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Thinking About Science

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Table of Contents

Bringing Science into the Classroom.....	1
Science and Science Education.....	2
Science is a Web.....	6
Thought Experiment Set 1.....	8
Realizing a Different View.....	10
The Problem.....	10
How We Fool Ourselves.....	12
Elements of Constructivist Theory.....	14
Thought Experiment Set 2.....	17
Effective Instructional Strategies.....	19
Instructionism and Constructivism.....	19
Projects: Student as Scientist.....	20
Learning Cycle Models.....	22
Key Experiments, Prototypes, and Principles.....	24
Synthesis.....	25
Thought Experiment Set 3.....	26
Technological Tools.....	27
You Haven't Seen Anything Yet.....	27
What Technology is NOT.....	27
Microcomputer-based Labs.....	28
Telecomputing.....	32
Thought Experiment Set 4.....	34
Conclusion	35
Bibliography.....	36

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BRINGING SCIENCE INTO THE CLASSROOM

The purpose of scientific inquiry is not to compile an inventory of factual information, nor to build up a totalitarian world picture of Natural Laws in which every event that is not compulsory is forbidden. We should think of it rather as a logically articulated structure of justifiable beliefs about a Possible World--a story which we invent and criticize and modify as we go along, so that it ends by being, as nearly as we can make it, a story about real life. (Medawar, 1987)

What you would select as the *essence* of science that you would like to convey to the next generation. What characterizes science? What makes scientists want to devote their professional lives to science? Of course, there are many responses to this question, but most scientists would agree that the excitement of exploring the unknown, of discovering something new, of adding to the storehouse of knowledge, is central to their vision of science and their own motivation.

Given this, you might conclude that discovery and exploration would play an important part in science education. Unfortunately, the excitement of exploration has been effectively squeezed out of most science education at all levels. In the rush to put more science into science education, to prepare students for the next exam, the *essence* of science has been largely ignored. Science education has developed into a separate entity divorced from science and scientists. From kindergarten through college, students rarely do science, they rarely participate in the creative act.

What a strange situation exists in science education: we expect the next generation of practitioners to learn without practicing, the next generation of voters to live in a technological society enriched by the fruits of science without having any appreciation for the creation of new scientific knowledge. This makes our citizens aliens in their own homes. This situation is like preparing painters by teaching would-be artists only art history or creating great quarterbacks solely by having recruits watch game reruns on TV. Even the audience needs an appreciation that can only be gained through participation as an amateur.

It is not only possible to bring real science into science education, permitting students to explore and giving them a realistic sense of the conduct of science, but this experience is good pedagogy, providing motivation that leads to lifelong learning. Science is an adventure into the unknown that can be

exciting and motivating. Students at all ages can participate in this adventure; in fact, the best way to teach science is to involve students in real science where the answers are not known and are of obvious importance.

Involvement in real science takes time away from the curriculum so carefully designed to cover all the relevant topics, and that sounds dangerous given all the pressure to prepare students for admissions tests and college. Even students not under pressure for college find themselves in the same environment, ever pushed to cover more. But "coverage at all costs" is dangerous, creating students who hate science, who have a completely incorrect view of it, and who really possess only the superficial knowledge tests require. Deep pursuit of very limited questions leads to deep knowledge that itself can be surprisingly broad. Science often turns out to be a web of ideas, so what seems to be a very limited study can lead to learning across a broad range of topics.

As a general rule, the closer science education approximates science, the better it is. This entire essay is directed to expounding the essential connection between science education and science. We begin by contrasting the science students see with the science scientists see.

Science and Science Education

I mean, we usually don't build things. It's usually just textbook sort of things. Sometimes working with a microscope. That's about it, and then working with like labs and stuff. (student quote in Weir, et. al. 1990)

The lab is where we give students a chance to try out science, but think about how dull and misleading so many standard science lab actually are. Too often the form of scientific study is slavishly followed with none of the substance of scientific adventure and thought. Perhaps an example would be helpful in showing how misleading standard science labs can be.

The Science Students See

A perfectly normal science lab would have students understand the relation between a liquid's vapor pressure and boiling temperature by measuring the boiling temperature of water under different reduced pressures. A typical lab for this requires detailed procedures that someone spent hours developing to ensure that the lab "worked". There would be instructions for using a manometer, a thick-wall, side-neck Erlenmeyer flask, a vacuum manifold, tubing, thermometer and hot plate. Detailed instructions would cover safety, operation, and data collection. Students might be instructed to heat distilled water to 100°C and then remove the heat and start reducing the pressure. As the water boiled and cooled, temperature and pressure readings need to be taken every minute.

Students can "do" this lab without too many mistakes in the limited time available and dutifully return a lab write-up that starts with "Hypothesis: the boiling point of water decreases as the pressure is reduced." The write-up would include a beautiful graph of boiling temperature as a function of pressure with error bars and a fit curve that nicely summarizes the results.

What does a student take away from such an experience? Some lab skills, certainly—safety and use of the apparatus. But most teachers would be shocked at how little *science* would be learned. Educational research, which we will review later, shows that in similar situations, students learn almost nothing from such a lab and can get through it without altering fundamental misconceptions about the most basic concepts supposedly elucidated by the lab. Instead of supporting the idea that there is only one boiling temperature at a given pressure, students could easily slip through this lab reinforced in the common view that water at atmospheric pressure will boil at different temperatures depending on how much you heat it. Students would also probably get through this lab unchanged in their belief that the bubbles and the space above the water are filled with air, not water vapor, and that boiling only happens when a liquid is hot.

Students would also learn little from this lab about the conduct of science; it would probably reinforce the idea that science is dull, procedural, and thoughtless. They have no particular reason to study this topic except to pass the course; they did not participate in planning the experiment or developing the procedures; nor was the stated hypothesis really a question they had. Since there was no internal motivation to study this, they would not really attend to the results or think about their consequences.

The lack of student learning in labs like this is directly related to the lack of thinking it requires. The careful procedures, the concern for safety, and the general atmosphere that penalizes mistakes all mitigate against questioning, risk-taking, thinking, and learning. It is as though both teachers and students subscribe to a mechanistic model of learning which posits that going through certain steps without thinking will somehow magically result in learning. This is antithetical to all science is about.

A Glimpse of Science: Helium Evaporation

I studied liquid helium evaporation for my PhD thesis, and it is useful to contrast this experience with the student lab. The importance of this tale is how I, as a typical graduate student, went about learning about experimental science, which I discovered was so different from the model I had learned in school.

Superfluid liquid helium is fascinating. It is the only substance that is liquid down to absolute zero. Below 2.17 K the common isotope, He-4, becomes a superfluid with amazing properties. For instance, if you put superfluid helium in a cup, it will creep up the sides, over the rim and out, emptying in no time. It conducts heat thousands of times better than silver, the next-best thermal conductor. It pours through molecule-size holes (super-leaks) that block all other substances, including liquid He above 2.17 K. Who knows what practical applications might result from a better understanding of such a remarkable substance. It might bathe future computers, keeping them cold and removing the heat they generate.

When I was a graduate student, the theoretical reasons for these odd properties were only beginning to be understood. Part of the answer lay in the thermal vibrations in the liquid which had to be thought of as particles, in much the way light waves must be considered as particles—photons—when they interact with atoms. If some wild guesses were made about the properties of these thermal wave/particles, called phonons and rotons, then many of the unusual properties of liquid helium could be calculated. But the calculations were esoteric and many questions remained. Experimental evidence was needed in several areas before there could be much advance.

Finding a good experiment that would contribute to this emerging theory was an enormous challenge. (For tale of a fellow graduate student's difficulties in selecting an experiment, see Cohen, 1974). The experiment had to be theoretically interesting and experimentally feasible. It had to provide valuable information whether or not some breathtaking new result was discovered. We (there was a team of graduate students in my group all on the prowl for good experiments) explored many ideas that led nowhere. Either the effect was immeasurably small, or the experiment far too complex, or the result unremarkable. I felt like we fooled around a lot, just wasting months as we played in the shop and speculated about many areas of physics; this was amusing but a bit scary because the end was nowhere in sight. In retrospect, we were sharpening a wide range of skills and giving ourselves enough background to recognize a good project. But this was not a conscious plan, and I was worried because there seemed to be no script we were following like the comforting "scientific method" I learned in school.

If there were a good experiment to be done but not already performed by the legions of other researchers, perhaps it would rely on the particular strengths of our group which lay in measurements on beams of atoms. So, while inventing and discarding experiments, I stumbled into the craft of atomic beams: metal machine shop skills, soldering and brazing, drafting, creating and controlling a high vacuum, electronic instrumentation and atom detection. One of the arts involved forming ultra-sharp needles using electrochemistry and observing them using microscopic techniques borrowed from biology. I also pursued the theory of helium and shopped around for mathematical techniques used in other

fields that might be applied. In retrospect, all these activities seem purposeful and coordinated to support the experiment I did. But in reality, the experiment was determined by what skills I learned, and that learning was haphazard, at best.

This was a time of waiting and deep personal doubt and frustration. What was THE experiment going to be? What if it revealed nothing? Who cares anyway? Is this a sensible way to spend one's life given the social crises erupting around us (this was the late 60's)? To stay sane and connected to reality, I consciously spent more than 50% of my time on political action, trying to increase minority employment at MIT. I increasingly saw the graduate school life as unnatural and cloistered; difficult primarily because of the sacrifices it demanded.

The final choice of experiment did not appear in a flash of inspiration but slowly emerged as the best of many contenders. In a way, it was disappointing because it was so obvious; none of our wilder speculations developed into a breathtaking experiment. A hunch that the rotons should influence the speed of the evaporating atoms seemed reasonable. There were supposed to be a lot of energetic rotons in the superfluid and this might directly influence evaporation causing an abnormal number of energetic evaporating atoms. This hunch was confirmed by increasingly sophisticated calculations that indicated that unusual evaporation around .3 K could be measured and would yield a clear answer to the hunch.

The measurement fit all the criteria. Even if my hunch was wrong it would be interesting to understand why. It suggested an experiment that used many of the traditional molecular beam approaches and equipment, so I could be fairly confident that the measurement could be done. Measurements could be made on both He-3 and He-4 yielding two theses, so I could team with another student who was weaker theoretically but a better experimentalist.

It still took years to design the apparatus, get it perfected, redesign it, and get it working. The extremely low temperatures were a challenge, the evaporated helium generated a fierce background signal, the rotating chopper just above the helium surface vibrated, and the apparatus generated too much heat to run the experiment long enough. We had to come up with numerous inventions to overcome these and other problems. Once I goofed and dropped an expensive glass Dewar that exploded like a small bomb on the concrete floor; it took weeks to replace. For months the maze of pipes leaked and I really began to doubt whether I could hold out. After we assembled some part of the equipment and finding it leaked for the ninetieth time, I was ready to throw in the towel.

It seemed I was working on a degree in plumbing instead of physics. Days were spent with a leak detector that could find a few atoms slithering into the vacuum system. I had known that science research was not glamorous, but I was not prepared for how non-intellectual but psychologically difficult it was. Weeks slipped by where I never thought once about rotons, where the biggest problem was summoning the psychic energy to find the next leak.

I was in awe of others around the lab who were not put off by these petty failures and setbacks, but just plunged back in and tried again. PhDs, even a young post-doc who was clearly an ass, because they had survived all this and triumphed, took on mythic stature in my eyes, their state of grace seemed so lofty and inaccessible.

