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HORACE

# Math and Science In the Essential School

***Integrating math and science across the disciplines, and preparing all students to use them in the tasks of the future, is now vital. But the obstacles to doing so are immense, shaking the very foundations of how teachers view their world.***

BY KATHLEEN CUSHMAN

JUST WHAT IS THE DIFFERENCE between quantum physics and the Newtonian physics that has shaped so much of our world view since the Enlightenment? Advanced physics and calculus students at one Essential school are asked to show they know, in a week-long assignment their teachers devised together. Take one cultural phenomenon, they are told—from Freudian psychology to atonal music, American constitutional law to Dadaist art—and demonstrate how it is influenced by one theory of physics or the other. Then, in a mind-boggling leap of imaginative reasoning, attempt to describe how that same phenomenon *would* look—if the tables were turned.

The assignment is an apt metaphor for what is going on just now in Essential school mathematics and science classrooms around the country. Accustomed to an older paradigm that once fit our educational capabilities and aspirations, teachers are being asked to make a quantum leap into the information age—to imagine something they have never seen, to define their home territory in ways altogether new.

No more can they prepare a few elite students to probe the frontiers of science and math, and teach the rest the arithmetical basics that will get them through a less ambitious life. Problem-solving and mathematical reasoning have become the lingua franca of our time, their skills fundamental to plumber and physicist alike. If our society is to survive and compete, our children must learn to ply these tools together, speaking a searching new language that is alien to the generation before.

The challenge alternately infuriates and exhilarates, terrifies and frustrates teachers trained in the certainties of another era and gripped by a high school structure that has long valued a linear progression through compartmentalized sub-disciplines of science and math. Algebra, geometry, trigonometry, pre-calculus march on in a progression dictated by university admissions requirements set down long ago and followed by virtually no other modern nation. Earth science, biology, chemistry, and physics make up a layer-cake of facts compressed into year-long sequences. But if we integrate these subjects into each other, teachers worry, will we not turn the curriculum completely upside down, make the standard national assessments meaningless, drag down the most able students and put the others at risk of learning nothing at all?

And yet it is beginning to happen. Scientific and mathematical organizations from the American Association for the Advancement of Science to the National Council of Teachers of Mathematics have put their weight behind an urgent call for change in the way their disciplines are taught. From Connecticut to California, state education offices are listening, alarmed at the statistics that show

American students far behind their international counterparts. Goaded by large-scale state adoption prospects, textbook publishers are slowly changing their tunes. And in Essential school classrooms, by ones and twos, teachers are starting to ask students for a new kind of thinking altogether.

## The Calls for Change

What is at stake is the very meat and potatoes of high school pedagogy—a progression of courses driven by a limited content that can be covered in a year-long course. In the industrial era of the first half of this century, such a view made a certain amount of sense. But as scientific and technological knowledge approaches the point where it doubles every 20 months, transmitting "the facts" in high school classes becomes impossible, and textbook exercises that ask students to repeat information are useless. Instead, teachers must find ways to get students to *use* information, calling on everything from computers to esthetic theory to address fundamental problems in every discipline.

These are the main points made by the organizations which, with varying emphases and approaches, are pushing math and science teachers to change their teaching methods and course content. The chief difference between our system and those of countries whose students perform better, these critics argue, is that we do not expect our students to master difficult material from the start. Instead, we sort and select them into tracked math and science curricula at such an early age that by the time they reach high school, only the top ten percent of students are even exposed to mathematical and scientific problem-solving.

Math is a language, the argument goes, in which we describe the world and solve its problems. ("I think of math as one of the humanities," mathematician and educator Stephen Willoughby says. "Plato would have his philosopher-king study it for 20 years before beginning philosophy.") But most students—especially minorities and females—are not expected to learn to speak this language, which is the gatekeeper to economic and political power in our society. Fully 75 percent of all jobs, reports the National Research Council, require proficiency in simple algebra and geometry. Yet three out of four high school graduates leave school unable to satisfy either college or job mathematical requirements, and the picture for science is just as bleak.

