parent whose child has attended MIMS classrooms.

A Classroom Example

In the fall, the teacher, Ms. Putz, asked her first-grade students to bring different varieties of apples to school and to describe them in terms of color, shape, and size. As days went by, students conjectured that apples change color as they ripen.

Apples, Tomatoes & Questions—Beginning a Web of Inquiry

Ms. Putz generalized the question to "*Why* do you think that happens? What makes fruit change color?" During the ensuing discussion, students speculated that the sun had something to do with it. Encouraged to think of a way to find out how the sun affects fruit, students suggested putting some fruit in the sun, then watching what happened. More discussion followed, and everyone agreed that bananas or tomatoes would work best because they change rather quickly, and in ways easy to see.

The next day, Ms. Putz brought green tomatoes to class. Building on students' previous ideas, Ms. Putz asked, "How do you think the sun helps change the color of the tomatoes?" Most students conjectured, "Because the sun gives light." Again encouraged to think of a way to test this idea, students quickly suggested putting one tomato in the sunlight and another somewhere in the dark, then waiting to see if color change resulted from the difference in light the tomatoes received. The students negotiated and eventually agreed as a class to put one tomato on the window sill and another elsewhere under a cover "to see what happens." Then, however, a student, drawing on informal knowledge, raised a related question, "But the sun is hot—Does heat matter?" Other students felt this was an important question, so the discussion now encompassed two variables ("things") to consider: light and heat.

Devising a Convincing Test

Encouraged by Ms. Putz, students hypothesized ways to test the role of heat in tomato color change. At first, some students suggested putting one tomato on the window sill and one in the refrigerator, tacitly assuming that the data they collected the tomato on the window sill would give them information about the effects of both light and heat on color change. As a class, the students also believed that observing change in the tomatoes in these two locations would be a good test. Noting that students were not separating the two variables in their discussions, Ms. Putz asked probing questions: "Is the window sill the warmest place in the room?" "How do you know?" "Can warm places be light?" "Are all dark places cold?" Such questions helped students think more deeply about the problem and about the test they were devising.

As students discussed and designed ways to separate the roles of light and heat, they touched on several important scientific and mathematical ideas, in first-grade terms, definitions of light and dark, for example. Students had to decide what "counted as dark." Is one location in the classroom "as light as" or "as dark as" another location? Does it matter? Students also had to define warm and cold. They easily agreed that the refrigerator was "cold," but what location was "warm?" Some thought the window sill was the warmest "because it's closest to the sun." Others were not convinced because the weather was cold. (When one student suggested using a thermometer to find out whether the sill was warm, teacher and students took an extended digression into the area of measurement.)

*After a thorough discussion and consideration of options, **students agreed** on four conditions necessary to "test" how light and heat affect color change in tomatoes.*

After a thorough discussion and consideration of options, students agreed on four conditions necessary to "test" how light and heat affect color change in tomatoes. They placed tomatoes (a) in the window sill, a *light and cool* place, (b) in a sunny spot away from the window, a *light and warm* place, (c) under a cover away

A First-Grade Inquiry into Decomposition

The following comments are based on material explained in detail in "Designing Classrooms That Support Inquiry" by Lehrer, Carpenter, Schauble, and Putz (1998) and in "Modeling in Mathematics and Science" by Lehrer and Schauble (in press-b). Capturing the scope, depth, and complexity of that work or doing justice to the grounding studies of a modeling approach to mathematics is impossible here. In this article, we touch only on a few important points and invite you to go to the sources to read more.

Given the condition of the tomatoes by this time, students agreed that the phenomenon they were observing was no longer "ripening" but "rotting." They were, however, still intensely interested in what was happening, so they found a place outside where they could put the tomatoes and continue their observations.

from the window, a *dark and warm* place, and (d) in the refrigerator, a *dark and cold* place. Students then waited with great interest and anticipation to see "what will happen."

Moving From Observations to Inscriptions

Lehrer and Schauble (in press-a) and Latour (1990) explain in detail the vital role students' *inscriptions* play in developing understanding and skill in mathematics and science. Such inscriptions include drawings, maps, graphs, bar or pie charts, tables, time lines, arrangements of physical objects, physical models, and mathematical formulae—in short, anything students produce to record, summarize, display, or analyze their observations and data.

By asking guiding questions, Ms. Putz helped students realize that they needed inscriptions of their tomato observations. Students recognized that, without these, they "might not all remember the same things," or they "might forget something important." At first, students decided to make drawings of the tomatoes, which sufficed until the tomatoes began to get "squishy," "smelly," and "stuff began to run out" of them.

As this happened, color became more problematic to depict, and new decisions had to be made about how to alter their inscriptions to show "oozing" and "degree of squishiness." It was not a simple matter to decide how to represent adequately more than simple color change in the tomatoes. During extensive discussions about this, Ms. Putz asked probing questions to help students focus on change over time and on the type and quantity of detail they needed to record in their inscriptions that would enable them later to draw conclusions, formulate new hypotheses, and pose new questions—to fruitfully extend their chain of inquiry. With guidance, students were able to negotiate choice of color shadings to represent squishiness.

