PRINCIPLED PRACTICE

In Mathematics & Science Education

NATIONAL CENTER FOR IMPROVING STUDENT LEARNING & ACHIEVEMENT IN MATHEMATICS & SCIENCE

In This Issue

Student Understanding in a High School Genetics Class

by **Susan Johnson**

In the fall of 1968 I stepped into a energetic classroom of 8th graders and began a learning journey that has continued for over 25 years. During that time I have taught a variety of students, grades 7 through 12, including the metropolitan area's Paper Carrier of the Year, a bright student on the way to MIT, a bright student on the way to prison, and the quiet student in the third row.

One of the main reasons I am still teaching is a simple statement that, when spoken by students, lasts me to the next paycheck. That statement is *I get it!* Such proclamations are usually accompanied by spontaneous smiles and other outward signs that a piece of knowledge is possibly fitting into place after a frustrating period of confusion. But what was actually happening in the minds of those students? Were my teaching strategies helping them get to the *I get it?* Did the students truly understand?

Until recently the strategies I have used to help students arrive at the *I get it!* have been pretty traditional. They have included explaining content, discussing solutions to problems, using demonstrations to illustrate concepts, providing laboratory activities, and testing for recall of information. My students were typically scoring well on quizzes and tests, but I still wondered whether they were truly understanding or just memorizing information.

Ten years ago when I wanted to update my knowledge of genetics, I decided to enter a master's degree program in science education, with an emphasis in genetics. The courses in genetics were fascinating. The courses in education, however, had the greatest effect on me. Now my classroom is a very different place.

MODELING IS CENTRAL

I now see my classroom as a place where students experience what Latour (1987) describes as *science in the making* rather than experiencing only *ready-made science*. Ready- made science is the science that students are most familiar with. Textbooks are filled with the hindsights of scientific research but provide students with little sense of why or how the research was conducted. In a classroom with

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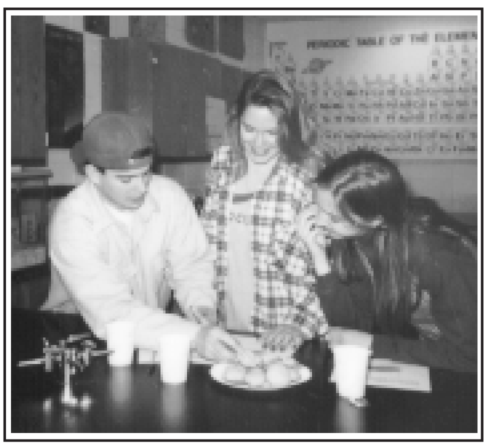
a science-in-the-making emphasis, however, the students work in research groups to pose and solve problems, to build explanatory models for phenomena, to revise those models in order to explain anomalies, and to defend and critique those models.

In the high school genetics course I teach, for example, the students develop an understanding of genetics by building explanatory models for modes of inheritance (such as recessive or dominant) and revising those models to explain new, unfamiliar modes. To begin that experience, they form research groups. The three-student groups are presented with a device whose workings are unknown. For example, they are given a carton of liquid laundry detergent that dispenses a set amount of liquid each time it is tipped. Students must develop a model that explains how the internal mechanism of the carton might work. Their model must explain the group's observations, and they must be able to use the model to predict changes that will occur when the carton is manipulated (e.g., turned upside down or turned to lie on its side).

[I have never cut open the carton to find out how it *really* works—although student reaction to my not doing so often borders on rebellion! At first, not being told the answer is new and somewhat frustrating for the students. However, I believe this is one of the strengths of the course, because students must develop and test their own ideas and rely on their own reasoning and judgment rather than look to an external authority.]

When they are satisfied with their model, the research groups present the models at a classroom conference and defend those models in response to critiques from other groups. Just as real scientists do, each group can revise their model in response to feedback from other student-scientists and present their revised model at a subsequent conference.



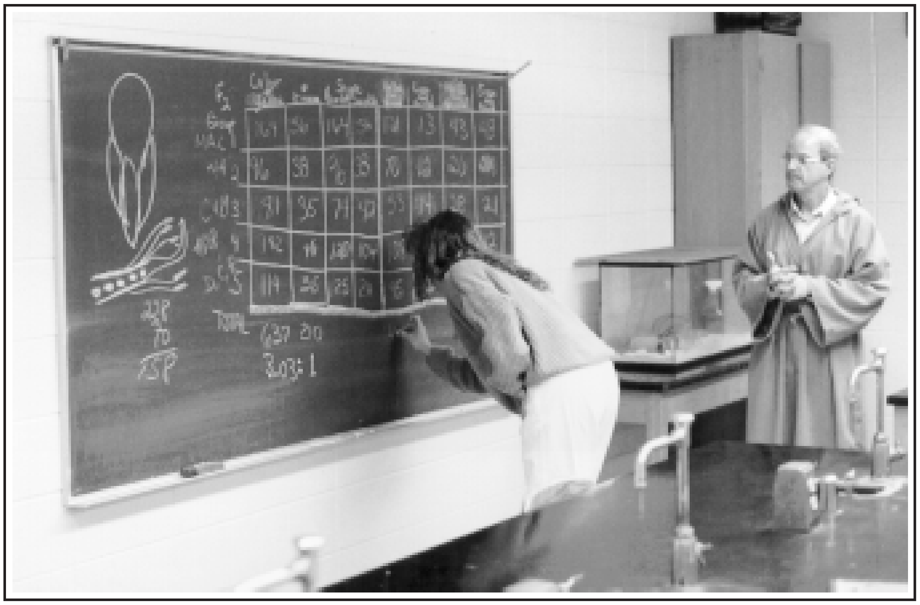
Students study the "DNA" of cookies by looking at recipe and cookie traits.