With this in mind, several top-level groups of scholars and teachers are working on alternatives to promote math and science literacy for all students and in every grade. Top among the forces for change right now are:

• The new **Curriculum and Evaluation Standards** of the National Council of Teachers of Mathematics (NCTM), which focus on mathematical problem-solving, communication, reasoning, and connections and relationships with the outside world. Students' mathematical literacy and power will increase, the NCTM says, when we pose them genuine and meaningful problems for which they can construct mathematical solutions. Designed by an extraordinary consensus of teachers and university scholars, the standards are accompanied by a steady flow of teaching aids and examples, including assessment rubrics.

• **Project 2061**, a long-term curricular reform effort of the American Association for the Advancement of Science (AAAS), focusing on educational reforms in

### Some Ways Math and Science Are Used

• To reapportion Congressional districts, using Huntington's method of least proportions. A useful social studies project could be to figure out how your state could be gerrymandered to benefit either Republicans or Democrats, given its voting habits, and how to apportion districts without gerrymandering.

• To investigate when the number of telephone area codes in the United States will run out, given the increasing number of uses for telephone lines, unanticipated at the time the system was designed. What are the alternatives the phone companies face?

• To figure out how much it cost to put out the oil fires in Kuwait. (Why were the original estimates so far off?) Involves chemistry, labor economics, math skills of estimation, size and scale, measure.

• To analyze statistically the frequency of letters in any document written in English, for the purpose of breaking various codes. (The same is possible in other languages, but frequencies differ from language to language.)

• In esthetics, to determine what proportions are pleasing to the human eye. The "golden section" is the result of dividing a line of length q into two lengths, r and s, so that the ratio of q to r is the same as the ratio of r to s. A simple mathematical derivation involving the quadratic formula can be used to show that the ratio of r to s is about 1.618. This ratio appears in architecture, art, various ratios of parts of the human body to each other, canned goods, and other places we find esthetically pleasing.

• To describe musical notes. If a length of musical string is divided in the ratio of 1:2, the note of the shorter section is exactly one octave higher than the note of the longer.

*Thanks to Stephen Willoughby, author of* Mathematics Education for a Changing World *(ASCD, 1990), and Herb Rosenfeld.*

## McDonald's Claim

You and a friend read in the newspaper that 7 percent of all Americans eat at McDonald's each day. Your friend says, "That's impossible!"

You know that there are approximately 250 million Americans and approximately 9,000 McDonald's restaurants in the U.S. Suppose you think the 7 percent claim is reasonable.

Write a paragraph arguing that the claim could be true. Show the mathematical reasoning you might use to support the claim as reasonable.

*Sampler item from the Connecticut Common Core of Learning Assessment Project, sponsored by the National Science Foundation.*

math, science, and technology. Named after the year Halley's Comet will next return to Earth, the project emphasizes common themes across disciplines and mastery of concepts over data. Its manifesto is a 100-page book called *Science for All Americans*, and its work is supported by a broad base of private and governmental funds. The first classroom-tested materials are expected in 1993.

• The **Scope, Sequence, and Coordination (SSC)** project of the National Science Teachers Association (NSTA), which aims to cut through the layer-cake curriculum by combining life sciences with physical sciences in thematic study units for grades 7 through 12. The project calls for fewer topics with more practical, activity-based applications and personal relevance to students, and heterogeneously grouped classes where students move from concrete experience toward abstract concepts, with less focus on memorizing facts. SSC is being tried in several states including California, where experimental state assessments are already using it as their basis.

• The **Math and Science Framework for California Public Schools,** which delineates new expectations in curricular content and instructional strategies for grades K-12. Because one out of seven U.S. students goes to school in California, its policies drive textbook publishers to reflect new ways, and eventually show up on state standardized tests that are used by other states as well.

## The Implications for Teachers

All these new standards—interdisciplinary connections, depth over coverage, students as active learners, teachers as guides, the expectation that all students can learn—have much in common with the Common Principles that Coalition member schools already embrace. Essential school teachers are familiar with the idea of the teacher as generalist and learner, who coaches students along new paths rather than delivering information to them. But is it actually easier for them to take up the challenge and make new practice happen in their schools?