Drawing First Conclusions

Students' initial conclusions were based on one dimension of the physical condition of the tomatoes at the time of their discussion. One student, in trying to make sense of the data, noticed "sort of a pattern." The tomato in the window sill and the tomato in the refrigerator (both cold places) took longer to change. Because the students had originally made no specific conjectures about the role of heat (although they had wondered about it), the conclusion that cold "made a difference" was new and somewhat surprising information to them.

Another student, also trying to make sense of the data, observed that of all the tomatoes the one in the refrigerator and the one under the cover in the room "changed the slowest." To encourage students to justify statements and explain observations, Ms. Putz asked, "*Why* do you think they changed the slowest?" The student reasoned that the other tomatoes had changed color faster "because they had light." At the beginning of the experiment, students conjectured "that light mattered," that is, that light brought about or hastened color change. Students were satisfied that their observations of the tomatoes had confirmed their original conjecture.

To help students consider both variables and to look at all their data, Ms. Putz asked, "So does this mean that light is the only factor in the changing color?" This question sparked a long discussion and encouraged students to look at the records of their observations as well as at the current state of the tomatoes. They carefully considered what happened to tomatoes in all four locations. Students noticed that the tomato in the location with both heat and light changed the fastest, and the one with neither heat or light changed the slowest. The change in the tomatoes in locations with only heat or only light was "in between." Students concluded that *both* heat and light "made a difference, "that is, both factors contributed to color change.

Tomatoes, Pumpkins, and New Questions— *Making Connections and Extending the Web of Inquiry*

Given the condition of the tomatoes by this time, students agreed that the phenomenon they were observing was no longer "ripening" but "rotting." They were, however, still intensely interested in what was happening, so they found a place outside to put the tomatoes and continued their observations. A bit later, students noticed signs of rot in some pumpkins they had carved (after using them to study measurement in mathematics) and were quite excited.

Building on their previous knowledge and understanding of both tomato rot and of the process of scientific inquiry, students observed and compared what was happening to the tomatoes and pumpkins and made inscriptions of their observations and speculations. They noticed that tomatoes had mold on the outside, whereas

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pumpkins had more mold on the inside—a difference they conjectured had occurred because the inside of the pumpkin had more space, air, and wetness. Comparing the fast change in the pumpkins, which they had carved, with the slow change in the tomatoes, which they had not carved, students connected the difference to the carving. They observed that the tomatoes changed color on the outside, but the pumpkins did not, and that the tomatoes did not get as soft as the pumpkins. Students also noted that both the tomatoes and pumpkins became softer, decomposed, had juice coming out, changed shape, and got moldy.

Observations and questions flowed: "There are different kinds of mold." "How does mold happen?" "Is it different for tomatoes than pumpkins?" "Why did pumpkins rot faster than tomatoes?" All agreed, however, that observations were becoming more and more difficult because of the cold weather and snow. Students were also concerned, as a result of their conclusions about the effect of heat on rotting, that not much would happen to the tomatoes until spring.

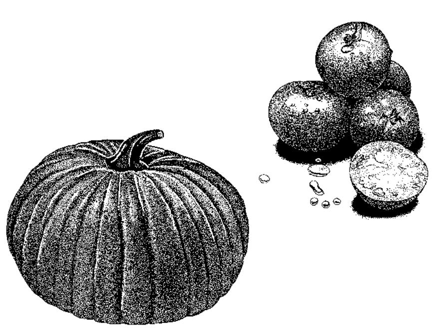
Introducing Modeling

Using students' interest and enthusiasm as an opportunity to extend their chain of inquiry, Ms. Putz introduced a new and purposeful tool of inquiry: She asked students if they thought it might be helpful to make a *compost column* out of clear, 2-liter bottles to model the rotting process. Students readily agreed that this would be better, especially during winter, than "watching the pile outside in the dirt." Ms. Putz asked questions that encouraged students to think more deeply about modeling (e.g., "Why would we do this?" "How will it [the compost column] help us understand rot?")

Students' initial approach to making this model was to replicate, in miniature, what they saw outside. Accordingly, they argued for including tomatoes, dirt, leaves, gum wrappers, and even a piece of foam and for watering the columns "like rain." Ms. Putz's probing questions guided lengthy classroom discussions. Students negotiated which outdoor conditions were essential to the function of the model and which could be left out; they did not, for example, include gum wrappers and foam.

Guided by questions that encouraged students to think more analytically about what phenomena they wanted to observe, what they wanted to know, what questions they wanted to answer, and what factors "matter in rotting" (i.e., affect decomposition), students decided to make two columns using tomatoes and to keep one column warm and one cold. Because they were interested in making comparisons, they also made two similar columns using pumpkins.

Observations & questions flowed.
"There are different kinds of mold."
"How does mold happen?"
"Is it different for tomatoes than for pumpkins?"
"Why did pumpkins rot faster than tomatoes?"



More Observations, More Conclusions, More Questions— *New Avenues in Students' Web of Inquiry*

Observing Mold

As students observed the compost columns, they noticed more and more mold, which quickly became a focus of attention and interest. When guided to think about why the mold was there, most students attributed the presence of the mold to the presence of "lots of dead things" in the columns.

To encourage students to think more analytically and to use their observational data to support their conjectures, Ms. Putz asked if all the columns had the same amount of mold. Students observed that one tomato column had more mold than the other. Pointing out that all the columns had the "same things [in addition to the tomatoes and pumpkins] in them to begin with," Ms. Putz asked students why that column had more mold. Noticing that the columns in the refrigerator had less mold, students suggested that "being cold" had something to do with it.