But eventually, the beast worked and yielded results; not all at once, but in fits and starts separated by months of additional leak-hunting. Unfortunately, we saw no sign of the rotons in the evaporating atoms, but it did not matter; the result was original and significant, and the thesis was quickly written.

I dwell at some length on this experience for two reasons. First, note that there is hardly a hint of the usual hypothesis-experiment-deduction paradigm in this story. There was a hypothesis—rotons influence evaporation—but it completely fails to encapsulate the thought process. A better description of our thinking was total immersion in a fascinating problem, permitting us to eventually find a niche where our skills and persistence helped uncover something original and valuable. Second, note the broad nature of what I learned while following this narrow, arcane speciality: construction, plumbing,

electronics, drafting, microscopy, electrochemistry, mathematics, and invention itself. I learned about heating and cooling, properties of metals, machine screw sizes, sharpening a metal lathe tool, and different kinds of solders. I also learned about boiling under reduced pressures, since the way we reached these low temperatures was to boil He-4 and He-3 in a vacuum. A similar breadth of learning through immersion in focused experimentation can be brought to almost any classroom.

The Real Scientific Method

The “scientific method” is often held up as a script scientists supposedly follow. As a child, the emphasis on scientific method at school—a seven step sequence leading inevitably to a conclusion—lead me to believe the way scientists proceeded was alogical, outside the realm of normal thinking. This is a perversion of the truth. You could map my graduate school experiences onto the scientific method: my hunch can be described as a hypothesis, I certainly had a method that was described in my thesis, and I did conclude something. It is just that converting my bumbling around in the lab to a rigid, semi-mystical, desiccated “scientific method” gives a completely wrong impression.

In reality, there is nothing mystical about the scientific method; scientists approach their problems much the way a carpenter approaches the problem of designing kitchen cabinets or a teacher devises a strategy for a difficult student. In each case, you think about the problem, draw heavily on your experience and intuition, perhaps consult some references to see what others may have done in similar situations, develop a hunch or two, devise a plan of action using that hunch, and see whether the plan was effective. In each case, it is just common sense.

The Lab Notebook provides a perfect case study of the erroneous impression of science schools convey. Most science students are compelled to keep a lab book consisting of a series of experiments, each starting with a hypothesis, detailing the apparatus, method, observations, and ending with a conclusion. All the best notebooks are virtually identical; the poorer ones have parts missing that should be there. The hidden message is that the lab book regimen is part of science; after all, one of the justifications for subjecting all students to science is to convey a sense of its intellectual traditions. And, of course, the intellectual tradition embodied in a school lab notebook is deadly; from it any student would conclude that in science there is no thought, no originality, no half-baked ideas, no departure from the norm.

Again this is a perversion. Most scientists do keep notebooks, but they read much like the personal journals a writer might keep, except with more math and equipment thrown in. Notebooks are used to help scientists remember things too easily forgotten—where to order special tools, what solder worked best at low temperatures, bright ideas, notes from interesting articles. They do also contain information about experimental apparatus and procedures, so again, school has conveyed a partial truth, but one that has all the juices squeezed out of it.

The common thread in all of science is the *search for simple, mechanistic explanations that tie together the largest number of observations*. The word “simple” may seem surprising here, since science is so often perceived as “hard”. This is unfortunate, and probably derives more from bad teaching than from the underlying concepts. The teaching about science too often emphasizes mathematics because it seems to simplify the concepts to the lecturer although, unfortunately, it usually obfuscates them for the learner. “Mechanistic” is also important in this definition to distinguish science from other perfectly valid human pursuits, such as art, poetry and astrology that do not put a premium on objective, verifiable chains of cause and effect. Finally, the idea that scientific explanations have power, in the sense that they tie together the largest number of observations, is an amazing comment on the world in which we live. It could be that general laws did not exist, or that huge numbers of scientific principles were needed. The remarkable fact about our reality is that a very few laws and principles have very broad applicability. Hence, we owe it to our students to convey an impression of this, that the search for general principles is often rewarded with understanding that brings order into our life.

Science progresses through the *application of common sense and involves communicating ideas that convince critics*. There is no special thought process scientists use. They are careful in their own work and critical of others' because they want to be right and have learned that it is easy to make mistakes. They eschew arguments from authority because the authority might be wrong, and they assume that their audience is as cranky as they are, only believing statements that can be reproduced by an objective observer. A consequence of this that surprises scientists and outsiders alike is that the ability to communicate is essential to success in science. The scientist must be able to present his or her views and defend them, often using persuasive writing and speaking skills that go beyond pure objectivity.

A final observation about contemporary science is in order: it is *collaborative*. The pervasive image of an Einstein independently inventing general relativity is highly misleading. While there continue to be a few isolated Einsteins, the vast bulk of science is a collaborative affair, in two senses. First, much of science is undertaken in groups, with the result that original scientific papers usually have multiple authors, sometimes dozens. My thesis work is a case in point, where the initial ideas were tossed about in a group of 5-10 and the actual research was done with one other graduate student. This is a commentary on the scale of much of science, requiring expensive equipment, big labs and team funding. It is also a commentary on human nature, which is stimulated by others with similar, but differing, outlooks, sharing an environment and goals. But, in a second sense, the collaboration extends even to the isolated researchers who, while working alone, must read the literature, attend meetings, obtain funding, and communicate results with the society of peer scientists.

This view of the work of scientists as simple, careful, common-sense, and collaborative is quite accessible to students and must not be transformed into some mystical, incomprehensible and illogical "scientific method". It should be easier for students to imagine becoming scientists using this demystified view of science. Still, it seems a long way between a simple lab on vapor pressure to thesis research on Helium vapor. Fortunately, it is not necessary to be a graduate student to ask scientifically interesting questions.

Science is a Web; Science is Everywhere.

How do you ask questions that lead to interesting science? Good science to investigate is all around us. The most prosaic objects can lead to a wealth of science, if you learn to ask the right questions.

The Faraday Christmas Lectures on a Candle

In the late 1850's Michael Faraday, the great English chemist, was fond of delivering Christmas lectures about candles as his way of illustrating how much science can be found in something this humble. His lecture began:

I propose to bring before you, in the course of these lectures, the Chemical History of a Candle. ... were it left to my own will, I should prefer to repeat it almost every year—so abundant is the interest that attaches itself to the subject, so wonderful are the varieties of outlet which it offers into the various departments of philosophy. There is not a law under which any part of this universe is governed which does not come into play, and is touched upon in these phenomena. There is no better, there is no more open door by which you can enter into the study of natural philosophy, than by considering the physical phenomena of a candle.

He goes on to perform dozens of fascinating experiments on fire, heat, capillary action, gas flow, convection, solid/liquid and liquid/gas transitions, light, spectra, and much more. Even though we now have a far better understanding of atomic phenomena, his lectures of 130 years ago remain a lively and extremely broad introduction to science that we would do well to emulate.

Any one of these experiments could lead to excellent student projects. As a teacher you need not fear that an entire curriculum concentrated on studying the candle would sacrifice breadth.

Almost Anything Works

As I was planning this section, I was driving through Connecticut and gave myself a challenge: I should be able to pick almost anything and weave an entire curriculum around it. So I looked outside and tried to pick something unlikely. The first thing that caught my eye was a wooden fence--that seemed challengingly humble and dull. I cannot imagine that fences would ever have high inherent attraction to students, but I surprised myself with the richness of the topic. Here is what I came up with:

Longevity. How long do they last? What causes them to rot? The cellulose which composes the bulk of wood is difficult for organisms to digest, but a variety of microbes can eat cellulose, as well as termites that carry such microbes in their guts. The turpentines used to protect fence posts from rot come from trees where they have the same function --poisoning microbes. How do turpentine poisons work? Are these dangerous to humans? Why do some trees have more turpentines than others? Are they a significant source of natural air pollution?

Fence design. What is the function of a fence? How strong and high must it be for different applications? What are the best designs? The depth a fence is set is probably related to both the required strength and, in northern climes, the frost line.

Fence mathematics. Given a fixed length of fencing, what is the largest area that can be enclosed? How would this be changed if part of the area to be enclosed was bounded by a natural barrier like a river? What is the minimum fence needed to divide a rectangular area into several equal-area sections?

Electrical fence. How does it work? How dangerous is high voltage? Does rain drain off the high voltage? What is the relation between voltage, current and danger? Why? Is it humane? How do solar-operated electrical fences work?

Fences and history. The enclosure movement in England remade farm economics. Fences were a major issue between cattlemen and sheep herders in the American West. What was the significance of the invention of barbed wire? The Iron Curtain and the Berlin wall.

I am not recommending wide use of a fence -based curriculum, but the point is that an in-depth study of almost any subject leads to an underlying web of important science ideas. This knowledge frees you to permit students to select what they study on the basis of what interests them. Perhaps there is a student somewhere who really would get a kick out of studying fences. Others may want to study the sound made by a siren, the origin of haze, the peeling of paint, or whales. Any of these can be used as the basis of student science learning.

The Voyage of the Mimi

The Voyage of the Mimi is an example of a highly successful, elementary science curriculum that bases an entire year of science education around the study of one topic. Mimi has been developed for three different years; the first year centers on whales, the second on Mayan archeology, and the third (still in proposal stage) on Mississippi River water pollution. As such, it illustrates how less can be more; how a focussed study leads to rich, integrated science learning.

When the Mimi project began, skeptics thought whales too narrow a topic on which to base an entire year of instruction, but it turned out to be extremely broad. Whales' prodigious size and grace is both fascinating and endearing for kids, and this basic attraction motivates much deeper study that can follow many paths:

They are mammals. They breath air, give birth, suckle their young and are called cows, calves and bulls. Their skeletons reveal typical mammal structures. Students can look at skeletons and hypothesize about evolutionary changes.

They sing. What do they sound like? What frequencies are present? How is this different from human sounds? On film students could see researchers investigating these questions. Later, they could use a computer with special software that captures and analyses the energy and frequencies present to analyze their own sounds just the way scientists were analyzing the whales'.

They migrate. Understanding migration starts with being able to identify individuals which is done by fluke markings entered into a database. Again, students see scientists doing this and then are given the same software tools and given tasks that require the use of these techniques. The need for migration is linked to ocean ecology, the distribution of nutrients and seasonal changes.

They dive deep. How do they hold their breath so long? How can they stand the pressures? How do they see in the dark? This opens up questions of comparative physiology, gas exchange, energy, hydrostatics and light absorption. Whales' ability to dive also poses questions of current research interest portrayed in the video.

There are other connections, too, with navigation, whale beaching, communication, ocean temperature and density layers, population dynamics, and much more. In short, the whale theme provides entrée into many important topics of biology, chemistry, physics, ecology, and science policy. These are treated not in isolation but in an interdisciplinary context that accurately mirrors the nature of much contemporary science.

When we were developing the ideas for the Mimi project, we explored other topics. Each was just as rich as whales, and the final decision was based on testing with kids that showed that whales were simply more appealing than the competing themes. While it may be surprising to select the major topic on the basis of superficial student interest, that interest is important to motivate prolonged study, and it is the depth of the investigation, much more than its actual topic, that makes Mimi good science and good education.

It is as though science is a web of ideas lingering just out of sight; any sustained effort to understand some part of the natural world draws forth this interconnected substrate. For those afraid of it, the web is a spider web that traps and holds; but to the student scientist, it is a web of powerful ideas and concepts that explain and illuminate.