The answer, it seems, is a qualified no. Though Essential school teachers may have a head start on the concepts involved, the new standards threaten the reality of most schools at their very foundations. In math and science more than in any other academic areas, Coalition teachers, like their colleagues elsewhere, must confront an array of internal and external obstacles to changing the way they teach.

The generalist-teacher must still, after all, submit her students to the standardized tests and college admissions officers of 1991. Her colleagues still expect certain chapters to be covered before students are passed their way, and her students (and their parents) still expect her to dispense answers crisply from the front of the class. The school schedule may not give her students time to flounder along the messy paths of critical discourse. Most important, the time and resources to try out and reflect on new teaching practices (to say nothing of new scientific frontiers) may be almost entirely denied to the teacher facing this enormous challenge.

Little wonder that, at the 1991 Fall Forum of the Coalition of Essential Schools, the tension in a packed workshop of math and science teachers was thick enough to slice. "You just can't teach math well without ability tracking," one teacher said emphatically. "You're dragging down the most able kids, and the others can't succeed. And where's the research to prove that it even works?" A science teacher spoke up: "Student-as-worker has always been part of science classes. What's so different about this? We're already doing it." "I have to cover certain material to make sure my kids meet state curriculum requirements and do well on the AP tests," argued another.

Other teachers question whether interdisciplinary units have been designed to make sure that the problems they pose are equally challenging in all areas. "The team picks some interesting problem from

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## Changing Words Into Graphs

Draw a graph to illustrate each of the following situations.

1. Prices are now rising more slowly than at any time during the last five years.
2. I really enjoy cold milk or hot milk, but I hate lukewarm milk!
3. The smaller the boxes are, then the more boxes we can load into the van.
4. After the concert there was a stunned silence. Then one person in the audience began to clap. Gradually those around her joined in and soon everyone was applauding and cheering.
5. If movie admissions are too low, then the owners will lose money. On the other hand, if they are too high, then few people will attend and again they will lose. A movie theatre must therefore charge a moderate price in order to stay profitable.

*Adapted from Malcolm Swan,* The Language of Functions and Graphs *(University of Nottingham, England: Dale Seymour Publications).*

the social sciences," one math teacher said, "and the math part of it turns out to be completely trivial. If I'm going to do this, I want something that really challenges my students and shows them how important math is in the real world." One way to frame this is to ask which discipline drives the study of which, an area where some teachers feel consistently shortchanged.

Finally, math and science teachers are challenging the assumption that when long blocks are assigned for interdisciplinary study, their two subject areas must always be linked. "Why not math and music or art?" one teacher asked me. "Why not biology and social studies? It's as if everything the humanities jocks don't feel comfortable with has got to be put in one corner of the curriculum."

### A Changing Pedagogy

Despite such confusion and resentment, however, when these teachers begin to talk about their own goals for their students, a surprising consensus begins to emerge. "What do you want your students to retain from your class ten years from now?" CES consultant Amy Gerstein asked the Forum group. From "critical thinking" and "creative problem-solving" to "how to ask questions" to "inductive and deductive reasoning," from "seeing patterns and connections" to "application of skills," the answers made a near-perfect match with the new national standards in both disciplines.

Given this, the problem becomes to shape courses, teaching strategies, and assessment methods so that they work toward those shared goals. Essential school teachers are struggling with this complex task in their own practice, and as with all authentic change, it is a slow process. In order to effectively turn their focus, they must not only alter the assignments they give but also the way they present material, and even the very way they think about it.

All the closely paced, teacher-controlled exercises of the "clinical teaching" method they were once urged to adopt are suddenly out of favor. Instead, they are asked to probe wrong answers for their reasoning, to get kids speculating in small groups about strategies, to think of knowledge as something that must be constructed from the student's own experience.