One student hypothesized that "maybe the mold was growing." Others thought that was a pretty wild idea—mold "isn't alive," so it "can't grow." At this point, students still associated mold with "dead things," and, to them, the amount of mold was somehow inexplicably related to "being cold." Seeing that students had no causal conjectures grounded in their observations and that they had dismissed the notion of mold being alive, Ms. Putz designed an extension of their chain of inquiry: the observation of dishes of wet bread, which began to mold within a short period of days. Ms. Putz made available magnifying glasses and microscopes so students could make detailed observations of the bread mold. To

Over the course of the year, students became more deliberate in making observations and inscriptions of their data; more sophisticated in posing questions, making conjectures, and designing experiments to answer their questions; and more adept at supporting their reasoning with evidence.

help students know what to look for, she also showed a video about fungi. Students observed that the bread mold had "something like stems on a plant" and had "different shapes" on top "kind of like a flower part." Connecting this observational data to the continuously increasing amount of mold, both on the bread and in their columns, students eventually concluded that the mold really was "growing" and that the bread and the leaves, dirt, and tomatoes (which steadily disappeared) were "food" for the mold. They also concluded that if they stopped watering their columns, the mold would die.

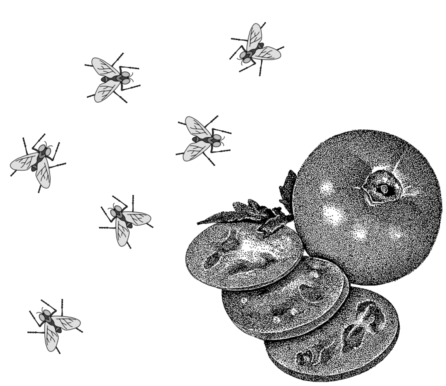
Observing Fruit Flies

Students noticed fruit flies in one of the pumpkin compost columns and wondered where they came from. Remembering that some of the pumpkins had worms, some students conjectured that the worms had "turned into fruit flies." Encouraging students to support their statements with evidence (as was, by now, the established norm) and to make connections to previous knowledge (from a story about the life cycle of insects), Ms. Putz asked students, "How do you know that?" Students supported their conjecture by reporting that they had noticed "bumps" on the side of the compost column. One student, delighted with his insight, said, "The larvae turn into bumps on the wall. Then they hatch into fruit flies! The fruit flies lay more eggs, and the eggs hatch more larvae!" Another excited student piped up, "It's just like the circle story!"

Complaints were soon coming from all over the school about the pesky population. Capitalizing on this opportunity, Ms. Putz and the students began to design another extension in their web of inquiry. Students collected data by doing fruit fly counts in every room. They decided that displaying their data on a school map would be most helpful in drawing conclusions about the dispersal of the fruit flies. From this map, students observed that fruit flies were, as they expected, in large concentrations near their classrooms and, surprisingly, in some areas far from their room. After some discussion, they realized that those areas contained large amounts of food. Encouraging students to make predictions based on their data, Ms. Putz asked, "What do you think will happen over time?" Students predicted that when the food was taken away or ran out, the fruit flies would be gone. Their subsequent observations verified their prediction.

Verification and Understanding

In the spring, students resumed observations of the rotting tomato pile outside. Their observations verified the accuracy of their models (the compost



*Students gain content knowledge—here, about decomposition, growth of (living) mold, and the life cycle of fruit flies—through **purposeful** inquiry connected to previous knowledge, extending what they know to the construction of new knowledge.*

columns) and gave them confidence in the conclusions they had drawn and the conjectures they had made based on the models. Over the course of the year, students became more deliberate in making observations and inscriptions of their data; more sophisticated in posing questions, making conjectures, and designing experiments to answer their questions; and more adept at supporting their reasoning with evidence. Students came to understand science learning as an ever-building process of inquiry rather than the opening and closing of discrete packages of isolated bits of knowledge. They had *done* science as scientists and come to deeper understandings by doing so.

Note that gaining content knowledge is important in this inquiry process. Students do not simply memorize facts unrelated to experience or other knowledge. They do not engage in isolated episodes of "active learning" for the sake of being active. Instead, students gain content knowledge—here, about decomposition, growth of (living) mold, and the life cycle of fruit flies—through *purposeful* inquiry connected to previous knowledge, extending what they know to the construction of new knowledge.

Comments on the Classroom Example

Student as Scientists and Mathematicians

In the MIMS approach, as illustrated in the classroom example, students ***do*** *mathematics and science. They* ***are*** *scientists and mathematicians, not in the sense of having the full-blown maturity of professionals in the field, but certainly in the sense of practicing science and mathematics as a* ***process*** *of inquiry and developing ever deeper knowledge and understanding.*

The following comments are based on material explained in detail in "Designing Classrooms That Support Inquiry" by Richard Lehrer, Susan Carpenter, Leona Schauble and Angie Putz (1998) and in "Modeling in Mathematics and Science" by Lehrer and Schauble (in press–b). Capturing the scope, depth, and complexity of that work or doing justice to the grounding studies of a modeling approach to mathematics is impossible here. In this article, we only touch on a few important points and invite you to go to the sources to read more.