An Ornithologist

Our kids' fourth grade teacher, William Walton, is a noted local naturalist and absolutely devoted to birds. He organized the entire year around birds: kids memorized bird songs, they wrote essays about birds, they studied maps of bird ranges; it seemed they added, multiplied and divided birds. He set up bird feeders in the school's courtyard, and the class observed what different species ate and kept track of when new species appeared in the spring. They speculated on the relation between bill shape and food, and watched dominance patterns between and among species. They wondered about how birds fly and experimented with different gliders. Someone brought in a mechanical bird and they tried to determine how this worked and whether it was a good model for bird flight. They read Rachel Carson's *Silent Spring* and understood how birds can be bio-indicators—early warning systems for planetary disorders.

Some parents of Mr. Walton's students were concerned about what was being omitted. Of course, the kids were not effected in the slightest by what was left out, and what was gained by this approach made the experience overwhelmingly positive. Mr Walton brought into the class enthusiasm and expertise that made him our kids' most popular teacher and kindled in one a life-long interest in the natural world.

Not everyone should adopt Mr. Walton's ornithological curriculum, but it was right for him and his students. From the perspective of science education, a key to his success was the depth of his approach. Students could see birds with new eyes and realize that, by careful study and observation, something as

common as birds could reveal a richness they never imagined. And from the perspective of motivation, his infectious enthusiasm and evident expertise was an essential part of the success of this approach.

Thought Experiment Set 1

- Working with a small team, if possible, pick a good theme and imagine what related science topics could be studied. Try to come up with general ways to approach the topic and turn it into a valuable set of strands for students to investigate. After 30 minutes, report your findings to another group. Critique both the content and approach of the other group. Would this make interesting learning for your students? Would this lead to active or passive learning in the classroom?
- Fix up the evaporation lab described in the section "The Science Students See". Can you put the lab in a context where it would be meaningful and compelling? Might it be part of an investigation of how to generate low temperatures, or designing a kitchen for a high-flying balloon?
- Naturally, the advice in this section raises some important questions:
 - Is it realistic to expect my students to discover something new?
 - Can I convey the spirit of science if I am not a scientist?
 - Isn't scientific investigation time-consuming and inefficient?
 - Wouldn't real science be only for the most advanced students?
 - What if my expertise is woefully lacking?

Much of the balance of this essay is devoted to answering these and related questions. Before proceeding, it might be helpful to think about these questions, debate answers, and formulate other concerns.

REALIZING A DIFFERENT VIEW

There is seldom real science in the science we teach; this peculiar situation is an indication that something is fundamentally wrong with science education. An immediate response to this problem is to provide some opportunity for students to experience science research, but this is not the only answer. One cannot fashion an entire science curriculum only around student research. To develop other responses, we have to understand better some of the causes for the well-heralded problems in science education and then understand better how science is really learned.

The Problem

Halloun and Hestenes (1985) performed one of the most revealing studies about the failure of traditional instruction. They created a simple, non-numerical test designed to probe basic understanding of physics concepts. By making their questions qualitative, they avoided testing learning that was related to using equations and were better able to probe student understanding of basic ideas. Although their results applied to college physics, subsequent research has revealed that their findings can be applied to most of science teaching.

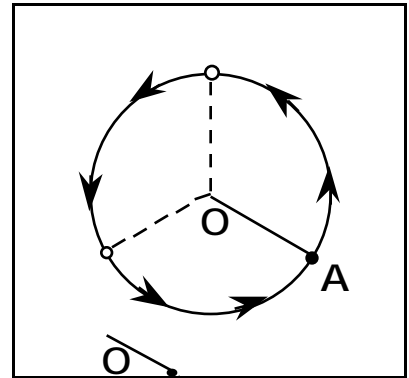
An example of the Halloun and Hestenes items is reproduced in the box nearby. Notice that the questions do not require calculations or the application of equations. In the case shown, one can answer the problem by having a good understanding of the effect of forces on the speed of the ball, the essential stuff of mechanics.

Let us consider problem (8) in more detail. Most people think that, when the ball is set free, it 'remembers' its previous circular motion and continues to curve, and thus select (d). In fact, this problem is a simple application of one of the most fundamental ideas about motion, Newton's laws. As soon as the string is cut, gravity is the only force on the ball, so it travels in a path that should be familiar to anyone who understands a bit of physics..

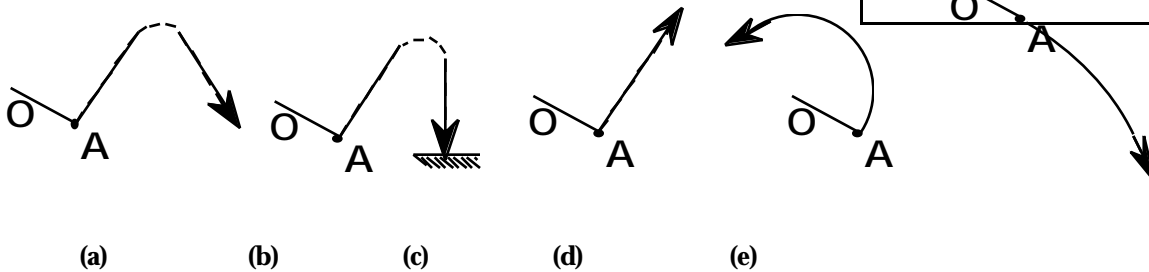
Halloun and Hestenes' amazing result is that after an entire year of college physics, *students show almost no progress on questions like these!* Their performance on these and similar items does not improve significantly between a test given before the course and an identical one given at the end of the course. In spite of having heard endlessly about Newton's laws, in spite of having worked problems about circular and parabolic motion, these students must have never grasped what was going on; they still respond to (8) with (d), indicating that they still think the ball remembers its circular motion. This result is very robust; it holds for both calculus and non-calculus treatments of physics, independent of the teacher: average teachers, good lecturers, and for faculty who are noted for their emphasis on laboratories.

The teachers in Halloun and Hestenes' study were good, conscientious teachers. Before the study, they would have scoffed at the simplicity of questions on the test, fully expecting perfect student scores on the exit test, and fully expecting good performance on the pre-test. The finding of no student gain in the test was so dramatic and so difficult to reconcile that the study has been repeated many times with different teachers, courses, and students. Individual teachers cannot understand why students do not improve in easy questions that are so much simpler than the kinds of problems routinely assigned and solved in class. But that is exactly what this study shows, so their students' grasp of the material studied is thin indeed.

(IV) The accompanying figure shows a ball attached to a string that you hold in your hand at point O, and rotate at high speed in a vertical plane in front of you. The circle shows the path of the ball, and the straight lines from the center O represent different directions of the string as you rotate it in the direction of the arrows. When the string reaches the direction OA, you let the ball go. Ignoring air resistance and any effect the string might have,



(8) Which of the paths below will the ball follow after you let it go at A?



(9) If you have chosen path (a), (b), or (d) from question (8), the speed of the ball along the path is:

- (a) Constant
- (b) Decreasing from A to the top of the path, increasing thereafter, on the way down.
- (c) Decreasing from A to the top of the path where that speed becomes zero, increasing thereafter, on the way down.
- (d) Increasing for a while, and constant thereafter.
- (e) Increasing for a while, then decreasing until the ball reaches the top of the path. The speed increases thereafter.

If you have chosen path (c) or (e) from question (8), the speed of the ball along the path is:

- (a) Constant
- (b) Continuously increasing.
- (c) Continuously decreasing.
- (d) Increasing for a while, and constant thereafter.
- (e) Decreasing for a while, and constant thereafter.

The answers are on the last page.

What happens too often in science instruction is that the teacher makes a lucid presentation of some basic ideas and assumes the material is then “covered”. Just to be sure the students interact with the

concepts, some problems are assigned that require application of the ideas presented. But it is well-known that students seldom grasp new ideas in lecture, so they attack the problems without a basic understanding but rather as examples of a class of problems that must be mastered for a test. Somehow, by chance or luck, or by following an example provided in the text, lecture or recitation section, (but probably not by reasoning from basic ideas), students figure out how to get through the problems. Then, for an exam, they review all the problems they worked so they can do similar ones. Some teachers even go so far as to break a course down into a certain number of problem types and assume that mastery of these constitutes the whole of the course. This is how students can fool both the teacher and themselves into thinking they understand a topic while lacking the kind of understanding required to solve the simple Halloun and Hestenes problems. The result is that some problem types are mastered but this does not lead to an understanding of the underlying concepts.

To see how this may happen, you should experience it. Try the two examples in Thought Experiment 2 of a problem type you have probably encountered, the "painting the house" problem type. Although the problems are similar, the technique for solving the first cannot be applied to the second without real understanding. Thus, mastering the problem type does not generalize sufficiently to help you solve a similar problem requiring understanding.

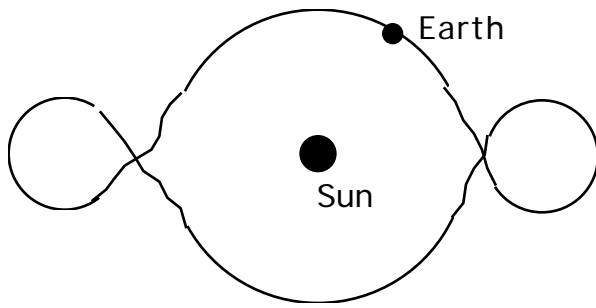
This process of dealing with only the superficial aspects of material happens far too often in science teaching. As a result, students can float through a course *without ever thinking*, as the following remarkable quote from a student reflecting on his experience in a radon measurement project attests:

Oh, like we didn't have to write as much, or, you had to think more. It wasn't like writing data charts, because data charts are really easy, you just copy things from the board or you do math, but this you have to sit down and think. You had to use your brain a little more than usual, so, that's how it was different.I think if we didn't do this radon activity *I wouldn't have to use my brain at all the whole year*. This is the only time that I really had to think and I really, like, I had to struggle a little, you know, and I'm not really used to doing that in science. (emphasis added) (Wier, et. al., 1990)

How We Fool Ourselves

Lest you think Halloun and Hestenes' result can be ignored because it was performed at an average state university and might apply only to college physics, consider the findings of project STAR, an astronomy curriculum development project at the Harvard University Observatory. Educators there set out to test the prevalence in astronomy of Halloun and Hestenes' results. They developed simple but probing questions about the phases of the moon, the reason for the seasons and the causes of the apparent motion of the planets and stars, material usually "covered" in elementary grades. They reviewed the questions first with teachers most of whom were confident students would perform very well with such simple concepts. The results were striking and discouraging, revealing deep disparities between teaching and student understanding in elementary school through college.

The breadth of the misconceptions about elementary astronomy is dramatically captured in *A Private Universe*, a film produced by project STAR (Schneps, 1988). In one particularly revealing interview, a very good ninth grade student correctly reproduces all the facts she learned about the moon going around the earth while it goes around the sun. If you stop the interview after this initial explanation, you conclude that this is an excellent student who clearly understands all the relevant ideas. But the researcher continues, trying to get the student to connect these facts with the moon's phases. The interview takes a dramatic turn for the worse, with the student making no sense. At one point, she draws a diagram of the path of the earth around the sun—that looks like this.



This apparently model student is clearly working on an explanation, and shows sufficient mental flexibility to both invent and consider novel solutions. But she clearly has not mastered the basic ideas of the earth's orbit and the causes of seasons; her initial lucid explanations were essentially a memorized recapitulation of what the teacher had said; the student apparently had no deep understanding backing up the rephrased words.