The results are necessarily rough at the start, with teachers often mixing old ways and new as they adjust to changing expectations. "In the middle of doing something differently I find myself worrying I'm falling behind other teachers," says Cheri Dedmon, a CES National Faculty member who teaches math at Tennessee's Hixson High School. "It's always in the back of my mind when I'm letting the kids have the time they need to think things through. I want to just give 'em what they need and get on with it."

Worse, Dedmon says, her students want that, too. "The brighter kids are often the hardest to get to change—they're as resistant as veteran teachers who have been working the same way for 30 years," she says. "They want to ace their ditto sheets, not to be pushed to think; and if there's a problem they want Mom and Dad to step in and solve it for them, not worry it through themselves. If there's one goal I have for their thinking habits, it's to break them of that."

### How to Do It?

Strategies to break through the old expectations must include ways to link math and science problems to things students care about already, teachers agree. These can include projects in the community, societal or artistic dilemmas they might face in which mathematical or scientific reasoning plays a part, or even games or puzzles.

Bruce Shotland's students at Thayer High School in Winchester, New Hampshire, for instance, keep ongoing records of local water quality from year to year, which helped block a toxic waste dump slated for the area some years ago. They are now embarked on a "genetic thumbprint" of their rural community, an interdisciplinary project made possible by Thayer's teaming of each grade's teachers in a long-block schedule.

At Louisville's Eastern High School, science teacher Gil Downs, who is a CES National Faculty member, will team this term with a math, a social studies, and an English teacher on a four- to six-week unit called "Order Out of Disorder" developed at a summer institute at Brown University. "We are working with a group of sophomores who move together, the same kids I have in first-year chemistry," he says. "Instead of four final exhibitions, they'll work together on the same one."

This interdisciplinary emphasis is the only way that math and science can move past a preoccupation with acquiring discrete skills and into a focus on solving real-life problems, says Herb Rosenfeld, a cofounder of New York's Central Park East Secondary School and a veteran math and science teacher who consults for the Coalition. "The curriculum has to be based on major strands, such as Counting, Measuring, and Location, instead of on contrived sequences," he says. "You may have to go from the real world to the world of letters, use equations together with techniques of counting."

Real-life problems, of course, can include sophisticated applications to other mathematical or scientific topics. By learning to think abstractly, for example, students can reach conclusions that might escape them if they are limited to their own physical senses. Or by using deductive proofs, students can construct mathematical models of hypothetical situations—in medicine or outer space, for instance—so as to predict what will happen in advance.

To insist on relating learning to students' own experience is not to say that classical thought has no part in the math and science curriculum. Indeed, at Chicago's Sullivan High School math and science teachers routinely use seminar discussions of texts from Aristotle, Galileo, and Newton as well as contemporaries like Isaac Asimov and Richard Feynmann to prod their students' thinking on critical issues those disciplines face.

"The paradox is that we must convince our students of the universality of the laws of nature," says science teacher Nancy Shlack, "and at the same time encourage them to leave room for doubt and the possibility of reshaping these laws as new information becomes available." Lectures and labs can go only so far in this task, Shlack says; by forcing a student to defend and explain his or her emerging understanding, the seminar provides the necessary third step.

In each one of these teaching strategies, says Stephen Willoughby, a professor at the University of Arizona and author of *Mathematics Education for a Changing World*, we must not limit students to textbook

## How Newton's Laws Shape Our Culture

*Background reading:* John Patrick Diggins, "Science and the American Experiment: How Newton's Laws Shaped the Constitution," from *The Sciences* (New York Academy of Science).

The major aim of this project is to give students an opportunity to explore the relationship between science and society. Since the Newtonian Revolution, science and scientists have gained an authority rivaling the priests and their dogma of an earlier period. Since the Enlightenment, societal institutions and cultural works have reflected the world view offered by scientists. Positive and negative responses to the implications of applying this Newtonian world view have dominated the production of art, music, literature, economics, and political philosophy. However, during the last century the "New Physics" has brought new insights into the functioning of our world, and these discoveries have brought new challenges to our thinking. How have our culture and its institutions responded, and how will they respond, to this new revolution? How can the non-scientific community be educated to understand the importance of learning scientific concepts?