Modeling

Making and testing models is central to practicing mathematics and science and, in the MIMS project, is central to elementary-school students' learning and understanding. Models are *not* products, finished once and preserved in that form. Modeling is a *process*, a tool used by scientists and mathematicians, not only to answer questions, but to fruitfully extend webs of inquiry. Models are made, tested, revised, and tested again. Conclusions are drawn, hypotheses formulated, new questions posed, and the cycle repeated.

Lehrer and Schauble (in press-b) propose a taxonomy of models (see Figure 1). At one end of the continuum are models based primarily on resemblance and similarity to the phenomenon being modeled, the referent system. At the other end are models based on relational structure and analogy, bearing little, if any, resemblance to the referent system.

In the classroom example, first graders made a major move from simply making direct observations of rotting to using a model, the compost column. Using such a physical microcosm of the referent system is, for students of any age who are new to this kind of thinking, an easy entry point into the practice of modeling. As students gain more and more experience using modeling as a tool for inquiry, they tend to employ models that emphasize function and relationships in the referent system more than those that primarily bear physical resemblance to that system. This shift, as Lehrer and Schauble point out, is essential for developing both deep understanding and the ability to use science and mathematics to interpret real situations and solve problems generated in those situations.

The map that students chose to use to make conjectures and predictions about the fruit-fly population was a representational system. Students chose this particular model *purposefully*, not through mere chance. By using a *map* to display fruit-fly population density instead of, for example, a bar graph or table, students readily made conjectures about *why* more fruit flies appeared in certain locations (e.g., places with available food). Students brought to bear their earlier experience with mathematical modeling and dealing with data. Lehrer and Schauble (in press-b) explain the development, importance, and interrelationship of students' experiences in modeling in mathematics to their webs of inquiry in science.

Devising Inscriptions

When teachers make inscriptions a classroom norm, the need for inscriptions quickly becomes apparent to students as they collect data. Inscriptions help them more accurately remember what they have seen and enable them to focus on and track change over time in the phenomena they are observing. As students gain experience and mature in understanding, their inscriptions become increasingly mathematical in nature. Lehrer, Carpenter, Schauble, and Putz (1998) give an example in which fifth-grade students extended previous experiences in modeling data to develop line graphs and frequency plots to display data about comparative growth rates of larvae fed with two different kinds of food.

Syntactic Models	Physical Microcosms	Representational Sysyems	Hypothetical-Deductive Models
• planetarium • terrarium • compost column	• map • diagram	• flipping a coin to represent birds' choices in foraging for two available kinds of food	• observing the behavior of billiard balls as they collide at different speeds to make inferences about gases and pressures

Figure 1. A taxonomy of models.

Fifth-grade students extended previous experiences in modeling data to develop line graphs and frequency plots to display data about comparative growth rates of larvae fed with two different kinds of food.

As the chain of inquiry extends and the cycle of modeling continues, inscriptions can either facilitate or constrain conclusions that are drawn, new questions that are asked, or arguments that are made, as illustrated in the questions arising from the map of fruit-fly infestations and in the early observations of rotting tomatoes. In still another example, the fifth graders growing larvae (Lehrer, Carpenter, Schauble, & Putz, in press) had speculated at the beginning of the experiment that growth rate and size of larvae were directly related to their longevity. However, after looking at their early line graphs and frequency plots, students changed their hypothesis: Their inscription suggested to students that "larvae that grow faster and bigger don't live as long."

Students' inscriptions also provide an important window on their thinking. Inscriptions give teachers a visible trace, not only of students' reasoning at the moment, but also of change in their thinking and understanding, making it possible to share and discuss an individual student's thinking.

Teachers as Designers

Though inquiry may be initiated by students' curiosity, students do not have the foundational knowledge in mathematics, science, and learning necessary to conduct a comprehensive web of inquiry that will result in learning with deep understanding. Teachers, using curricular materials and activities, adapt, elaborate on, or invent the context of learning in ways that ensure that students in their classrooms study important central concepts in science and mathematics and that the understandings students develop are accurate and rich.

One of the most powerful tools teachers have is questioning. Teachers use questions to set the direction of study and to guide students into new avenues in a given web of inquiry. Teachers, through the use of primarily open-ended questions, can encourage students to give evidence and scientific or mathematical arguments to support their conjectures or conclusions. Through the examples teachers set and the norms of inquiry they establish, students can learn to question and challenge each other—and learn what constitutes a good question, what counts as evidence, what serves as validation of a conclusion.

Teachers can help students clarify their thinking and modify their plans for inquiry by asking *why* students think something is true or *how* something happens, or by *explaining* how elements of a system are related. In the classroom example, when Ms. Putz saw that students were confounding the effects of heat and light on tomato color change, she did not tell them what was wrong and how to fix it. Instead, she asked questions such as, "Is the window sill the warmest place in the room?" or "Is light the only thing that matters?" Eventually, students themselves settled on a classic two-by-two experimental design (though they did not call it such). This process took longer than if the teacher had had the students follow a set of preplanned steps, but the students developed a better understanding of what they were doing and why.