After this initial modeling experience, students do several lab activities that introduce them to phenomena for which geneticists need to build models. The first activity, "Food for Thought: The Cookie Analogy," (Johnson, 1993) has students bake and bring to class one of several recipes of cookies. The cookie recipes are equated with the DNA "recipes" for living things. Using that analogy, we discuss the phenomena of similarity, diversity, continuity, and change, as seen in cookie recipes. Then we extend the discussion of those phenomena to living things. Why are there different types of cookies (living things)? How might recipes for cookies (living things) change from one generation of bakers to the next?

A second activity, "Reflections on Variation," also deals with similarity and diversity. In this activity, students determine the type of variation they themselves display for a limited number of traits, such as color of eyes, shape of earlobe, or relative length of their toes. In the third activity, hypothetical family trees are studied to further familiarize students with genetic phenomena pertaining to generations within a family, such as offspring with a variation of a trait found in neither of the parents (e.g., two brown-eyed parents with a blue-eyed offspring)..

Students Do What Scientists Do

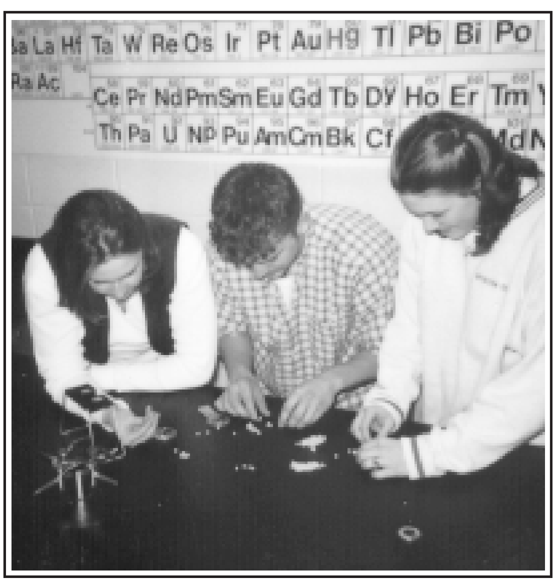
To extend the scientific modeling methods learned in the detergent carton activity into the field of genetics, the students study Gregor Mendel's basic model of inheritance (Exhibit 1). They read Mendel's original paper (1865) in which he develops an explanatory model for the simple dominance mode of inheritance. "Mendel" himself (played by a graduate student) comes to help them recreate the model. With Mendel, they look at the flower



Student and "Mendel" study data on the three generations of peas.

structure of the pea plants he used in his famous experiments. Together they count and classify peas previously gathered from three generations of plants to see how different traits, such as color or shape of seed, pass from one generation to another.

The research groups are then provided, via a computer simulation (Genetics Construction Kit), with various random collections of hypothetical organisms that follow the simple dominance model. Over several days the students become more familiar with the model by producing several generations of organisms from the random collections. They determine which variation of a particular trait is dominant and which recessive. They match genotypes (genetic makeup) to phenotypes (appearance), and they explain and predict the types of offspring possible from any two parent organisms.



Students count and classify three generations of peas.

Over the next few weeks, the collections of organisms (generated by the computer) exhibit anomalous data that are the result of modes of inheritance other than simple dominance. Because the students have no preexisting models that explain the data, they must revise Mendel's model to explain the anomalies. However, as in the detergent carton activity, they do not go to text or teacher for the answer. In this effect-to-cause problem solving, similar to

The model revising that students do is truly remarkable. They regularly construct explanatory models, some of which are the same as those currently held by geneticists; other student models are unique to the course.

that done by classical geneticists, the problems are open ended. There is no one-and-only-one solution, because multiple models can be proposed and defended.

The model revising that students do is truly remarkable. They regularly construct explanatory models, some of which are the same as those currently held by geneticists; other student models are unique to the course. One model, which was proposed by a student group (and later by subsequent groups), is particularly fascinating because it is strikingly similar to one published by Nobel laureate Thomas Hunt Morgan in 1906. In that model, all males with the dominant variation of a trait also carry genetic information for the recessive variation. It was in response to such sophisticated problem solving that I decided to begin our own tradition of awarding student research groups our school's version of the Nobel Prize.

The following is a more detailed example of the problem solving that goes on in the genetics class. Students are given this problem: Suppose a particular organism can have one of four variations of eye color — brown, ruby, carmine, or cinnabar. Up to this point, all the traits you have studied have had two or three variations. Now you need to determine not only if any of the variations are dominant or recessive with respect to one another, but

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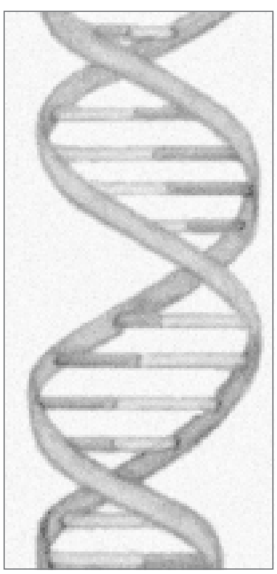
Understanding Is Evident in the Classroom

you must also revise your models for two and three variations to explain the fourth variation.

One group, when dealing with a similar problem, produced and tested about a dozen hypothetical models over a three-day period. At this point, they were testing a model they had proposed, in which there were three forms (alleles) of the gene responsible for eye color in the hypothetical organisms. The students spent most of the third day testing that model by using it to explain the types of offspring produced by breeding (crossing) organisms having various eye colors.