In the same film, researchers ask ninth graders and Harvard seniors—interviewed as they graduate, still dressed in their graduating robes—the same questions about the causes of the seasons and phases of the moon. It is bad enough that the high schoolers, like almost everyone, think that summer is due to the earth getting nearer to the sun. But worse, the Harvard graduates respond the same, in the same overwhelming numbers. Members of both groups, when pressed, come up with unusual explanations to buttress their arguments.

The only real difference between the two groups is that the Harvard students project much more confidence while they mouth their inanities, while the public high school students show some hesitancy. Is building confidence in ignorance what education is really all about? Does four expensive years of college only produce more literate ignorance?

I find this result baffling. Everyone knows energy comes from the sun, even those claiming distance to the sun as the cause of the seasons. Everyone has experienced shorter days in the winter, longer in the summer. Anyone can notice that the sun climbs higher in the sky in the summer. The artist must notice the way the lower sun backlights scenes in the fall and glares off snow in the winter, while the summer sun shortens shadows and bakes us from almost directly overhead. Most people are familiar with the idea that seasons are reversed between the northern and southern hemispheres and that arctic nights can be months long in the winter.

Clearly, this common knowledge accounts for less sun energy reaching us in the winter, more in the summer. Admittedly, the connection between these ideas and the tilt of the earth's axis is not immediately obvious, but they all seem to be in conflict with the sun-earth distance as the explanation.

How can all this be reconciled? First, note that the idea of distance, as commonly used, is not precise. Winter's cool sun seems distant, in the metaphoric sense used in the sentence "You seem distant today." Cool and distant are paired in our culture, as are their opposites hot and close. But distance also has its literal meaning, so students are naturally inclined to ascribe the sun-earth distance to the cause of seasons. The confusion is fueled by the fact, usually mentioned in textbook explanations of the seasons and exaggerated in illustrations, that the earth's orbit is not perfectly circular. What students overlook is that the earth is closest to the sun during the northern hemisphere's winter, so distance could not account for the seasons. While the effect of non-circularity on the heating of the earth is negligible, many students remember non-circularity because it superficially fits the cultural pairing of cool with distance.

The resulting educational problem is often encountered when attempting to replace students' common sense explanations with scientific explanations that appear to be in direct conflict. Often this results in a kind of schizophrenia, with students reserving one kind of superficial knowledge for school and keeping a separate reality in which they place their faith because it is used in everyday life. The school knowledge is not integrated into everyday life and not retained beyond the last test.

The picture that is emerging from this line of research is that most science teachers regularly fool themselves into thinking that instruction is successful by asking problems on tests that students can solve without deep understanding. Understanding is difficult to evaluate and harder to teach, so we

too often settle for the more superficial. Instead, there is an implicit compact between teachers and students to not probe too deeply.

Elements of Constructivist Theory

How is it possible to teach for understanding? How can one avoid teaching only superficially? To teach well, we must first understand how students learn. The most successful theory of learning is the constructivist view which is based on the idea that the learner must construct his or her own knowledge. Hardly a new idea, in 1916 Dewey defined education as a “continual reorganization, *reconstruction* and transformation of experience” (emphasis added).

The constructivist view of learning holds that the way we learn anything, including science, is by integrating observations and experiences into one's personal explanatory framework. This framework is a network of associations between memories of events, feelings, sounds, rules and the like. The framework has explanatory capacity because current observations can be matched to remembered ones and, hence, to their associations. If these associations are rich, they will have the ability to explain; that is to predict what will happen, to provide analogies, or to provide new perspectives.

For this to make sense, we must examine what *explanation* is. One can view explanation as a series of accurate associations that resolve an observation. The need for explanation occurs when something unexpected is observed. Associations are often conditional and then we must evaluate whether the conditions are met. So, for an association to be accurate, the conditions must be correctly evaluated. For instance, an elephant walking down the street certainly grabs your attention and demands an explanation. You may associate elephants with Africa, zoos and circuses. This latter association might trigger another association with a recent ad on the TV for a circus. This, it turn, may be connected with a Ringling Bros. logo that you then recognize in the distance, confirming your associations and providing the explanation that the circus is in town.

The need for each learner to actively create understanding from experiences based on observation is the central idea of the constructivist educational theory. As we have seen, the apparently shorter route of simply being told the answer, of memorizing facts, figures, equations and problem types may produce measurable gains on shallow tests but does not necessarily result in understanding.

The Importance of Experiences

The basic tenet of constructivism is that learning is based on experiences that require active and thoughtful participation of the learner. As one student put it:

Normally we're given like basically how passive solar heating works and stuff, but we kind of had to find out for ourselves, you know? Discover it, because sometimes when you're told something you just don't understand it, but this way you understood in your own way. It wasn't like somebody trying something and you just memorizing it. (Wier, et. al., 1990)

One key corollary of constructivist theory is the importance of a range of experiences. Mental templates that arise from the need to integrate specific experiences often stay associated with those experiences, resulting in a kind of embedded knowledge that does not easily generalize.

For example, suppose you wanted students to understand thermal conductivity, so you created a single lab experience about how water in different kinds of cups cools at different rates. If you subsequently asked questions about home insulation, you would probably find no carryover from the lab. The two situations are too different and are related only through an understanding of the basic concepts. Most students will leave the thermal conductivity lab with situated learning, that is, learning specific to that situation.

The problem of situated learning was recognized by Whitehead who wrote (1929) about “inert knowledge”—knowledge that can be recalled when specifically requested, but is not recognized as applying to the solution of related problems. There is a simple explanation for the difficulty students have in generalizing concepts. As a teacher, you may see the generality of thermal conductivity as illustrated in the lab, but realize that the student, having never encountered the idea before, has no way to judge how widely the idea applies. If applying the idea to other area requires the student to abandon his or her current concepts, you can be sure this will be resisted.

Two additional steps are probably needed before students could free their learning from the situation in which it was first encountered in order to arrive at a deep understanding of thermal conductivity: they would need to encounter it in a variety of contexts, and they would need to abstract the basic ideas from these contexts. One lab on thermal conductivity is probably not enough; students need to have experienced the cluster of related ideas and thought about the application of these ideas in many situations, in and out of school. The depth of thoughtful prior experiences is important to new learning.

There is a recent line of research that supports these ideas. It has been widely confirmed that kids who are familiar with a subject are better able to remember new material in that subject area. For instance, third graders expert in soccer are able to remember a passage about soccer better than seventh graders who are not expert (Schneider, et al, 1989). Over and over, younger experts have been shown to be able to out-perform developmentally more advanced non-experts at all ages and in many different, academic and non-academic, subjects. This suggests that, when confronted with a new idea or problem, an expert familiar with the general subject requires less effort to simply remember the facts of the problem and to summon relevant related ideas. This would seem to suggest that kids could learn abstract science ideas at an earlier age if they were already expert or experienced in the more concrete phenomena that undergird the abstractions.

Our class was put together with another class which was an environmental class and ours was a physics, so they had already learned a lot about radon, they did it last year, and they know more about it than we did even though it was a lower level class, so they had to kind of teach us and that was weird but everyone worked together I guess....Well, at first it was kind of weird to have them explain stuff to us because it was like the lower level, but they already had it for a year and they knew what they were talking about and we didn't. I mean we never did anything with radon before so. (Wier, et. al., 1990)

Part of the explanation of the expert's performance can be traced to vocabulary. The soccer expert has special concepts embedded in words such as dribble, off-sides, pass, shin guards, center, penalty box, and the like. The new passage to be learned will be constructed from the concepts captured in these terms. No one taught the expert these as vocabulary words, but they were learned, like all language, in order to express ideas that are needed to be communicated on the soccer field. To the expert, each of these terms is deeply evocative, suggesting a rich set of associations, experiences and actions. The accurate use of these terms tells us that this expert constructed a mental framework appropriate to soccer. When confronted with the new soccer passage, this vocabulary with its rich associations is available to help the expert soccer player break the passage into meaningful large chunks.

Being mentally engaged in almost anything can be a source of important experiences, raw data for future explanations. Imagine how much a farm child learns by sharing in the drama of weather: growing up over many planting seasons, sharing the family debates about when to plant and reap, the concerns about late season thunderstorms, seeing storm clouds grow, watching hawks circling on rising thermals, and wondering why all clouds have flat bottoms on some days.

Suppose a child, expert in weather because of such experiences, is presented with a new concept: "cold fronts represent cold air sliding under warmer, moist air that then rises, condenses into clouds, and creates storms." This student can draw upon her experiences—the many storms she has observed, the wind before a storm, how the air cooled, the feelings of relief after a drought, the images of storm

clouds, the water in a rain gauge after the storm. While not all of these experiences are directly relevant to understanding, their very richness is important in her success in learning this new concept in several ways. First, her experience gives her a vocabulary. "Cold front", "warm, moist air", "condenses", help simply remember the new concept. Second, experience leads to understanding of actions and causes from which the new concept is built. Important ideas are captured in the phrases "air rises" and "condenses into clouds", ideas familiar to the expert, but novel to the novice. Without understanding these smaller ideas, the new concept of cold front is meaningless, so the novice has much more to process than the expert.

The important point is that the richness of prior experience will greatly influence new learning. This richness can be supplied both in and outside school. Ironically, our increasingly technological world is increasingly arid from an experiential viewpoint. Cars, computers, heating systems, telephones and even computers increasingly hide their technological richness in order to be effortless and transparent. But the kid in the beginning of the century from the farm who had helped breed animals and fix ploughs or a cousin from the coast who had helped a parent repair a boat, forecast weather and spot marlin had a far richer store of raw experiences on which to draw than today's children. We must compensate by providing a rich range of experiences for all students in the classroom.

Beyond Experience

Teaching involves linking associations and experiences. If a student has experience with control of body temperature and of the motion of a computer-controlled car, then, when the question arises, she may be able to grasp the common concept of feedback that spans these two disparate experiences. The problem for the teacher is to help the student make that link at just the right time—not too soon, or the concept will be meaningless, but not too late, or the student may be bored or frustrated. This kind of teaching is far different from more common direct instruction in which the teacher would tell students that these two situations were examples of feedback.

Raw experience is of limited intrinsic value--the time it takes for a specific race car to descend a particular ramp is better forgotten. What is important is what is retained from the experience, how it is codified and integrated with other experience. This implies that the learner be immediately and actively involved on an abstract plane. As Dewey, a strong advocate of experience, observed:

But observation alone is not enough. We have to understand the significance of what we see, hear, and touch. This significance consists of the consequences that will result when what is seen is acted upon... . We can be aware of consequences only because of previous experiences. In cases that are familiar because of many prior experiences we do not have to stop to remember just what those experiences were... . But in unfamiliar cases, we cannot tell just what the consequences of observed conditions will be unless we go over past experiences in our mind, unless we reflect upon them and by seeing what is similar in them to those now present, go on to form a judgement of what may be expected in the present situation. ...The crucial educational problem is that of procuring the postponement of immediate action upon desire until observation and judgment have intervened. (Dewey 1938, p. 79-81)

Communication, Groups, and Motivation

Another corollary of constructivist theory is the importance of communication in helping create mental frameworks. The act of communicating observations forces one to make choices about what to relate and what to ignore, and how to compress a rich experience into a manageable size. A new idea must almost always be expressed in words not designed for that idea by using metaphors. The act of making the right selections, of choosing the right metaphor, creates new associations that challenge the mental

framework. This is when new vocabulary is helpful and easily assimilated, because the right word encapsulates a concept and solves a communication problem.