To introduce students to a new tool or to nudge them along in thinking about models, teachers might make specific suggestions. In the classroom example, at a time when students would have been stymied in their investigation of rotting, Ms. Putz introduced the idea of using compost columns: replication in miniature, modeling at its most basic level. Ms. Putz did not hand out a set of

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directions to be followed; rather, students, through extensive discussions, made important decisions about exactly what to include in their model. This process focused their attention on the *function* of the "ingredients" in the compost column, which led eventually to their excluding such elements as gum wrappers and foam.

During the extended investigation of rotting, students showed intense interest in mold. Ms. Putz recognized, however, that they had a basic misconception: Mold couldn't be alive. To help students investigate this, Ms. Putz designed a way of enabling students to observe more mold, this time on bread. She also showed a video about fungi to help students know what to look for as they inspected their bread mold under a microscope.

Ms. Putz's questions, in these and other situations, encouraged students to plan the details of the investigation, to make connections, and to draw supported conclusions. *Ms. Putz gave students room to think, not a recipe to follow.* Eventually, by connecting their observations of the mold in the compost columns, which increased as other material disappeared, to their observations of the bread mold and the information from the video, students concluded that mold is, after all, alive.

Ms. Putz could have simply told the students they were wrong (that mold is alive), shown the video to prove it, and moved on. Instead, she designed an extension of their web of inquiry that

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resulted in students' building deeper knowledge *connected meaningfully* to things they already knew and understood.

The Need for Support

The new perspective and new practice fostered by the MIMS project can only be sustained by support that teachers and students do not typically receive.

Students

To study science through inquiry and to use mathematical modeling, students need substantial grounding, over an extended period of time, in areas of mathematics not typically emphasized or studied in depth: geometry and the mathematics of space, measurement, uncertainty and probability, and the collection, representation, structuring, and analysis of data. The primary focus of the MIMS project has been to develop these forms of mathematics. Moreover, students need opportunities to pursue a cumulative and coherent curriculum in science, not a series of 2-week "units" that do not build on each other. Students in MIMS classrooms gain extensive experience, *over the course of their elementary-school years*, in these domains of mathematics and science.

Teachers

Teachers, as well as students, need opportunities to engage in *doing* mathematics and science. In order to design fruitful webs of inquiry and develop/provide worthwhile tasks for students, teachers must be able to draw on their own rich, *growing* understanding of mathematics and science phenomena, systems, and processes. To discern, for example, whether students have chosen wisely or poorly from among various mathematical tools they might use to aid their inquiry, teachers must understand the power and potential of the tools students choose or invent. Teachers cannot present and facilitate learning through inquiry, using modeling as a tool, unless they themselves continue to learn through inquiry.

*If **teachers** are to adopt this new perspective and new practice, then they **must work within a professional community** that values, promotes, and supports teacher engagement in inquiry and knowledge building.*

Teachers must also have a solid understanding of children's thinking in general and of their own students' thinking in particular. The MIMS project, through its researcher–teacher collaborations, is gathering information about students' thinking as they engage in science and mathematics.

MIMS is demonstrating that the new perspective and new practice described here pay off for both students and teachers. There is, however, no cookbook full of step-by-step pedagogical recipes. If teachers are to adopt this new perspective and new practice, then they *must work within a professional community* that values, promotes, and supports teacher engagement in inquiry and knowledge building in several areas: mathematics and science; student thinking, understanding, and cognitive development; and pedagogy. MIMS has focused on providing this vital teacher support, not only through its teacher–researcher collaboratives, but also through summer workshops and monthly meetings focusing on both content and pedagogy.

The Larger Community

Finally, to sustain such an approach to mathematics and science teaching and learning, parents and the community must be informed about the program and be aware of its benefits. MIMS teachers regularly hold Family Math Nights, which provide parents (and others) experiences similar to that of students and encourage participants to ask questions. As parents see the benefits in the MIMS approach, they give support and encouragement to the teachers and the school as well as to their own children. u

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Speaking From Experience

by **Anne Turnbaugh Lockwood**

To Carmen Curtis, a second-grade teacher at Country View Elementary School in Verona, Wisconsin, *teaching mathematics and science for understanding* is far from an elusive, theoretical concept used only by researchers. She and her colleagues are actively involved in a teacher–researcher collaborative focusing on webs of inquiry in mathematics and science.

In 1995, Curtis participated in the Teaching and Learning Geometry for Understanding project directed by Richard Lehrer (funded by the National Science Foundation). Because of the impact of this project, she chose to continue her involvement through participation in the Modeling in Mathematics and Science (MIMS) project, directed by Richard Lehrer and Leona Schauble (funded by the National Science Foundation, the James S. McDonnell Foundation, and the National Center for Achieving Student Learning and Achievement in Mathematics and Science).

Involvement in the MIMS project, Curtis says, has affected not only what children learn in the school's participating classrooms, but also *how* these children learn. The growth of teachers' knowledge about how their students learn, she explains, not only powers the ways in which students at Country View think about and solve mathematical and scientific problems, but also fuels significant changes in classroom practices. In this article, Curtis speaks primarily of her experience and students' learning in mathematics, but points out the powerful connection of that learning to students' work in science.

Student Thinking

Curtis's students develop mathematical ideas as resources for their understanding of science. The ways students learn about space and geometry in Curtis's classroom, and the classrooms of her colleagues who have become part of the MIMS project, build first on students' prior knowledge and understanding, nudging lively, sustained inquiry from both teachers and students. "As we've participated in this project," Curtis says, "we've learned that kids can do much more than we thought they could. In fact, they can do many things in geometry that many people would think impossible."