It was impressive to see how they stayed with it until they seemed tentatively confident that they had a working model and then began predicting the resulting eye colors in the offspring based on that model. Note that students use the eye colors (brown, ruby, carmine, cinnabar) and numbers for those colors (1, 2, 3, 4) interchangeably.



Objects in the Simple Dominance Model

# of Traits under Consideration	1
# of Variations/Trait	2
# of Genes/Trait	1
# of Alleles/Gene in the Population	2
# of Alleles/Gene in an Individual	2
# of Possible Allele Combinations	3

Objects in the Simple Dominance Model

Allele Combinations

1,1 or 2,2: Homozygous
1,2: Heterozygous

Genotype/Phenotype Combinations

1,1 Variation A-Yellow Peas
1,2 Variation A-Yellow Peas
2,2 Variation B-Green Peas

Processes in the Simple Dominance Model

Segregation
separation of the members of a pair of alleles such that each gamete produced contains only one member of the pair.

Independent Assortment
segregation of the members of pairs of alleles for two different traits, the genes for which are found on separate, chrmosome pairs. Therefore the segregation of one pair of alleles is independent of the segregation of the other pair.

Fertilization
the union of sperm and egg with a single allele resulting in a zygote with pairs of alleles.

Cross Possibilities Phenotypes	Genotype	Probable Results
1. Variation A x Variation A	1,1 x 1,1	Variation A
2. Variation A x Variation A	1,1 x 1,2	Variation A
3. Variation A x Variation A	1,2 x 1,2	Variation A & B (3:1)
4. Variation A x Variation B	1,1 x 2,2	Variation A
5. Variation A x Variation A	1,2 x 2,2	Variation A & B (1:1)
6. Variation B x Variation B	2,2 x 2,2	Variation B

Exhibit 1 MENDEL'S SIMPLE DOMINANCE MODEL OF INHERITANCE

Student 1: *We think there should be another thing* [cross result] *that should happen.*

Student 2: *Cross brown and ruby* [breed an organism with brown eyes with one that has ruby- colored eyes].

Student 3: *Brown and ruby?*

Student 2: *Yeah.*

Student 1: [continuing after some discussion] *Or another time we should get 1,1 and a 2,3. We should get a 1,2.* [1,1; 2,3; and 1,2 are examples of representations that the students have chosen for the types of genetic information that will produce the different eye colors.]

Student 3: *Brown and ruby* [parents], *we got all four* [variations in the offspring].

Student 2: *Yeah, yeah, yeah, that's all right, we got – We know that.* [Discussion continues.]

Student 1: *So what could be the parents?* [pauses] *No, no.* [pauses] *Oh! OK.*

Teacher [to the entire class] *OK, it's time to start* [turning off the computers, because the bell is about to ring].

Group: *No, no, no! No it's not!* [They keep on working at the computer. Just then, they get the results they predicted.]

Group: *Oh! Yes!* [They clap, cheer, and give high fives.] *We got it!*

The students were elated. They celebrated all the way out the door and down the hall.

Objects in the Multiple Alleles Model—Three Alleles

# of Traits under Consideration	1
# of Variations/Trait	4
# of Genes/Trait	1
# of Alleles/Gene in the Population	3
# of Alleles/Gene in an Individual	2
# of Possible Allele Combinations	6

Processes in the Multiple Alleles Model-Three Alleles

Segregation
separation of the members of a pair of alleles such that each gamete produced contains only one member of the pair.

Fertilization
the union of sperm and egg with a single allele resulting in a zygote with pairs of alleles.

States in the Multiple Allelels Model—Three Alleles

Allele Combinations

1,1; 2,2; 3,3 Homozygous
1,2; 1,3; 2,3 Heterozygous

Genotype/Phenotype Combinations

1,1 Variation A-Brown Eye Color
1,2 Variation A-Brown Eye Color
2,2 Variation B-Cinnabar Eye Color
2,3 Variation C-Ruby Eye Color
3,3 Variation C-Ruby Eye Color
1,3 Variation D-Carmine Eye Color

Independent Assortment
segregation of the members of pairs of alleles for two different traits, the genes for which are found on separate chromosome pairs. Therefore the segregation of one pair of alleles is independent of the segregation of the other pair.

Cross Possibilities Phenotypes	Genotype	Probable Results
1. Variation A x Variation A	1,1 x 1,1	Variation A
2. Variation A x Variation A	1,1 x 1,2	Variation A
3. Variation A x Variation A	1,2 x 1,2	Variation A & B (3:1)
4. Variation A x Variation B	1,1 x 2,2	Variation A
5. Variation A x Variation C	1,2 x 2,3	Variation A & Ds(1:1)
6. Variation A x Variation B	1,2 x 2,2	Variation A & B (1:1)
7. Variation A x Variation C	1,2 x 2,3	Variation A,B, C, & D (1:1:1:1)
8. Variation A x Variation C	1,2 x 3,3	Variation D
9. Variation A x Variation D	1,1 x 1,3	Variation A & D (1:1)
10. Variation A x Variation C	1,2 x 3,3	Variation C & D (1:1)
11. Variation A x Variation D	1,2 x 1,3	Variation A, C & D (2:1:1)
12. Variation B x Variation B	2,2 x 2,2	Variation B
13. Variation B x Variation C	2,2 x 2,3	Variation B & C (1:1)
14. Variation C x Variation C	2,3 x 2,3	Variation B & C (1:3)
15. Variation B x Variation C	2,2 x 3,3	Variation C
16. Variation B x Variation D	2,2 x 1,3	Variation A & C (1:1)
17. Variation C x Variation C	2,3 x 3,3	Variation C
18. Variation C x Variation D	2,3 x 1,3	Variation A,C, & D (1:2:1)
19. Variation C x Variation C	3,3 x 3,3	Variation C
20. Variation C x Variation D	3,3 x 1,3	Variation C & D (1:1)
21. Variation D x Variation D	1,3 x 1,3	Variation A, C, & D (1:1:2)