1. You will demonstrate that you understand the differences between Newtonian and quantum physics by describing in writing how Newtonian and quantum physics treat each of the following:
   - scientist as neutral observer
   - outcomes as certainty, as probability (causality)
   - the world as one in change vs. the world as having permanence and an absolute set of underpinnings
   - common sense vs. mathematical prediction

(20 points)

2. You will choose a work from one of the following fields (or a field of your choosing) and show how an interpretation of one work in the field could contain underlying assumptions based on either Newtonian or quantum physics. (10 points for brief description of topic and plan; 20 points for initial analysis and notes; critical feedback from group required)
   - Economic theory (Marx, Smith, Keynes, Friedman, etc.)
   - Political theory (Social Darwinism, Leninism, etc.)
   - Psychology (Freud, Jung, Adler, Skinner, Erikson, etc.)
   - Art (Romantics, Realists, Dada, Impressionists, etc.)
   - Music (classical, atonal, etc.)
   - Literature (Cummings, Swift, Existentialists, etc.)
   - Urban planning and architecture

3. You will then take this speculative reasoning one step further and ask: *What if* the assumptions of the other physics (Newtonian or quantum) *were to be applied* to that work? How would that work look? In what ways would it have to change? In short, you will show that you know how to apply the underlying assumptions of a world view based upon a field of physics to a work from another field. (10 points, 4-6 minute in-class presentations, feedback from class; 40 points, final project submission incorporating revisions after feedback)

*—Physics teacher Arthur Eisenkraft and social studies teacher Dan Berman, Fox Lane High School in Bedford, NY*

exercises like formal derivations of proof. Rather, students should investigate and identify their own problems and theorems, then test their conjectures in absence of an authority who will say whether the conjecture is true or false. Finally, they must learn to define their audience and give that audience a convincing argument. Only as they learn to use math as a language with which to communicate with each other about common problems will they begin to acquire for themselves the real power of these disciplines.

With this in mind, many math and science teachers use journals as a regular way of prompting students to reflect on their work.

## What About Ability Grouping?

Clearly, cooperative learning is implicit in all the new ways of approaching math and science. "Whether you're talking about cooking or research, one's best work usually takes place in a group," says Stephen Willoughby. But how can one combine students of vastly different abilities in problem-solving situations without holding back the best students and defeating the less able?

One answer, it seems, is to combine ability levels from an early enough age that all kids are exposed to the same concepts from year to year. More able students should take group projects to deeper levels than others will attempt, but they will share the same basic conceptual problems. Kids who don't get the concept in one way can be coached to understand it in another, and

## Order Out of Chaos

**The Essential Question:** How would you take a large collection of facts and information and organize them in a useful way that will allow for:

- a quick, facile, and reliable location for each piece of information available,
- a reliable and accurate view of any relationships which exist between any sets of variables being organized,
- the capability of predicting an unknown or missing value or piece of information when one knows some closely related values or data?

For the first two classifications below, choose one option and design an efficient system of organization which satisfies the three criteria of organization listed in the opening essential question. For the last classification, try both of the unfamiliar sets of data.

**I. The Familiar.** A collection of VCR tapes, a set of stereo cassette recordings, your locker at school, your clothes closet at home, the physical arrangement of all the components of an ideal high school classroom, or the group of students in this class.

**II. The Somewhat Familiar.** The classified advertisements in a large metropolitan newspaper, the stock market quotations from the Wall Street Journal, the foods in a grocery store, the tools and associated items in a hardware store, a set of baseball cards, or the items of a salad bar.

**III. The Unfamiliar.** A Model. The "Set of Nine" informational squares, and the "Set of Twenty Elements."

**Some Helpful Hints:** The first two classifications are easily organized by a variety of criteria, most of which are qualitative and quite subjective. The last classification, however, involves a system of both quantitative and qualitative data. In this last classification it might be easiest to organize the "squares" of the elemental cards into as compact as possible a two-dimensional array that will satisfy the statements of the essential question. The baseball cards could also fit into this type of pattern. To test your organizational pattern, remove one of the cards in the system and see if you can predict the properties of the missing card.