Her own beliefs about how children learn, she says, have changed fundamentally. "Previously, I never bothered to find out what kids thought about mathematical concepts," she admits. "Even if you are not a particularly traditional teacher, you still have the district's curriculum or your grade level curriculum. These curricula send out a message: This is what kids are supposed to do."

Curtis says, "As we've participated in this project, we've learned that kids can do much more than we thought they could. In fact, they can do many things in geometry that many people would think impossible."

Understanding that young learners can model mathematical concepts was nothing less than a paradigm shift for Curtis as well as for her peers: "I know now that all kids are capable of thinking about math in very different ways. As we went through the early years of the project, I learned right along with them. I saw that they could be given complex, difficult problems and could handle them with the greatest of ease."

This notion of early access to powerful mathematical ideas generates teacher eagerness to participate, Curtis believes. Perhaps the most important lesson for teachers was the need to take time to listen and learn from their students, rather than pouring as many facts into them as possible. "I had to take the time to learn what kids thought about things," Curtis says candidly. Although this may sound simple, it was revelatory, she explains. "I learned that they didn't know many things that textbooks, teachers, or schools have always assumed they did know," she says. "I also gained access to really sophisticated and intriguing thinking—from young children—that I had never asked about before. Their questions, their interest, and their prior knowledge provide the guide for where we start and where we go, once we are into the process."

Teaching for Understanding

Teaching mathematics for understanding requires that teachers engage in purposeful inquiry, learning first the extent of students' prior knowledge about the intended concepts and then engaging students along fruitful paths that lead naturally into the next stage of instruction: the web of inquiry in a particular domain.

Discussion with researchers and colleagues about teaching for understanding, Curtis maintains, helps ease instructional transitions and leads to greater teacher comfort with dramatically different practice. "Today, I have a much better sense of what I will hear from the kids," she says. "Certainly, each group is unique, but I have learned how they develop their understanding, how they begin to think about concepts such as three-dimensional shapes, for instance."

This does not mean, she adds, that she does not continue to be surprised. "I do know now the milestones that kids experience, that move them forward, that get them to explore, to investigate, and to wrestle with complicated concepts. This means that when a student says something that may not have seemed particularly important to me in the past, I have learned that it is something to follow up through a series of questions."

A Parent's Voice

by Anne Turnbaugh Lockwood

When Karen Spencer compares her daughters' math instruction to her own early experiences learning math, the distinction is sharply apparent. "When I was growing up," she recollects, "story problems were always the hardest part of math for me. But with my daughters, the story problems are so easy because they've learned to solve problems so many different ways . . . We were taught through memorization, but they are so used to thinking in so many different ways about problem solving that before long they can come up with the right formula to find the answer."

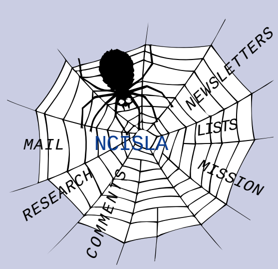
Spencer notes that her daughters (Brittany, a fifth grader, and Avery, a third grader) have both benefited from Carmen Curtis's approach to math instruction. "Some people don't understand this way of teaching or doing math," Spencer says, "and call it 'feel-good' math." She sees that as inaccurate: "Carmen still expects them to get results, but the kids don't think of it as work. Instead, it's fun to learn and problem-solve."

Curtis's popular Math Night, held monthly for parents and their children, features a variety of activities that families can do together. "Avery always wants to get to all the activities in the hour provided," Spencer says, "and wants to make sure we're going to make it to Math Night. She is very comfortable with her math and very proud of her math. She just isn't intimidated by any math problem she encounters."

Brittany, Avery's older sister, has been approached by her teacher about starting a math club just for girls and notes that Brittany's teacher "can pick out the kids in his class that learned math in this way because their ability to problem-solve is so apparent."

Whether instruction involves putting together an imaginary pizza using pieces of paper cut into slices or solving a complicated story problem, Karen Spencer is convinced of the benefits of this new way of approaching mathematics. Her son, who learned math in a more traditional way, is a seventh grader in accelerated math classes and, she notes, admires his sisters' achievement: "He'll say: 'I can't do it that! How can she?' "

"I just hope, " Spencer concludes, "that my first grader learns math this way."



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Prepared statement for Presidential Meeting on Mathematics & Science Education by Walter G. Secada

. . . continued from page 11

Teaching for understanding also demands flexibility. Curtis notes, "I always say: This isn't what we were going to do today, but it was really valuable. I am still the teacher, but the children teach each other so much. Each group of students arrives at things in different ways. Sometimes they take some very interesting, winding paths and then rejoin the main track that I had in mind." These winding roads, Curtis emphasizes, lead to valuable places: "They are constructing knowledge in ways that makes the most sense to them. That is really powerful."

Teachers also have to be willing to relinquish their unchallenged roles as authorities. She adds gently, "When you teach for understanding, it is fine for kids to perceive that the teacher is asking a question to which she or he doesn't know the answer. They also perceive that there is no one right answer. Instead, in this type of a classroom, they get credit for finding a neat or different way to find an answer. It is not a zero-sum game, where only one person can be right."