Exhibit 2
STUDENT'S MODEL OF INHERITANCE FOR THREE FORMS (ALLELES) OF GENE

In courses I have taught in the past, students were fairly willing to move on to their next class when the bell rang. So what was it, in this case, that made them so emphatic about wanting to continue testing their model? Although we aren't privy to what was going on between the lines of their discussion, it is obvious that they were invested in what they were doing. The *We got it!* they were celebrating was an explanatory model (Exhibit 2), which *they* developed, that allowed them to explain their research results and accurately predict the offspring possible from any two parent organisms. There was an ownership of ideas, which, as seen from their excitement, was a very powerful motivator. They also had a deeper understanding of genetics, because they had developed *their own* models rather than solely memorizing something presented to them already in final form.

In these classes, students experience the important scientific activity of persuasion. First, they persuade themselves as to the adequacy of a particular model. Then they persuade others within their research group. But, as with the detergent carton activity, models are also shared at classroom conferences in which the presenting groups start with a new random collection of organisms that follow the same mode of inheritance as the organisms with which they worked during their model building. After making only a few crosses, students are asked to explain those crosses using their model and to predict the results of crosses not yet done.

Watching students defend their models & explain their thinking is convincing evidence that the contribution students can make to their own learning, and to that of their classmates, is greatly underestimated.

It is a very powerful moment when a student model is successfully used to predict the results of a particular cross. Watching students defend their models and explain their thinking is convincing evidence that the contribution students can make to their own learning, and to that of their classmates, is greatly underestimated.

The culminating act of persuasion for the course is also patterned after a common scientific practice, the preparation of a manuscript for review and publication. Each group writes a research paper in which they document their methods, the data they used, and a model they developed. The articles are then reviewed, and a final draft is submitted for publication in our own student journal, *The Proceedings of Monona Grove Science.*

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Students used existing knowledge, such as Mendel's simple dominance model, to generate their own new knowledge and to develop models that explained more complex inheritance patterns.

Roles Change

My role in this course has been quite different from the more traditional one that I played for most of my teaching career. Rather than acting primarily as a disseminator of information, I have become a director of a scientific laboratory, giving encouragement when it is needed and asking questions of the student researchers: What anomalies have you encountered? How does the model you are proposing explain this cross? What strategies have you used to test your model?

This new role is refreshing but challenging. It seems to be programmed into my own DNA that I take an active role helping students who are wrestling with a problem. In the past, when students were working on a problem, it was typically a matter of helping them figure out what equations to use to arrive at the expected answer. As valuable as that might be in some cases, I have found that helping them develop strategies for producing tentative models, judging the adequacy of those models, and dealing with anomalies that arise in the problem solving process are far more valuable in a science classroom devoted to having students *do* and *understand* science.

At times, this means watching them wrestle in frustration — for example, with a model that explains *all* but one of the crosses that they have performed. But it also means seeing their eyes light up when a tentative model that they have proposed explains all the crosses they have performed, including that difficult cross. It is a very powerful moment that the students themselves have described as euphoric. In this case, it is not just the *I get it!* moment, which is the result of assimilation and practice, but also the *We did it!* moment, in which the knowledge they constructed has been used to solve a difficult problem.

Instead of my having presented them with the inheritance patterns of classical genetics, they have used existing knowledge, such as Mendel's simple dominance model, to generate their own new knowledge and to develop models that can explain more complex inheritance patterns.

Throughout this process students reflect on their models and on the strategies they use to construct them. They also persuade themselves and others (classmates and teacher) as to the adequacy of those models. By articulating their explanatory models (and the strategies used to produce those models) to others during the problem– solving process, and ultimately during the classroom conferences, genetics becomes "a language for thought rather than a collection of ways to get answers" (Carpenter and Lehrer, in press). The pride of ownership in their models and the richer understanding of those models validate my new role in the classroom, a role that I thoroughly enjoy!

One of the main reasons for the success of this course is that it has been developed as a collaborative effort between my high school and the science education researchers at the University of Wisconsin–Madison. The course has changed since its beginnings — also due, in great part, to that collaboration between research and practice. During that

We got it! *Students celebrate when their model accurately predicts eye color.*

collaboration, studies were done on the model-revising processes that the students use (Finkel, 1993; Hafner, 1991; Johnson, 1996) and on the relationship between students' problem solving and their use of a model of the distribution of chromosomes during egg and sperm production (Wynne, 1995). The effects of those studies on this course include such changes as an increased attention to meiosis, more emphasis on persuasion through the writing of research papers, and explicit discussion of problem–solving strategies.

Over time, that link between the university and my high school has expanded. I now spend my mornings at the National Center for Improving Student Learning and Achievement in Mathematics and Science and return each afternoon to my classroom. One of the benefits of the new collaboration is the development of a combined research group from the Center and the high school. This group is conducting research on an evolutionary biology course based on the same philosophy used in the development of the genetics course. From this perspective, students are honored as intellectually capable and curious; they engage in intellectually honest and challenging thinking, and they articulate their ideas to others. We are currently linking that research to our earlier studies.