**The Exhibition:** Your group will present and defend your system of organization for the choices from classes I and II and for one of the two items worked on from class III. Your presentation should utilize visuals in some fashion to help others better understand your thoughts concerning systems of organization.

**Evaluation:** You can use the following scoring rubric to help score your or another group's exhibition of an organizational system:

18-20: The organizational scheme worked exceptionally well with the provided set of test data proposed by another group. The scheme involved minimal revision of procedures and produced an excellent and well organized product. The final product can now be used to predict effectively missing or future entries that fit into the system of organization.

15-17: The organizational scheme contained only minor flaws and handled the test data in a relatively easy fashion. The scheme produced an acceptable but not exceptional final product.

12-16: The organizational scheme needed some minor revisions, but once adjusted, could handle the test data in an acceptable fashion. The scheme produced an acceptable but not exceptional final product.

9-11: The organizational scheme failed to handle the test data provided by another group despite the fact that the data appeared to be easily understood by the majority of group members.

Below 9: The organizational scheme as is, or revised, could not handle the set of test data provided by another group.

*—Developed for the Brown Summer High School course "Order Out of Disorder" by CES National Faculty members Gil Downs, Colleen Gurley, and Simon Hole.*

ties abound for teachers to explore new methods. Supported by the National Science Foundation's restructuring initiative, the state is focusing on improving math, science, and technical education, and six schools in Re:Learning are involved in a major NSF grant for that purpose. At Middletown High School, a grant from Kraft-General Foods funds a summer high school demonstration session for developing interdisciplinary courses, linked with a University of Delaware education course. Over the last two summers, eight Middletown math and science teachers have taken away new ideas to spark change in their school's curriculum.

At Broadmoor Junior High School in Pekin, Illinois, Stacy Garman moved into science teaching from another discipline altogether, teaming with a seventh-grade math teacher to plan a unit on problem solving and the scientific method. "We mapped out our plan over the summer, using discretionary funds from our team," Garman says. "Now we've just asked for two more days because we need to sit down for more sustained planning time."

Herb Rosenfeld is emphatic about the need for math and science teachers to meet in continuing professional study groups if they are to revise their practice. "We must broaden teachers' base of knowledge so they can see that choices are there to make," he argues. "They should be meeting monthly with a group of other teachers, including university mathematicians, who can identify provocative literature to read. Then they can take that material and start to shape a new curriculum." Rosenfeld hopes that the Coalition will soon sponsor such efforts around the country, and is seeking modest funding to support it.

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A more ambitious turn could hardly be envisioned than the one now brewing in math and science departments across the country. Because it will require such fundamental shifts at every level, only a sustained and focused long-term effort holds any hope of real progress. But if any teachers are to succeed at this sea change across the disciplines, those in Essential schools may have a better chance than most. They have already begun to see, after all, how curricular and pedagogical change shakes every aspect of a school's structure. They know exactly how hard it is to move away from the front of the class into the coach's sideline spot, urging their students to discover new things for themselves. As the 21st century bears down, a revolution of knowledge will force students to function in a world we can as yet barely contemplate, and schools will have to help.

"It's scary when you ask a class of high-achieving students to think and you get utter silence," says Gloria Campion. "They're still as hooked into the old system as we are, waiting for us to turn cartwheels and do it for them. In an ideal world I'd like sequential course constraints lifted. I personally haven't yet come to grips with the balance of problem solving and other skills. And assessment needs to be totally changed, though I'm not ready to say at advanced levels that just doing any project is enough. We've got to teach them enough so that the culmination of the course would be to construct something that uses sophisticated skills—you design the heating of the airport hangar, you design the cooling, you design the roof, put it all together. In a very traditional school and community, I don't see it happening soon. But we're going in that direction." ❑

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