Connecting Mathematics and Science

Teaching mathematics for understanding, Curtis points out, has direct benefits for the ways in which students understand and apply scientific concepts. She illustrates with an example drawn from her experience working with third graders on fast-growing plants. "Before teaching mathematics in this way," she says, "my students thought of growth in basic ways, such as getting bigger."

Students' conceptions of growth changed dramatically once they began experiencing the mathematics of space, in which students were actively involved in explorations of volume and three-dimensional shapes. "This background in mathematics," Curtis explains, "helped them develop very strong understandings of measurement, three-dimensional shapes, and

"In this type of a classroom, they get credit for finding a neat or different way to find an answer. It is not a zero-sum game, where only one person can be right."

their own personal sense of what measurement really means."

Students who had rich experiences in mathematics in the classroom, she says, were the most sophisticated students she has ever taught in terms of their ability to display and interpret data. "They understood," she notes, "how the height of a plant changed over time. They could compare an individual line graph with the line graph of another student. They also could look at a chalkboard covered with 20 individual line graphs and have a fascinating discussion about what a typical line would look like for the growth [of a given plant]."

This understanding, Curtis adds, deepened when students decided to investigate how the structure of a plant changes over time, considering volume and space as well as height. "I didn't dream any of this up," she emphasizes. "Everything came from the kids. These are very scientific tools, and they applied them on their own."

Benefits

Curtis knows from her years of teaching that students' self-concepts about performance in mathematics are frequently formed as early as the beginning of the second grade. "Too often," she says, "a child will believe another student is good in math, but that he or she is not, and cannot become, good at math or science."

"Kids used to come to me with firm ideas about what 'a good math student' meant," she adds. "It was someone who got the answer quickly—and they believed there was one right answer. Now I am raising an entirely different breed of math learners, because each one of my kids knows he or she is good in math."

Not only do students discover the power of their own reasoning when taught mathematical concepts in ways that emphasize multiple approaches to solving problems, but their parents have been won over as well. "At Country View, our philosophy about teaching in this way has spread to many teams of teachers," Curtis reflects. "We have worked long and hard to bring the parents along. At first, they [the parents] may be skeptical, but then they see that their kids take a whole different approach to learning, whether it is about fractions or something about three-dimensional space."

Parents see their children come home and do very complex addition, adding two different mixed fractions together, subtracting another, and finding the answer in their heads. "Not only are they able to do that," she adds, "but they have a perfect understanding of it. As a result, their parents see that their children are developing understanding and strategies that can be used very flexibly and then applied to many different situations. These same understandings and strategies connect to other kinds of math."

Collaborating With Parents

Working closely with parents so that they understand this different way of learning mathematics is imperative, Curtis adds, and she sends weekly math newsletters home that report what was done in mathematics during that week, why it was done, how their children might discuss what they are learning at home, and how parents might talk about the math with their children.

This proactive parental outreach, she believes, helps engage parents in the educational process, particularly crucial when that process is not similar to their own experiences with math. "Twice a week, students take their math homework home so that their parents see and understand what they are doing. Parents need to be in the loop," she insists, "because the quickest way to alienate them is to leave them out."

Beyond weekly newsletters and math homework, Curtis holds a monthly Math Night for parents and children: "They come into a classroom where they investigate problems the same way we do in class. Parents see how excited their children are and are able to see them collaborating with their peers. They see a child solving a problem they never believed she could solve. Or, a parent might tell me his child cried because they couldn't come to Math Night that particular night because of a prior commitment." Curtis adds, "They see something good is going on here."

Country View's principal, Heidi Carvin, is quick to agree. "One of the most remarkable aspects of the MIMS project," she says, "is the number of staff who have been involved and the energy that it has created." Carvin said that at her school MIMS began with 21 classroom teachers and still has a solid core of teachers who have stayed involved all three years. Presently, all but three Country View teachers participate in the project. Professional benefits, Carvin believes, are clear: "Teachers have the opportunity to observe each other's classrooms, to gain new ideas, and to learn about an inquiry-based approach."

As principal, Carvin believes the most important support she can provide has to be tangible, not solely rhetorical: "Teachers need time, resources, and encouragement. My challenge as principal is to be careful with the staff development agenda, because many other things need to be done in the school besides work on the math and science curriculum." Carvin works judiciously so that a new and promising area can receive full support. "I also work," Carvin says, " with parents to make sure we highlight the good things that are happening with this project through vehicles such as the

. . . continued from page 13

school newsletter, parent advisory council meetings, and the PTA."

What about barriers and problems? Have there been obstacles to this way of working with mathematical concepts? "The main barrier occurs when only one or two staff aren't involved in a project like this," Carvin answers. "Our fundamental philosophy is that people do best when they work in their spheres of excellence. At what point does one intervene and insist that a teacher join the effort? This is especially critical when the bugs have been worked out, people are involved, and for the sake of the children's learning, all teachers need to use some of these materials and teaching approaches."

Research that bears such positive results, Carvin attests, can only be positive overall. "Any time teachers have the opportunity to reflect on their craft," she says thoughtfully, "it is an invaluable opportunity. In this situation, they not only are a part of the research, but in many ways are conducting the research. The reflection in which they are engaged helps them reflect on other parts of their teaching, not just this project. Being a part of a research project also brings home the value of data. It makes teachers more comfortable working with it and designing projects that utilize data."