I feel very fortunate to be a part of this rich association between research and practice. It has caused me to be more reflective about teaching, changed the way I think about the roles of teachers and students, and allowed me to improve what happens in my classroom on a daily basis. Although I had a lot to offer that first group of energetic 8th graders in 1968, including a mind full of "new" ideas, I am more excited about what is going on in my classroom now. I am educating that quiet student in the third row by helping her take a more active role in her own learning and in the learning of her peers. These changes have been good for all of us.

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Understanding in Mathematics & Science

by **Walter G. Secada**

The core mission of the National Center for Improving Student Learning and Achievement in Mathematics and Science is to craft, implement in schools, and validate a set of principles for designing classrooms that promote student understanding in mathematics and science.

This mission is important because (1) classrooms that promote understanding fundamentally respect students' dignity; (2) understanding promotes student achievement, learning, and persistence in mathematics and science; (3) understanding draws upon what students already know and provides a basis for students to use mathematics and science both in their everyday lives and as they study other subjects, and (4) understanding of mathematics and science prepares students to live in a technological world where important personal and ethical decisions, career opportunities, and civic participation will require levels of scientific and mathematical literacy never before necessary in this society.

Understanding is not in conflict with learning basic skills. However, students should *understand* the basic skills that they are expected to learn. A focus on student understanding provides educators and policymakers with criteria for making decisions about curriculum and assessment. If something is not worth the time needed to teach it so students can understand it, then it should not be taught.

What Is Understanding?

Understanding means that new knowledge is related to existing knowledge. One's understanding of an idea depends on how many *other* ideas it is related to, on the nature and strength of the relationships between the ideas in question, and on the overall coherence (or structure) of one's knowledge. Because people are always building new relationships among their ideas and reorganizing their ideas as they build those new relationships, their understanding is dynamic, changing, and growing. Hence, understanding of mathematics and science involves mathematical and scientific ideas, the relationships among those ideas, and the connections to other nonmathematical and nonscientific ideas.

Not all relationships among mathematical or scientific ideas are equally valid. For example, students often assume that, because two phenomena usually occur simultaneously, one causes the other. They might think, for instance, that clouds cause rain. Not all relationships are equally useful, either. For example, true causal relationships are generally more useful than proximity relationships. It is more useful to understand the atmospheric conditions that cause rain than to know that it is cloudy when it rains. The goal of school mathematics and school science should be to promote the development of those concepts that have the greatest validity *and* utility—both immediately and in the long run—to *students.*

How Does Understanding Develop?

Understanding develops as students construct new relationships among ideas, as they strengthen existing relationships among those ideas, and as they reorganize their ideas. Therefore, a mathematics or science curriculum that promotes student understanding should be a curriculum that supports students' development of relationships among the important ideas of those disciplines.

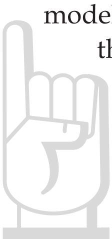
Center researchers Thomas Carpenter and Richard Lehrer (in press) have proposed that understanding develops as a result of five mental activities: (1) constructing relationships among ideas, (2) extending and applying what one knows in new situations, (3) reflecting on one's own and others' experiences, (4) communicating what one knows, and (5) actively trying to acquire knowledge. Students construct new relationships when they try to relate a new mathematical or scientific idea to other ideas that they already understand—that is, when they try to fit new knowledge into or add new knowledge onto an already existing, complex network of interrelated ideas.

Students are more likely to understand a scientific or mathematical idea when they consciously try to examine its ramifications and to think about where and when it applies – or does not apply.

Students extend their ideas by applying them in new settings. Typically, people think that students should master calculations, so-called problem solving procedures, and basic number facts before applying them. However, recent research suggests that the best way for students to learn these skills is to develop them as they try to solve problems, that is, to apply what they know in new settings. When they do so, students better understand when and how to apply the skills.

According to Carpenter and Lehrer (in press), "reflection involves the conscious examination of activity or thought." That is, students are more likely to understand a scientific or mathematical idea when they consciously try to examine its ramifications and to think about where and when it applies—or does not apply. When students reflect in this way, they often encounter points of uncertainty. They try to resolve that uncertainty by drawing distinctions and relating new ideas to what they already understand. As a result, students forge connections among new and existing ideas and either change or reinforce their notions about old connections. They develop understanding.

Students communicate what they know when they try to explain an idea to someone else verbally, manually (as in the case of American Sign Language), in writing, or through pictures, diagrams, and models. In order to explain how they are solving a problem, students must recognize the problem's important features, and they must reflect on how they have been trying to solve it. When a student communicates what she or he knows, then that oral, written, or signed message can, in turn, become an object for further reflection.



To develop understanding of mathematical or scientific ideas, students must *actively* try to acquire that knowledge. In order to understand something, they must invest themselves in the effort. This does *not* mean that students cannot learn by listening to what teachers or other students have to say; indeed, a critical feature of classrooms that promote student understanding is that students listen carefully to one another. It *does* mean that, in order to understand those explanations, students have to actively assimilate and adapt what they hear to their own purposes and actively connect new ideas to knowledge they already have.

This Newsletter

In this newsletter, we read how Center researchers are studying students' understanding in mathematics and science. Their efforts are slightly removed from the day-to-day immediacy of teaching and making on-the-spot instructional decisions. In addition, a Center teacher-researcher reflects on her own practice and how she tries to identify and develop students' understanding in the context of that practice.