Groups that interact meaningfully help make this happen, because a well-functioning group can help raise and address the questions that arise from observations. This is one of the reasons the ideas of the cooperative education movement can be so powerful in science education (Nergendoller, 1989; Sharan, 1976; Slavin, 1983). A well-functioning cooperative student group can raise and solve many of the conceptual problems generated by a rich experience, as students in a recent project attest:

They [the activities] help us learn more from kids instead of teachers. But more important, most of us learned to find information out on our own. And that working together and listening to one another helped, but it wasn't always easy. (Wier, et. al., 1990)

An essential prerequisite for any of this educational theory to be successful is student interest and motivation. If there is no connection to the individual, if the activity seems meaningless or irrelevant, then there is little reason to put out the required mental effort. Fortunately student motivation is not that difficult to arouse in science education; it is usually sufficient to avoid destroying through incomprehensibility children's natural curiosity about their world and how it works.

Motivation can be enhanced many ways--by linking activities with questions that arise from students, through parent-figure identification and modeling, and by giving students a sense of personal power and competence (Seymour Papert likes to ask why else kids would persist at video games for which the only reward is a harder game). As the following quotes show, giving students freedom to learn can be powerful motivation:

Yeah, building solar houses, it was fun building them, cause we got to design our own and we got to record all like our materials and stuff. We got to use our own imagination... to create.

They [the activities] are different, yeah, a lot different, 'cause I mean you have more hands-on and there's no real boundary to what we can do.

Like other projects, we do experiments in the classroom, but this one was something that we would be responsible for. We would have to watch over a period of time and just take down data. So it was basically up to us. The teacher, he wasn't around to supervise us or anything. (Wier, et. al., 1990)

In summary, a constructivist perspective endorses the central role of *thoughtful processing of a rich and varied set of observations made in a motivated, small group environment where communication is essential and valued.*

Thought Experiment Set 2

- If possible, view *A Private Universe*, and discuss its implications with others.
- Design an Halloun and Hestenes test for your course. First try to list the criteria for such a test, then develop the items. Ask other teachers whether it is clear and addresses important ideas in your field.
- Try an expert/novice experiment with your colleagues or students. Pick a subject in that about half your population is expert (non-academic subjects often result in greater disparities of expertise in an otherwise homogeneous population). Have one expert write or select a paragraph of moderate complexity that uses concepts in the subject area. Then devise a simple memory test based on the paragraph.

- Explore the importance of experience by carefully examining how a range of experience might help a student through a difficult concept. Pick an academic topic that you know is difficult to teach. Build a concept map of ideas that support your topic by listing the related concepts and connecting them by arrows that indicate priority. Next each member of the group should imagine the background of a different archetypical student (e.g. the turn-of-century farm child, the couch potato, a student who learned to fly airplanes, a baker's apprentice, a basketball fanatic). Finally, list a few out-of-school experiences each of these students might have that would support each of these concepts.
- Try to solve problem 1, the painting-the-house problem, in a group and pay particular attention to *how* you solve it.

Problem 1: Working alone, June can paint a particular room in six hours and Dick can paint it in ten. How long does it take them working together to paint the room?

Problem 2: The drain on my tub can empty the tub in 6 minutes. Once I tried to empty the tub by opening the drain and turning on the faucet and it took 10 minutes to empty. How long does it take my faucet to fill the tub when the drain is closed?

See the box on the last page for the answers

Even though most people have encountered this problem type sometime, few can solve it, probably because they never understood the idea behind it--it was learned the same way Halloun and Hestenes' physics students learned their problem types, as an example of a class of problems that you better master because one of these might be on a test.

The basic idea is that the painting times are not additive--you cannot add 6 hours to 10 hours to get the result. But the reciprocals are additive--June gets $1/6$ th of the job done per hour and Dick, the laggard, can get $1/10$ th completed in an hour. These reciprocals are the rates of completion measured in (job per hour). There are many problems for which rates or reciprocals are the right thing to add. Then, working together June and Dick can get $1/6 + 1/10 = 16/60 =$ (after some reduction) $4/15$ ths of the job done per hour. How many hours does it take them? If you have an intuition about the reciprocal idea, you will see that the result is the reciprocal of the sum, or $15/4$ hours.

These are difficult ideas, not easily learned by reading. If you fail to understand the explanation above, it is not because you are mathematically incapable; explanation-based instruction fails you, as it does most people.

Now let's see how strong your intuitive grasp of these ideas is by solving a problem that depends on the same general ideas but cannot be solved with mindless application of the same formula. With a good intuition, you are more likely to be able to solve problem 2, so give it a try now.

The point of this exercise is to show how it possible to solve, albeit superficially, problems without understanding the ideas the problems were supposed to illustrate. It also shows how difficult it is to generalize to a related problem without an intuitive understanding of the ideas. This seems to be how most students got through in the physics courses studied by Halloun and Hestenes. And there is growing evidence that this is the norm in science education at most levels. Under the pressure to cover ever more material, there is no time to develop intuition, no time to mess around.

One could legitimately question whether it is important for everyone to master this kind of problem. If the answer is positive, then considerable time should be devoted to building up student intuition for these ideas. Students should have an opportunity to mess around with several situations in which reciprocals add. They should get their hands on water, paint, resistors, and moving cars and pose questions that give them familiarity with quantities, their reciprocals and their additive properties. If you conclude this type of problem is probably not worth the effort, then it should be eliminated to give more time for important concepts.

The reason usually given for having students do problems is that by so doing, students learn the underlying ideas. However, even people who can do the painting problem do not usually understand the underlying idea of adding reciprocals. In fact, research shows that repetitive problem solution does not lead to understanding of basic principles, and may even interfere.

EFFECTIVE INSTRUCTIONAL STRATEGIES

Perhaps too much space in this essay has been devoted to the shortcomings of science education. This was done to emphasize the depth of the problems we face. Science teaching has a perplexing, chronic problem not amenable to the quick fix. We fool ourselves by teaching and then testing facts and formulas that turn out to be a cheap but inadequate substitute for science understanding. Only by examining in detail what is wrong does it become clear why difficult alternatives are better and worth the inevitable extra effort.

The preceding sections hint at the solution: science involves deep understanding that comes only from the hard work of constructing understanding. This section explores how this constructivist approach can be incorporated into the classroom through alternatives to the usual forms of instruction.

Instructionism and Constructivism

Better learning will not come from finding better ways for the teacher to instruct but from giving the learner better opportunities to construct. (Papert, 1990)

Much of science reform involves making superficial changes that have little chance of making any significant impact on the deep problems we have discussed and the difficult business of helping students construct their own knowledge. Papert brands the philosophy behind the reform efforts that focus on instruction, “instructionism”, in contrast to approaches that have the potential of increasing learning by incorporating constructivist principles.

One popular instructionist pastime in science curriculum reform is “the content shuffle”—attempting to find just the right sequence of topics that will magically generate vast improvements in student learning and performance. Two such efforts currently underway in science education, at the cost of tens of millions of dollars, are Project 2061 by the American Association for the Advancement of Science (AAAS) and the National Science Teacher Association's Scope and Sequence Content (SSC) project. While both profess to consider improvements in instructional method, both are basically content shuffles, because both began by asking whether there are better topics to be taught. Project 2061 asked scientists what topics students need to learn for the year of Haley's comet's return (2061) and the SSC project asked whether we should sequence topics so there is some of each science discipline each year. Both are doomed because their central focus is not what is needed—“giving the learner better opportunities to construct.”

Another instructionist pastime is the “better book syndrome”. Maybe if we select just the right text font, get enough pictures, arrange the borders just so, find the right author, and get the order of topics just right, kids will learn much better. So every few years we throw out the discredited old texts and bring in the new, more attractive and better designed ones. All this great expense for taxpayers and students solves nothing fundamental. As Halloun and Hestenes and others have shown, the dismal results are independent of text, course or instructor.

There must be fundamental change before we can expect improved student learning. This change will not come from simply a new order of topics or a better book taught in the same old way. The classroom must look different; students will no longer sit taking notes at lecture and following cookbooks in the lab. Students will be thoughtfully engaged, deeply motivated, and working in animated groups. The classroom will be messy, loud, and vibrant, filled with scrounged parts, scavenged experiments, computers and electronics. The teacher will be a consultant, coach, and judge, but very seldom a lecturer. And the texts, if any, will be used as references, not the bible.

In the following three sections we will discuss how to create this fundamental change. In the first part, an impassioned plea is made for using project-oriented activities as a cornerstone of this change. Recognizing that projects cannot be all there is in science education, we also present the only tradition of curriculum that is based on constructionist theory, the learning cycle models. Following sections will discuss implementation issues and the role of technology.

Projects: Student as Scientist

I'm convinced that one could develop a marvelous method of participatory education giving a child the apparatus to do experiments and thus discover a lot of things by himself. –Piaget (in Bringuier, 1980)

An antidote to the standard lecture, facts, and formula approach to education is engaging students in collaborative projects that involve their own studies in an environment that forces them to construct and reconstruct their own knowledge and understanding.

As indicated in the first chapter, laboratory experiences should be a central part of science education, but not laboratory experiences in which all the method is worked out. Few students have the opportunity to *do* mathematics and science. They may learn what other people have done, they may memorize equations, proofs and definitions, they may repeat historic experiments, but they seldom learn firsthand the excitement of discovery, rarely attempt to create new understandings.

Many educators might feel that original work is beyond the capability of beginning students and has no place in introductory level instruction. However, the pursuit of topics that are original for the beginning student is both possible and highly desirable. In technical fields where information is exploding, the most important educational goal is to teach students how to obtain new information themselves. Student projects in mathematics and science allow students to face a range of issues involved with learning to learn that are not addressed in the text-and-lecture format.

The title of a wide-ranging review of science education by Philip Morrison published in 1963 says it all: "Less May Be More". This seeming self-contradiction has become the rallying call for advocates of a project oriented approach. Phil, the theorist of the Elementary Science Study and an MIT astrophysicist, explicitly endorses this in his speech years ago: "...I am speaking for ... a laboratory involvement that may be painfully slow, that 'doesn't get anywhere.' You don't 'cover the material,' but you spend a good many hours of the week doing something. That's what I'd like to see....the free use of simple materials, ...[with] *analysis*." He advocates a "branched program" based on tools. "It is not impossible that they [the students] could find something that nobody else knows." (Morrison, 1965)

Example: Cheche Konnen.

Project activities are widely used in the very best schools, especially specialized schools of math and science, so perhaps projects have gained an unjustified reputation as being only for the elite and academically advanced students. This misconception can be dispelled by an example, a study (Warren and Rosebery, 1990) of a seventh grade bilingual Haitian Creole class. The best of these students were performing two grades below level. Some were illiterate in Creole, spoke English only with difficulty, and had little idea about Western science; magic was more a part of their culture. An unlikely choice for a project approach to science? Not at all.

After an animated discussion about what to investigate, the class decided to study something they really cared about, the quality of the water in the drinking fountains on the different floors of the school. The students were sure that the water on their floor would be much better than that on the first floor used by "little kids". The students transformed their feeling about "better water" into a taste test and thought about the problems associated with a subjective test. They developed the idea of a blind protocol to protect the results from accidental operator bias, although they, of course, did not use these abstract terms.