Carvin reports that Country View's students have performed well in various content areas on standardized state tests, which they take in fourth grade. In mathematics and science, students show impressive scores compared nationally to peers tested on the same material. When tested on geometry and spatial sense, for example, Country View's students show 81 percent attaining mastery, compared to only 35 percent nationally. In life science, 92 percent of Country View's students master performance objectives, where as only 53 percent of their peers do so nationally.

Carmen Curtis can't imagine teaching mathematics and science any other way, not when the benefits are so starkly apparent. "I learned this immediately," she explains, "when I first asked seven- and eight-year-olds what it meant to measure something. Two and a half hours later they were still explaining to me what they thought about when they measured.

"Today," Curtis says, "instead of thinking about what an expert on kids thinks they should be doing, or what someone else thinks they should be doing by the end of third grade, I think about how my students start their thinking about something and where that thinking will lead. This is a very key difference, and a powerful one." u

NOTE: *Richard Lehrer reports that some of the original 21 teachers at Country View have since moved to schools in the same district where they continue to participate. Since the beginning of the project, only two teachers have dropped out, and the total number of participating teachers is now approaching 50.*

CENTER MISSION

The Center's mission is to craft, implement in schools, and validate a set of principles for designing classrooms that promote student understanding in mathematics and science.

To achieve this mission, we are conducting a sustained program of research and development in school classrooms in collaboration with school staffs to do the following:

1. *Identify a set of design principles.*
2. *Demonstrate, **in classrooms**, the impact of the design principles on student achievement.*
3. *Clarify how schools can be organized to support teaching for understanding.*
4. *Develop a theory of instruction related to teaching for understanding.*
5. *Find ways to provide both information and procedures for policymakers, school administrators, and teachers so they can use our findings to create, and sustain, class rooms that promote student understanding.*

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Comments From . . . Walter G. Secada, Associate Director, NCISLA

Curriculum Matters (continued from back cover)

NCISLA research on the development of classrooms that promote student understanding in mathematics and science suggests that students can understand—and therefore achieve—much more than conventional curricula have allowed them. Second, research suggests that teachers create a synergy between curricula and their students' understandings by posing challenging curricular tasks and, as they discover what their students are understanding about those tasks (based on the responses that students make and the discussions that they engage in among themselves), that teachers nudge their students in directions that they think will be especially productive. Teachers use their students' understanding to point to the most productive directions for the development of ideas in mathematics and science.

Center research also suggests that the curricular tasks should be *worth* understanding in the first place: Mathematics and science should be interesting, and there must be some reason for the given content's inclusion in the curricula. Such reasons include the idea's social worth (a useful idea that can be applied to solve a social or scientific problem), disciplinary worth (an idea or a method of doing science and/or mathematics that has central importance in the history of the discipline), or inherent interest (an idea that provokes student interest). Documents such as the *Curriculum and Evaluation Standards for School Mathematics* (NCTM, 1989), *Science for all Americans* (AAAS, 1989), and the *National Science Education Standards* (National Research Council, 1996) incorporate some of the best judgments of the professional organizations on the characteristics of content that is worth understanding. NCISLA research extends these documents in some new and interesting directions by elucidating the complex interrelationships among curriculum, student reasoning, and classrooms that promote student understanding.

The articles in this newsletter suggest that students can develop impressive understandings of important mathematical and scientific ideas when they engage in a challenging curriculum—and when teachers play an important role in creating and implementing such a curriculum. Truly, the *curriculum—what students study and how they are engaged in the classroom—matters*. Students deserve to encounter challenging content in classrooms where teachers build upon students' prior knowledge, guide them to do analytical thinking, and encourage them to draw, and provide evidence for, their own conclusions. Anything less will not enable students to achieve the mathematical and scientific understandings that they need to carry them, not just through the later grades, but through their lives.

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Address inquiries to the Center, Attention: Pat Boustany, or to our E-mail address.

Comments From . . . Walter Secada, Associate Director, NCISLA

Curriculum Matters

Traditionally, school mathematics and science curricula comprise everything students are expected to do and to learn in those fields: the goals and objectives, the organization of the content covered, the depth to which content is pursued, the formal classroom tasks, and the actual activities that engage students. Regardless of the *way* students experience the ideas and concepts in school mathematics or science, the formal curricula provide the foundation for most classroom "opportunities to learn."

In the United States, mathematics and science curricula, as typically conceived and implemented, are largely responsible for the relatively low performance of even America's *best* students, according to the conclusions of the authors of both the Second and Third International Mathematics and Science Studies. When the Center on Organization and Restructuring of Schools (CORS) looked at achievement in mathematics involving higher-order thinking and understanding (rather than memorization, computation unrelated to problem solving, and recall of isolated fact, which the conventional curricula emphasize), their unpublished data analyses suggested that this kind of achievement in mathematics is more dependent on students' engagement in *tasks* specifically designed to elicit thinking and demonstrate understanding than it is dependent on the specific *instruction* students receive. According to results from the High School and Beyond database, secondary mathematics achievement is more related to relevant course taking than is achievement in any other school subject. Research on academic tracking has also shown an increasing achievement disparity between students who are limited to engaging in low-track content and those who experience more challenging content in higher tracks.

continued on page 15 . . .

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