Future issues of this newsletter will return to the central problem of developing student understanding in mathematics and science and to the many unanswered questions that remain in this area of research and development. We will focus on *assessment, professional development, organizational support,* and *equity.* How can we assess student understanding both for classroom purposes and for purposes of reporting to the outside world how instruction can promote student understanding of important ideas in mathematics and science? What is the role of professional development in helping teachers to develop classrooms that foster understanding? How can schools be organized to support the creation of classrooms that promote understanding? How can concerns for equity be addressed through these classrooms? Throughout the life of this Center, student understanding in mathematics and science will be the focus of our work. Through these newsletters, we hope to provide some ideas by which mathematics and science teachers, curriculum coordinators, school board personnel, and other people who are concerned about mathematics and science education might think about their roles and their practices in a sound manner.

REFERENCE

Carpenter, Thomas P. and Richard Lehrer. "Teaching and Learning Mathematics with Understanding." In *Classrooms That Promote Understanding*, edited by Elizabeth Fennema and Thomas A. Romberg. Mahwah, NJ: Erlbaum, in press.

Center Research on Student Understanding

by **Sherian Foster**

Understanding is, instance by instance, a remarkably everyday event. What people take as understanding in everyday life is much the same as what the Center calls ***student understanding****.*

Consider the following three examples of everyday understanding. A friend told me her son, originally unhappy about taking cooking at school, now loved the class. She added, "And I know he's really learning something because the other day I made some banana bread that flopped, and he said, 'You must have forgot the baking powder, Mom.'"

In another instance, my niece, trying very hard to understand something in algebra, went to a tutor for help but came home frustrated: "The tutor doesn't understand this either! When he explained it, and I still didn't get it, he just said the same thing over again." Later she went to a teacher and came home relieved saying, "Well, I found someone who understands this! At first she explained it the same way. But then, when I didn't get it, she explained it another way, and I understood it. Now, I even understand the way the tutor explained it, and I can do problems either way."

In a third situation involving everyday understanding, a couple of preteen neighbors who had often borrowed an old three-speed bike we have, spent quite awhile examining the chain, gears and pedals. They came to me very excited: "Come here! We know why it's harder to pedal in third gear when you're going slow." They took me to the garage and explained what they had figured out about gear ratios (although they didn't use that term) and speed.

In each of these examples, what was taken as understanding? My friend felt her son understood something about cooking because he could apply what he was learning in a new situation. My niece thought her teacher understood what the class was doing in algebra because she could explain it in more than one way. My niece, in turn, developed a deeper understanding and could tackle new problems in more than one way. I was impressed with the understanding my preteen neighbors had developed because they could describe how a bike works and could explain in detail *why* it does what it does.

Models, and the arguments students use to explain them, provide nice windows to the evolution of student thinking.

– Lehrer

In more and more classrooms around the country, students develop understanding by constructing knowledge for themselves. They demonstrate that understanding in the same ways the learners above did: by applying their knowledge in new situations, by explaining or using their knowledge in more than one way, and by using models and arguments to explain *how* they analyzed a situation or solved a problem and *why* their analysis or solution is sound. We have an example of this in Susan Johnson's genetics class. She said she knows her students understand certain concepts when they can construct a model that explains what they observe in a given population, when their model can be used to accurately predict what will occur in succeeding generations, and when students explain and defend their model with a convincing argument.

Current reform is calling for educators to design classroom experiences and to change teaching in order to create learning environments that promote student understanding. Following is a discussion of some of the research being conducted by the Center, with comments from Richard Lehrer, Angelo Collins, Leona Schauble, and James Stewart, who study student understanding and the classrooms that support it.

Modeling as a Key to Student Understanding

A model is a streamlined symbolic *representation* of a complicated problem or situation. When students use models to represent scientific phenomena or to solve mathematical problems, at least two things happen: Students develop new ways of solving problems, and teachers acquire new windows onto students' thinking and understanding.

In earlier *Cognitively Guided Instruction* (CGI) studies by Thomas

Carpenter and Elizabeth Fennema and their colleagues, very young children readily used cubes or other physical items to model and solve addition/subtraction and multiplication/division word problems. (These children had not first mastered basic facts and were not immediately required to use paper and pencil to formally record their mathematics.) Their use of modeling enabled them to informally solve problems usually considered too difficult for children of that age.

Richard Lehrer, Center Associate Director, points out, "Modeling, and the arguments students make using their models, leaves a visible trace of students' transformation of knowledge, which we can observe and document." Lehrer and his colleagues are developing student tasks (activities, assignments, questions to answer) that are specifically designed to *elicit* reasoning and understanding and to leave that visible trace of students' thinking. From this rich student work, teachers (as well as parents, administrators, etc.) can follow the growth of understanding, not only of the class as a whole, but also of the individual student, and can plan subsequent tasks that will help students strengthen and build on their existing knowledge.

Richard Lehrer and Leona Schauble have been working with approximately 50 teachers in five elementary schools in two districts. In this teacher–researcher collaboration, teachers design most of the science and mathematics tasks students are given. In one such task, for example, students are asked to build a model of the elbow and use it to explain how the elbow works. The students, in small teams, are given "a bunch of junk" to work with. Usually, according to Lehrer, they begin by relying on general and rather unscientific knowledge. Not surprisingly, the first models students develop are "something like a Styrofoam ball with two sticks stuck in it." When students share their models for peer feedback, they confront the concept of elbow motion: The elbow can bend, but their models cannot. Teams go back to work refining their models. Lehrer notes that the next models often have no constraints on motion — the "forearm" now moves in any direction. This peer-critique, model-refining process continues until students are satisfied that their final model accurately represents the elbow. At this point, they must construct a complete and well-developed argument to explain and defend their final model. The models and the arguments students use to explain them, Lehrer notes, provide "nice windows to the evolution of student thinking."