When they ran the test, they were appalled that the data gave what they clearly understood as the wrong result—the first floor water tested better! They then decided to do what any reasonable researcher would, they repeated the experiment more carefully with a larger N. This time, they decided to use other students' opinions, so they picked a day to test water at lunch time in the cafeteria using their taste test.

The results of the larger test only confirmed the earlier, inexplicable results; the first floor water was better!. Then the students had to begin to understand why. They came up with all sorts of interesting hypotheses: temperature, lead, pH. This involved quantitative measurements which they eagerly undertook.

The student studies had a number of interesting affective results. The students had to communicate with the larger community in English, and they actually became the experts and leaders about anything concerning the test. Warren and Rosebery, particularly interested in communication, saw major advances in student use of language. The confidence and autonomy conveyed by this project seemed to generalize, so student interest in other subject increased and absenteeism dropped.

This work is remarkable, in part, because a drinking fountain project seems so improbable. At first sight, there appears to be little of intrinsic interest and no interesting science. But, as we have seen, interesting science lurks behind almost anything. Even with faith that the science could be found, no publisher would make it part of a text, and it would be risky to include it in any curriculum. And, of course, it would not be right for most classes; it worked here because the class cared about the result and owned the idea. We can generalize not the fountain study itself, but the idea of investigating something that a class cares about. Almost any project can lead to good science.

...robust learning, whether in a discipline such as science or in language, grows out of purposeful engagement with complex, ill-defined problems rather than mastery of oversimplified and decontextualized facts and procedures...(Warren, et. al., 1989)

The MIT Project Lab

For contrast, take another example of project-based learning at the other end of the educational spectrum: in the physics courses at MIT. Since most teachers will find their classes somewhere between these two extremes, perhaps the power of projects will be convincing if they are seen in such different educational settings.

At MIT twenty-five years ago the faculty realized the standard cookbook laboratories associated with the required physics course were so useless educationally they were abolished. To this day, students can take the two-year physics sequence required of all students without a laboratory, but any serious science major is urged to take one of the alternative laboratory courses which are offered. One is John King's project lab, a course in which students undertake their own projects.

Over the years, John and his colleagues have become expert in getting students to create a valuable project out of their interests. They are confident that important physics can be found in many places, and their first task is getting students to open their eyes to see the physics around them. John has urged students to twirl a coin on a table, crumple paper, or rap a steel lamp-post and listen to the sound; each has led to interesting studies. Another student watched how a Superball™ bounces and launched into a study of the frequencies at which it resonates.

One of John's favorite student projects involved burning out light bulbs. The question was, what actually happens when a light bulb burns out? What causes it to fail? A pair of students worked on this together and actually burned out dozens of flashlight bulbs by over-voltaging them and capturing the transient voltages and currents as they failed. They learned that the filament establishes an equilibrium between heating caused by the current and cooling due to its black body radiation. This equilibrium establishes a temperature that determines the rate at which the tungsten evaporates. If

the temperature is too high, the evaporation will cause the wire to get noticeably thinner, increasing the electrical heating and creating positive feedback that causes runaway heating and evaporation. This runaway heating causes the filament to get white hot and vaporize, leading to the usual “pop” as the light fails.

Notice how, in understanding this humble and commonplace problem, students had to understand an assortment of important and interesting physics topics: black body radiation and the Stefan-Boltzman Law, tungsten evaporation (an amazing concept since tungsten melts at so high a temperature), electrical heating, thermal equilibrium, positive feedback, instrumentation, and much more. This illustrates again the richness lurking behind many apparently humble projects.

Do Projects!

Usually what we do is just reading and doing some works on the desk. And kind of just memorizing and we don't really, well, you can understand it in the brain but you can't kind of really learn, how it's really like. -OK, those are just kind of knowledge, but knowledge is important but it doesn't really, you don't really understand it unless you do it by yourself, things like projects. (Weir, et. al., 1990)

As defined, projects are what scientists do. Students who are thoroughly engaged in a project, having selected the topic, decided on the approach, performed the experiment, drawn conclusions, and communicated the results, are doing science. They are seeing science not as a noun, an object consisting of facts and formulas, but as a verb, a process, a set of activities, a way of proceeding and thinking. This approach is not only good pedagogy, but good science; it can convey not only the content of science but its process.

Student projects should be an indispensable part of every student's introduction to math and science, because projects introduce students to the nature of original work, because they are motivating and integrative in a way that traditional science instruction is not and because they provide a powerful learning environment that increase students' learning and retention of math and science concepts.

This view is echoed by many experts in science education. Robert Yeager (1983) asserts that “to experience science is to begin to understand it” and that the process requires students to explore, explain and test. Current research syntheses support this contention (Shymansky 1990, Bredderman 1985, Weinstein 1982). While student exploration takes time, “programs designed to encourage laboratory science...do in fact result in improved student performance in a number of valued curricula areas.” (Bredderman 1985).

One of the most important aspects of project activities, is that they can be selected to match students' interests. Science usually seems remote and unconnected with students' lives, but a well-selected project can intersect with immediate reality, as the following student quote attests:

Building the house. Gee, that was just, it was something that I wouldn't expect that we would do, something like solar houses and stuff, it's just, people hear about it all the time. It's something that's kind of interesting to most people. I think of school as a little bit behind and I was kind of impressed. I was like, hey this is what's going on outside. (Weir, et. al., 1990)

Although there is need for more project activities in the curriculum, one cannot simply convert all science courses to project labs. A strategy for students' intellectual development is needed. Some of the needed strategies can be found in learning cycle models and from the work of Marcia Linn to which we will now turn.

Learning Cycle Models

An important teaching strategy that keeps being re-invented is what Bob Karplus, the driving force behind the widely respected SCIS project, called the learning cycle (see, for example, Karplus and Their, 1967). The approach can be summarized as the sequence: specific, general, specific, (specific). The idea is to organize instruction to first present some well-chosen, specific instance of a general idea, then the general principle, and follow this by one or more additional specific applications of this principle. The specific instances should be experience-rich and lab-oriented, if possible.

For instance, suppose you want students to appreciate the importance of co-evolution. Following a learning cycle strategy, you might have students begin with a careful study of the pollination of a particular species of flower in bloom. This might involve field observation of flower visitors and lab examination of the structure of the flower and corresponding structures of the pollinators. Only after this experience do you introduce the idea of co-evolution as an answer to the questions raised in the pollination study. The unit is then concluded with two more co-evolved pairs chosen to illustrate the breadth of the concept so it does not get situated in student's minds with only the flower example.

Roger Bybee has called attention to the need to surround the learning cycle with an initial motivational experience and a concluding self-evaluation. With these added ideas, Bybee reformulated the Karplus learning cycle as five steps known as the five E's: explore, experiment, explain, extend and evaluate (Trowbridge and Bybee, 1990). The idea is to start an instructional experience with an engaging, relatively unstructured exploration that generates interest and questions. This should lead to a more careful experiment from which a general explanation emerges. This is then extended to explain other phenomena and ideas. The sequence ends with a self-evaluation of what was learned.

Both of these approaches--the learning cycle and the "five E's"--contain instructional wisdom. They are in the constructionist tradition because they recognize the importance of experimental evidence and experiential learning, while focusing on the student construction of meaning and elevating abstract learning to a central, integrating role. They delay the presentation of the general rule until students are sufficiently motivated and experienced to appreciate it. But then time is given to continuing to work with the general rule so students integrate it into their experience by seeing its application in multiple situations.

The most prevalent mistake of science instruction is "theorism", a focus on theory devoid of meaningful context, assuming that kids naturally will understand the implications of a theory without help. How often have you heard a variation of the following: "but they should understand the role of infrared radiation in the greenhouse effect, I taught 'em that last month"? By following a learning cycle, you are forced to ground the theory in its application, and you may avoid theorism.

The second most common mistake is to go too far the other way with "experimentism". Having understood the weakness of theorism, many teachers (and educational researchers) throw theory out altogether and simply advocate an experimental, or "discovery", approach to education. In its extreme form, this requires kids to re-create all the knowledge of science through sufficiently rich experiences. This approach has more merit than theorism because at least students leave an experiment-rich environment with a wealth of unassimilated experiences they may be able to draw upon at a later time. However, extreme experimentism is wasteful because it misses opportunities to teach organizing theory. This was the criticism of the science education reform movement of the '60's.

The learning cycle idea helps avoid the pitfalls of experimentism by placing theory at the center of the instructional strategy. The precursor exploration and experiment are important both because they involve experiences and because they are selected to support a central idea with real explanatory value. Similarly, follow-up extensions are selected to enhance experience related to the central idea.

Learning cycle approaches can generate stupid results if they are applied to curriculum design in a mechanical and thoughtless manner. It is too easy for a curriculum designer to hope that by adhering to

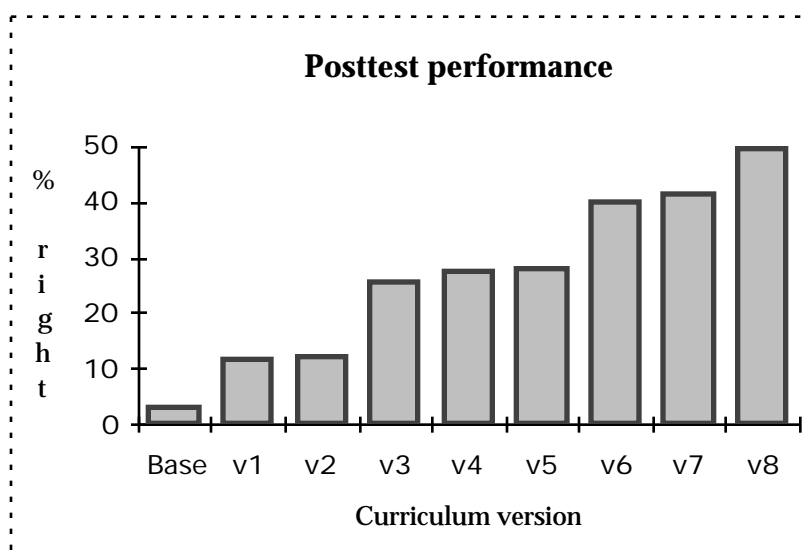
one of these almost mechanistic design principles, the curriculum will be based on solid cognitive theory, and that no additional thought about student mental processes will be needed. What can result is an approach with the form of good instruction, but without its substance.

At best, learning cycle models provide some general guidance, but no automatic solution to the challenge of teaching. Learning cycle models can be helpful, but they are too abstract to give detailed guidance about what topics to present and how to treat them. As the next section shows, there is no substitute for careful curriculum design that takes into account student thinking.

Key Experiments, Prototypes, and Principles

Marcia Linn has recently documented the need to balance experiment and theory in a remarkable series of instructional experiments (reported in Linn, et al, 1990, and Linn and Songer, 1991). She and her colleagues have taught an entire semester of heat and temperature at a middle school for eleven successive semesters. Each semester, they have measured student gains in understanding of important ideas and then adjusted their instructional strategy, and each time they get better. The figure below illustrates the improvement they achieved. Starting with only 3% of the students able to accurately distinguish between heat and temperature, they were able to reach 50% with a carefully designed curriculum. (The later versions of the curriculum had different instructional goals so these results are not shown.)