> *Teachers often go through "conversion experience," confronting the mismatch between traditional teaching practice and the teaching necessary to foster student understanding.*
>
> *– Collins*

After tasks are used in the classroom, teachers and researchers go through a process similar to that of their students: Together, they refine the tasks to best elicit reasoning, develop understanding, and leave a trace of student thinking. Lehrer and Schauble are developing a web-based hypermedia system that will give any teacher, via the Internet, access to a bank of classroom-tested science and mathematics tasks. Teachers will be able to call up a topic, get a list of tasks dealing with that topic along with a brief description of each task, see or obtain a video example of the task being used in a classroom, read examples of student work, and obtain benchmarks of student thinking and understanding for that task. Ultimately, Lehrer and Schauble are "trying to evolve an instructional ecology in which teachers are the instructional leaders. They [teachers] will lead the development of model-based reasoning in both mathematics and science."

Focusing on Teachers

Angelo Collins, Center Associate Director, is focusing her research on teachers themselves. Collins is very concerned about the "incredible burden the movement to teach for understanding puts on teachers." She points out that these are conceptual burdens because teachers are being asked to change the image of what science is all about, to change the nature of their instruction, to change their role in the classroom, and to change the way they plan. Collins is investigating how and why teachers change their notions of science and of teaching as they teach units designed to elicit students' thinking and understanding (as called for in current reform).

In previous work with more than 60 teachers over three years, Collins noticed that teachers went through "conversion experiences" early in the second year. At that point, they seemed to realize and confront the mismatch between traditional teaching practice and the teaching necessary to foster student understanding. As a result, a teacher either decided to retreat to traditional practice or developed "a growing knowledge of student understanding that often ended up supersatisfying." Collins is especially interested in finding out what brings teachers to this critical

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point, and why some retreat whereas others make the dramatic shift.

Teachers in Collins' study will teach *full inquiry* science units (in chemistry, earth science, physics, and biology) being developed by others at Peabody College. According to Collins, full inquiry "has to do with asking questions and using multiple ways to answer them." She notes that it is important that students work on problems they might actually encounter in the real world and that they use some methods " that are held in high esteem by the scientific community" to pose and answer questions. For example, the chemistry unit begins with a letter saying that five jars of chemicals without labels have been found in the lab. Students are given the jars of chemicals, and they must figure out how to dispose of them safely. According to Collins, "during the course of the unit students move from classifying the liquids by visual inspection, to learning about models of acids and bases, to learning about models for the process of neutralization." Ultimately students have to communicate convincingly to an environmental authority a way to dispose of the liquids in a reasonable, safe, and cost effective manner.

Collins will observe classrooms, videotape classes, and meet with teachers frequently. She will ask teachers about their beliefs about science, students, and their own roles as teachers. Teachers will be asked to reflect on classroom events and on students' work — what science was done that day, what was most significant, what students understood. Collins is currently in the process of developing the protocols for observations and questions for teachers, and she notes, "If this sounds fuzzy, it's because part of it will have to evolve as we go along." Collins emphasizes, however, that the current open-ended nature of their work *does not* mean "anything goes" or that "we'll just see what happens." Her research team is specifically interested in discovering how and why teachers' beliefs change when they teach a unit that is very different from those found in most textbooks and when students are required to model scientific phenomena, frame arguments, and build understanding rather than simply engage in hands-on activities.

Teacher–Researcher Collaboration

Teacher–researcher collaboratives are an important aspect of achieving the Center mission. Teacher–researcher collaboration often means that teachers, or their classes, are the focus of the research efforts of others, and that teachers cooperate more than collaborate. James Stewart, Center researcher collaborating with Susan Johnson, emphasizes that, at the Center, Johnson is "an integral part of all aspects of our research, from the posing of problems to pursue, to gathering and analyzing data, to authoring manuscripts." Through this collaboration, Stewart asserts, they have been able to create classrooms "where interesting student thinking occurs, thinking that is quite rare in many high school students' experiences with science." In these classrooms, the team is able to investigate that thinking and what it takes to promote it.

Leona Schauble, Center researcher and colleague of Richard Lehrer, notes several important outcomes from their collaboration with elementary teachers. She sees teachers making the conceptual changes mentioned by Collins and taking the lead in reforming the teaching of mathematics and science. For example, Schauble points out, their collaborating teachers now pay more attention to analyzing student work and understanding unusual student strategies. They call meetings, set their own agenda, and develop, for themselves, ways to further reform.

Teachers have been able to create classrooms "where interesting student thinking occurs, thinking that is quite rare in many high school students' experiences with science."
–Stewart

According to Schauble, through their teacher–researcher collaboration, several things have become clear. First, in order to bring about reform, there must be a clear focus on student learning and understanding: "Student thinking is important." Second, teachers must have structural supports in order to change: "This cannot just be an add-on to all the other demands placed upon teachers." Third, change takes a long time: "much longer than anyone imagined." This kind of change is evolutionary, not revolutionary.

Johnson provides us with a powerful example of a classroom, created by a teacher–researcher collaboration, that elicits impressive student thinking and understanding. Clearly, teacher–researcher collaboratives (those discussed here and others) will be an important part of investigating what it takes to create and sustain such classroom environments and part of realizing the mission of the Center.

Comments From . . . Thomas A. Romberg, Director *(continued from back cover)*

High Achievement for All Students in Mathematics and Science

A shared research design brings coherence across the Center's entire range of activity. Center research treats classrooms as complex ecologies where understanding of mathematics and science emerges from the interactions of student learning, teachers' professional development, organizational capacities of the school, and the larger community beyond the walls of the school, including parents.

Undergirding the shared research design are five themes that highlight conceptual issues central to both mathematics and science and that support the conceptual coordination for study of the two disciplines. The themes are (1) *modeling*, including both student modeling of scientific and mathematical relationships and teacher modeling of student thinking; (2) *mathematical and scientific argument and standards of evidence*, including students' making generalizations in science and mathematics; (3) *important ideas and technologies in mathematics and science*, meaning that students' work needs to be about important mathematical and scientific content with enabling technologies of pedagogical promise; (4) *equity*, meaning that *all* students have access to instruction that promotes understanding in mathematics and science and that there is equity in the distribution of student accomplishment; (5) *assessment* that documents what students are learning and that is aligned with the purposes of instruction.

Most of the Center work is being pursued through *design collaboratives*, one at each level—elementary, middle, and high school. In each design collaborative, teachers and researchers work together to design, implement, and test innovations in curriculum and instructional technology; in teaching strategies, including assessment; in professional development; and in the development of supportive organizational structures.

Our research agenda is both innovative and ambitious. By the end of five years, we expect to have (1) produced a set of design principles for creating classrooms that promote understanding in mathematics and science; (2) demonstrated, in classrooms, the impact of these design principles on student achievement; (3) clarified the organizational structure of schools that supports teaching for understanding; and (4) provided information and procedures for policymakers, school administrators, and teachers, so that they can use the Center's findings across the country to create classrooms that promote understanding in mathematics and science.

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UNDERLYING BELIEFS

Central to the Center's mission is the belief that there is a direct and powerful relationship between student understanding and student achievement. In fact, we have high expectations for all students, and we believe the way to high student achievement rests on students' understanding of important mathematical and scientific ideas taught in school classrooms by professional teachers.

More specifically, we believe the following:

1. All students can and must learn more, and somewhat different, mathematics and science than has been expected in the past. In particular, all students need to have the opportunity to learn important mathematics and science regardless of socioeconomic class, gender, and ethnicity.

2. Our society has long underestimated the capability of all students to learn both mathematics and science.

3. Some of the important notions we expect students to learn in both disciplines have changed. This is in large part due to changes in technology and new applications for mathematics and science. Thus, at every stage in the design of instructional settings we must continually ask, "Are these *important ideas* in mathematics and science that students need tounderstand?"

4. Technological tools increasingly make it possible to create new, different, and engaging instructional environments. Technological tools are not only calculators and computers, but also include a wide range of things such as manipulatives and other hands-on materials in mathematics, lab equipment in science, distance learning via satellite broadcast, audio- and videotapes, measuring instruments, building materials, access to natural resources, new ways of grouping students and new possible assignments (because technology gives teachers new ways to monitor student work and new things students can produce).

5. Student understanding develops as a result of students' building on prior knowledge via purposeful engagement in problem solving and substantive discussions with other students and teachers in classrooms.

6. Real reform in the teaching and learning of mathematics and science will occur only when the advocated changes in content, work of students, role of teachers, and assessment practices become *common practices* in school classrooms.

7. Such reforms will happen only if teachers are professionally supported by other teachers, administrators, parents, and the public.

RESEARCH QUESTIONS

To achieve this mission, in keeping with our beliefs, Center research has been planned to address the following questions:

1. *How is learning for understanding in both school mathematics and school science best characterized?*

2. *What are the important ideas in both school mathematics and school science that we expect students to understand?*

3. *What are the critical instructional features in classrooms that promote understanding for all students?*

4. *What is the appropriate role for teachers in such classrooms? How can they be helped to effectively assume that role? How can important changes in teacher beliefs and practices be made self-sustaining?*

5. *What is the impact on achievement as students develop understanding of important ideas in mathematics and science?* (This involves deciding what information can be collected to demonstrate student growth in understanding and high levels of student achievement.)

6. *How can the school, and larger community, be organized to support and sustain the development of classrooms that promote understanding?*

7. *How can we ensure the equitable distribution of opportunity to learn mathematics and science with understanding?* (No matter how well intentioned, unless our design principles address this question, we will have failed.)

8. *How can we effectively provide both information and support to policymakers, school administrators, and teachers so they can use Center findings to create and support classrooms that promote understanding in mathematics and science?*

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.

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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, classrooms that promote student understanding.*

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Comments From . . . Thomas A. Romberg, Director

High Achievement for All Students in Mathematics and Science

Recent dissatisfaction with student achievement in mathematics and science in U.S. public schools is as much due to changing expectations as to any decline in the quality of schooling. In the past we were satisfied if our elite were well prepared for college. Now we are proposing that students from all social, ethnic, and economic backgrounds have an opportunity to learn with understanding the important ideas in both mathematics and science. National professional standards for the content, teaching, and assessment of school mathematics and science provide an increasingly clear vision of what those important ideas are that students need to know and understand and what they should be able to do. Standards, however, specify goals but not the means to attain them. Therefore, for this and other reasons, the vision provided by these standards has barely begun to be realized in classrooms across the nation.

The work of the National Center for Improving Student Learning and Achievement in Mathematics and Science has been designed to identify the means by which high achievement for all students can be attained. Our work is based on past research but strikes out boldly on a new agenda to investigate and produce information about classrooms that promote understanding in mathematics and science, to clarify the features of school organization that support such classrooms, and to identify instructional processes that would undergird an emerging theory of instruction for mathematics and science.

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