There were strong similarities between all eleven curricula—they were all lab-oriented, involved the same teacher, used computers in the lab, and devoted an entire semester to heat and temperature. It is important to note that changes in the curriculum caused large changes in student learning *even though there were strong superficial similarities in all eleven offerings*. This shows how important the curriculum design is. It is also interesting that, as the figure shows, after all this care and an entire semester of instruction, 50% of the students were unable to distinguish heat and temperature.



Improvement of student performance on a problem over eight versions of the curriculum. The problem requires students to accurately distinguish between heat and temperature. (adapted from Linn, et al, 1990)

After all this experience, Linn and her co-workers have some important insights into science curriculum design. They see student scientific reasoning ability as a continuum characterized by three ways of thinking:

- **Using action knowledge.** This involves using relatively unreasoned actions, such as putting on a sweater when it is cold, derived from experience or authority.
- **Intuitive construction.** This involves ideas generated when students combine action knowledge with observation. An intuitive construction might be “Metal feels cold”. These constructions can be quite superficial, but can be improved through experience and good instruction.

- **Principle-based reasoning.** This is the goal of most science instruction, often presented in a totally inaccessible way in texts. An example might be “An object at room feels cold if it conducts heat well, as do most metals.”

Marcia Linn sees much of the failure of science education in the gap between intuitive construction and principle-based reasoning. So long as student intuition remains primitive, students see no logic in the principle-based reasoning encountered in science class, so science seems illogical. She also decries the current willingness to brand incorrect intuitive constructions students often generate as *misconceptions*, since such branding can even widen the gap between science principles and what students know. She prefers to think of these inaccurate conceptions as steps along the way of constructing more powerful conceptions.

Thus, much of Linn's work involves improving students' ability to construct knowledge based on their accurate intuitions. One important aspect of this is the “prototype” example, a common-place observation that illustrates a general concept. One prototype she uses in the heat and temperature curriculum is the observation that, when cooking marshmallows over a fire, the handle of a metal spear will get hotter than a wooden one of the same size. Key experiments can serve the same function as these prototype observations. Minstrell (1982) uses key experiments in physics as “cognitive benchmarks” that form stepping stones in each student's understanding.

Good instruction makes continual reference to a few key prototypes and experiments that help students reason. When confronted with a new heat flow problem, a student might conclude “well, it is just like the marshmallow stick, heat goes through metal better than wood.” Linn has seen the power of returning again and again to these key ideas:

Our investigations reveal that as time goes on, most students form more powerful and effective, intuitive conceptions as the result of being asked to integrate scientific events with their action knowledge. A primary role for experiments in science classes is to provide data for this constructive process. When students are encouraged through a variety of techniques to form more robust and cohesive constructions of scientific knowledge, we find that experimental results—especially those for which students have direct experience—play a strong role in their understanding. When asked to construct ideas that bridge their action knowledge and their classroom experiments, many students come up with intuitive conceptions that have predictive power. (Linn et al, p. 31)

But the gulf between intuitive conceptions and scientific principle-based reasoning is large, and some students at the middle school level simply cannot cross it. For these students having the key experiments and prototypes to fall back on is both reassuring and an important alternative to abstractions. Others are able and willing to make the jump to more abstract reasoning and prefer its power.

Over the eleven times Linn's group has studied the one-semester course, they have totally restructured its curriculum four times. As it has been changed, they have improved learning by increasing students' active involvement in thinking about their experiments. The researchers have settled on a highly experimental approach that engages students in predicting, in reconciling the results of their experiments with their predictions, and in integrating their results with abstract models.

One wonders whether Linn has discovered some sort of developmental barrier with these students: could it be that something between a quarter and a half of typical middle school American kids cannot reason from simple principles—a sobering possibility? It is probably the case that this semester course was the first good science instruction these kids ever had, that they could have done as well some years earlier in their academic career. Similarly, having had earlier exposures to good science teaching, the

heat and temperature concepts would probably have been more easily mastered. We simply do not know enough about what is possible.

Synthesis

The ideal science course involves a synthesis, on the one hand, of the experimental approach of the learning cycle models and Linn's thermodynamics course, and, on the other hand, more open-ended, collaborative projects. The former gives students the required background, experience in experimentation, and an image of scientific explanation. The latter is intensely motivating, a better representation of science, but less predictable in its outcome. Every science course should provide an opportunity for original student projects for several important reasons:

Projects introduce students to real science

Projects provide an ideal learning environment.

Projects drive the curriculum in needed directions.

The first two of these points have been made previously, but the last is a new thought. The significance of projects is that, while they are important by themselves, they also torque the system, getting schools and teachers to re-evaluate their teaching goals, and to change the rest of their teaching to prepare students for projects. One cannot prepare students for projects through drill and practice.

Unfortunately, we do not know how best to prepare students for their own original projects. There have been no long-term studies of students, no multi-year curriculum experimentation. But presumably the approach is two-fold: announce that original work is an expected part of science education at every level, and then start students making small steps in that direction. The announcement is probably important to get both students and teachers thinking about what will be required, how to select a project, and what will be learned. The small steps might be to write a biography of a scientist, spend 30 minutes analyzing a particular situation, collect environmental data, or invent a variant of a standard lab.

Courses reflecting a synthesis of the experiment-rich learning cycle models and more open-ended, collaborative projects will reflect a far better appreciation for the way kids learn. As a direct consequence, they will try to “cover” far fewer topics, but will insure students really understand those topics addressed.

Thought Experiment Set 3

- Think about the Cheche Konnen experience and what the students learned. Imagine how you would organize the first few classes that might have led to the water fountain project. What are some other directions such a discussion might lead?
- Listen to conversations in a project-organized classroom. For example, the videos “Eureka”, “Star Schools”, and “How it Ought to Be” from the Technical Education Research Center (TERC) have sections that show student conversations in a project environment. Try to analyze what the students are struggling to understand and how the educational environment supports this.
- Select a topic and outline a full-year curriculum for both of the learning cycle formats, and for a synthesis of projects and an experimental approach. Try to keep true to the idea of “less may be more”.
- Think about a multi-year curriculum plan that would prepare students to undertake successive more sophisticated original projects. How would you prepare students for the “ultimate” project in their senior year?
- An important criticism of the constructivism of the '60's, then called “discovery learning”, was that it was unrealistic to require students to recreate the discoveries of legions of brilliant scientists, that

students had to be instructed in these results to save time. Is this a fair criticism of constructivism? Are there shortcuts to recapitulating all previous science?

TECHNOLOGICAL TOOLS

Technology can help bridge the gap between the conduct of science and the teaching of science. The technologies that seem most supportive of the educational perspective presented in this essay are those that empower students and support increasingly independent student investigations. There are three that are particularly attractive from this perspective: telecommunications, microcomputer-based labs, and analytical tools.

Telecommunications and microcomputers can give students the tools they need singly and in groups to begin to experience investigations that are original and important. Telecommunications provides unique opportunities for students to collaborate and share ideas, techniques, and data. It also gives scientists a convenient means to contribute to education, and to enrich their own work through contact with young minds. Inexpensive microcomputers can be versatile instruments giving students the functionality of racks of electronics not long ago reserved for advanced research. With these microcomputer-based instruments, students become better experimenters, able to explore first-hand a broad range of phenomena on which science is based. These same microcomputers can be used for computations, allowing students to be theorists, and to move between theory-building and experimenting with ease.

You Haven't Seen Anything Yet

It is important to realize that both digital technology and the idea of applying it to education is in its infancy. Microlithography began to yield useful integrated circuits in the early 1970's and the 1,000 fold improvements we have seen in the first score of years since then will be repeated again by the 2010's and perhaps once again before further advances are capped by fundamental physical principles. This will create low cost computational and storage power unimaginable now. Similar advances in communications capacity should follow these advances in circuits. Soon all telephones will be digital with much greater capacity than needed only for voice. As the world is increasingly girdled by fiber optics and satellite communications, digital telecommunications will get far easier, cheaper, and more commonplace.

Education is hardly the economic force driving the development of digital technology, because education is poor and highly diverse. Education requires large numbers of low-cost applications, but not enough of any one to create a mass market capable of attracting investment and special development. As a consequence, educational technology is derived from the applications developed for business, science, space, and the military. Furthermore, it takes time for education to figure out what to do with technology. As a result of these factors, the technologies presented in this section are more of a promise for what will come than a prescription for the present.

Of course, technology alone will not make the difference; needed are major changes in the way science is taught as described in the earlier chapters. The technology creates new opportunities to institute these changes, but the choice to exploit these opportunities always remains.

What Technology is NOT

Before addressing the role of technology in learning science, it is important to note the role technology should **not** have.

Tutor

Far too many people think technology is a panacea, a solution for every imaginable difficulty in education. It has been popular to claim that the problem with education is poor teaching and that

technology offers a solution through “teacher-proof” software. The idea is that the computer becomes the tutor, able to present material, ask questions, and provide quick feedback. When the initial versions of tutorials did not prove their worth, self-styled “knowledge engineers” created “intelligent tutors” that supposedly have some knowledge of the student and the subject matter and are able to draw upon this knowledge to make flexible and appropriate responses (see, for example, Wenger, 1987). These approaches are technically very difficult and successful only for direct instruction in very limited, highly structured domains of knowledge. This technology offers scant help in achieving the major goals of education—fostering the growth of independent, creative, and wise individuals.

There is simply no way to shift the primary responsibility for teaching onto technology; anyone claiming otherwise understands neither teaching nor learning. Teaching is a subtle art that requires knowledge, empathy, and experience on which teachers regularly draw to improvise strategies and responses that contribute to long-range goals of individual expression and development. Educational researchers do not even understand most aspects of this process, and it is folly to think it could be cataloged and squeezed into a computer. Even if this were possible, it would be unwise to rely substantially on electronic tutors because they create the wrong learning environment. A successful tutorial teaching a student to get the right answers under the control of technology would subvert the broader educational goals of fostering autonomous, creative individuals who can work in groups and employ technological tools as appropriate. Intelligent tutors give the appearance of teaching with little of its substance.

Laboratory Substitute

Another of the false hopes for technology in science education, constantly rediscovered by budget-cutters, is the “simulated laboratory”. This oxymoron is seductive because labs are expensive and potentially dangerous, they require extra space and complicate scheduling. The idea would be to get rid of those messy labs and substitute clean, predictable simulations. The simulated frog dissection has become particularly popular because misguided animal rights groups object to student dissections. Simulations have their role for experiments that are too expensive, dangerous or difficult, but this role must always be supplementary to hands-on lab experiences. A good lab is infinitely richer in experiences than the best simulation, which is, after all, just another form of tutorial, giving some options and telling the student whether the right selection was made.

That said, there remains many roles for technology that support quality science education in the hands of imaginative and creative teachers. Technology should be viewed as providing a rich set of new options that support quality teaching and empower students. This is the information age and information technology is an integral part of the conduct of contemporary science, so it is foolish to not take advantage of its benefits in teaching science.

Microcomputer-based Labs

With a dozen sensors, a lab interface and a low-cost microcomputer, kids now have unprecedented measurement and computational power that can support student projects. The author named the educational application of lab interfaces microcomputer-based labs (MBL). Beginning in the early 1970's, my organization, the Technical Education Research Centers (TERC) began developing numerous interfaces, transducers and associated instructional units. Good MBL material is now available for Apple, Macintosh and IBM computers from numerous vendors and is increasingly common in both college and pre-college labs. The importance of MBL is that it provides an excellent, highly interactive learning experience that removes much of the drudgery often associated with labs, and allows students to focus on the underlying science. It has a proven ability to improve students' science intuition.

Two Misconceptions About MBL

It is important to dispel two misconceptions about the use of computers as laboratory instruments. A well-designed MBL laboratory is neither a simulation nor an automatization of the lab. The Bank

Street Laboratory we developed for grades four through six as part of the Voyage of the Mimi is a typical MBL application. One of the videos produced for the project shows some young scientists studying the frequency spectrum of whale sounds. In the lab, students can use the Bank Street Laboratory hardware and software with an Apple II to record their own whistles, grunts, speech and musical instruments and to create real-time audio frequency spectra. Students are encouraged to use this apparatus to undertake careful studies of musical instruments and of their own voices. The lab is not simulated, the kids are doing actual real measurements. Neither is the lab automatic; some of the dull work of graphing and calculating is, but the kids are fully in control of the science investigation.

Example: A Temperature Grapher

The best way to understand the educational importance of MBL is to experience it, to work through a well-designed experiment that uses a probe and associated software. This is better than a written description because much of the learning happens through the interactions, quickly and at a non-verbal level.

Tim Barclay and I discovered this in the first trials of MBL with fourth graders in 1974. At the time we were wonderfully naive and unburdened by the conventional wisdom of what could be expected from children of this age. Had we known that these kids could not learn about graphs and decimals, we would not have graphed the temperature and simultaneously displayed the temperature of the probe in tenths of a degree.

In an effort to be careful about recording our educational experiment, we brought along a tape recorder. But again, not being experienced in all this, and being rushed, we first set up the computers and then the audio tape. Of course, the kids were attracted to the first computer as soon as it was operating, and immediately began to ask and answer among themselves questions about how it worked, where the probe was sensitive, what the display meant, and whether 23.5 was bigger than 24. Before we were able to start the recorder, the kids had solved most of these instrumental problems, and were on to using the probes to pose and answer deeper questions like “what is it measuring when it is not touching anything?” and “what if we put it outside”, and “what if we measure all night?”.

I particularly remember a shower of enthusiastic “What if...?” questions from those first sessions. The range and intensity of those questions were significant because they indicated two important things: 1) the kids grasped the idea of a powerful tool that could be applied to many different situations—long times, short times, high and low temperatures, two different temperatures, wide and narrow swings of temperature, measuring air, water, snow or anything else, and 2) the kids were enthusiastic about this power and were full of ideas about how to utilize it.

We were interested in whether kids were able to interpret the graphs of temperature against time that the software produced, particularly when we learned that line graphs were first encountered in the sixth grade curriculum. We had the kids produce a graph and then asked what points on the graph recorded the hottest and coldest points, where the temperature was changing the fastest or slowest, how they would describe a particular graphical feature. There answers were astonishingly accurate. The only kind of problem that tripped them up were ones like “how long was it between the two hottest points?” We later learned that young kids had little concept of the magnitude of short times, but that this, too, could be quickly remedied with appropriate MBL experiences.

What Should be Taught First?

This first experience with MBL led us to realize that graph production and graph interpretation were not necessarily related. Starting at sixth grade, most students can take a list of number pairs and produce a graph, albeit painfully. Of course, our fourth graders had no clue about how to produce a graph. On the other hand, studies at the University of Massachusetts at Amherst of engineering students in physics classes, have shown that while all can produce graphs, less than half (Clement & Lochhead, 1979) can make the kinds interpretations of graphs our fourth graders were doing after a few

sessions! Clearly, both graph production and interpretation are important, but we usually teach the dull, mindless graph production first, and too often forget to even show how interesting and valuable that skill is by using it to solve problems. The reverse strategy makes more sense: introduce the meaning and interpretation of graphs first and use that to motivate the later acquisition of production skills.

This rule can be generalized. Too often in education, we assume that teaching procedures and underlying theory will lead to understanding the associated concepts in just the way teaching graph production is mistakenly thought to teach graph interpretation. Thus, we fill our curricula with mind-numbing procedural material to the exclusion of content that involves meaning and interpretation, because we see this as obvious or a waste of time. This is how it is possible for students to pass a college physics course in which they learn the procedures for solving circular motion problems while never gaining a physical intuition about circular motion. The same thing happens at all educational levels: teaching about three types of levers, how to differentiate polynomials, and arthropod identification while failing to address issues of meaning and interpretation.

The problem with applying the teach-meaning-first rule is that this is hard advice to follow. This is where MBL can sometimes be a great help. A range of sensors and powerful software vastly simplifies, and consequently makes possible, a very large number of experiments that can help give students needed observational background.

Further, the MBL display is instantaneous—a “real-time” graph—and this helps students see the relation between their experiment and its representation. Heather Brasell (1986) has shown that this quick feedback is essential to learning. Finally, the ease with which MBL experiments can be performed encourages repetitions and further learning.

Ron Thornton's Results

The value of MBL to learning has been carefully studied in respect to some important and difficult concepts in mechanics. The relation between the position of an object over time, its velocity, acceleration and the net force acting on it are central concepts in mechanics. The relations between these quantities are mathematically simple but difficult to teach because of the misconceptions based on casual experiences with which most students start. Ron Thornton has shown that neither lectures, problem sets, nor conventional labs, singly or in combination are able to convey crucial mechanics ideas the way a well-constructed MBL lab can. (Thornton, 1990).

Ron has developed a simple, qualitative matching test, much in the spirit of Halloun and Hestenes, to gauge student intuition for these concepts. Representative items from the velocity section of the test are shown in the nearby box; similar items test position, acceleration and force. Ron has used these tests on hundreds of students. He reports:

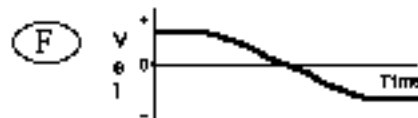
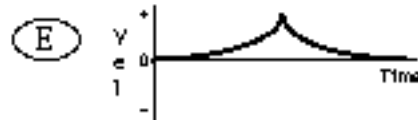
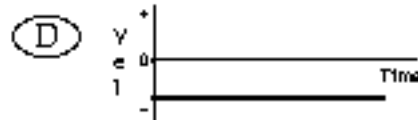
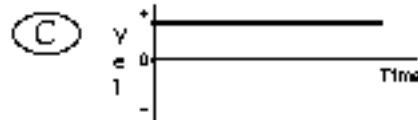
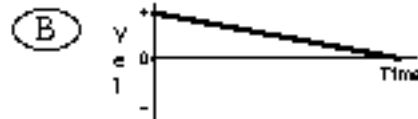
It was surprising to find error rates as high as 40%-60% on these simple velocity questions *after kinematics had been covered in lecture*. Most physics professors had predicted that fewer than 10% of their students would miss these questions and felt that students who were unable to answer such simple questions understood very little kinematics.

He found that, student error rates stayed high, even when students were exposed to lectures, traditional labs, and related homework. This was true at both the high-school and college level in physics courses for majors and non-majors using calculus and non-calculus treatments, for advanced and remedial students, before and after many combinations of lecture, lab, homework and standard tests. This simply confirms Halloun and Hestenes' results.

A breakthrough in learning came only when students had a good MBL lab, coupled with appropriate curriculum material. Then the error rates dropped to the 5%-15% range and stayed there, even after a while. There is no doubt from this research that one good MBL experience was uniquely able to convey basic intuitive ideas that seem to elude most students.

An object can move in either direction along the + distance axis. Choose the correct velocity-time graph(s) for each of the following questions. You may use a graph more than once or not at all. If you think that none is correct, answer J.

- ___1. Which velocity graph shows the object moving away from the origin at a steady (constant) velocity?
- ___2. Which velocity graph shows the object standing still?
- ___3. Which velocity graph shows the object moving toward the origin at a steady (constant) velocity?
- ___4. Which velocity graph shows the object reversing direction?
- ___5. Which velocity graph shows the object increasing its speed at a constant rate?



The velocity questions used by Ron Thornton, based on formative evaluation of TERC MBL units. The answers and the most common errors are listed at the end of this manuscript.

The key to the MBL success in mechanics is the ultrasonic motion detector first applied to education by Jim Pengra during his sabbatical from Whitman College at TERC in 1985. This detector determines the distance to the nearest object in its field of view by emitting an ultrasonic pulse and measuring the time for the first echo to return. By repeating this up to 40 times per second, the detector gives the computer instant data on the location of an object that can be displayed in real time as position, velocity, or acceleration. A good way to get acquainted with this capacity is to walk back and forth in front of the detector and try to make the resulting graph match a pre-recorded graph.

This richly kinesthetic activity helps kids at all grades connect aspects of their motion with features on the graph. While Ron Thornton's students were high-school and college physics students, Mei-Hung

Chiu (1990) has obtained remarkably similar results at the seventh grade. She used a control group and showed that the group using the motion detector and suitable curriculum material improved significantly, regardless of gender and general level of performance. Informal observation by researchers at TERC confirms this result with students at least as early as third grade.

MBL is not magic and it cannot make a good learning experience without good teaching and curricula. This has been well documented by Marcia Linn's work mentioned previously. Each time her group offered this MBL-based curriculum student gains have been greater as the curriculum and instruction has become better. One key improvement has been learning to make best use of the time and freedom from drudgery that MBL offers. Unless you focus student attention, students will ignore the apparatus while it records temperature and think about more pressing things.

A Look Into the Future

We are nearing a time when students could have a shoebox filled with a few dozen transducers that could measure a very wide range of phenomena. One or more of these could be plugged into a universal interface and be recognized by a single, powerful software package that would combine all the features of an expensive storage oscilloscope, function generator, pulse analyzer and a rack full of other electronics. This would provide the ideal environment for student-initiated projects. The interface will function independently of the computer so it could function as a field measurement device, measuring environmental data day in and out.

Computer interface probes to measure light, sound and temperature are now commonplace. Packages that involve measurement of pH, voltage, heart rate, skin resistance, ECG, EMG, optical absorption, earthquakes, visual illusions and response time are commercially available. TERC staff and collaborators are currently designing inexpensive interfaces for measuring dissolved oxygen, force, magnetic field, pressure, turbidity, wind speed, insolation, heat flow, humidity and much more. Initial battery-operated interfaces for field measurements are available. Because Apple II's dominate the pre-college market, the bulk of curriculum-oriented MBL packages have been developed specifically for this computer. However, several IBM- and Macintosh-compatible products are currently beginning to make their appearance.

Telecomputing

Telecomputing, the use of a communications channel to inexpensively link computers all over the world, offers another technology that can support student project-based learning. Low cost communications can be used by teachers and students in many ways. Perhaps the most dramatic example of its support of project activities is the Kids Network.

The NGS Kids Network™

April 20, 1988 was a historic moment for science education. On that date more than 4,000 kids world-wide first began one of the largest collaborative endeavors in science. After an introductory set of experiments in February and March, kids in grades 4-6 throughout the world began a study of acid rain. At 200 schools, these young scientists took measurements and shared their results over a telecommunications network with each other and a participating scientist. They collected rain samples in 50 states, Puerto Rico, two Canadian provinces, Mexico, Hong Kong, Argentina, and Israel and used telecommunications to share pH measurements of these samples among themselves and with John Miller, a NOAA scientist professionally involved in acid rain measurement. Along the way, participating kids learned about measuring pH, the effects of acids on plants and metal, the sources and distribution of acid rain, determinants of the pH of runoff and tap water, and much more.

This set of experiments was part of a classroom test by TERC of the Kids Network funded by the NSF and the National Geographic Society (NGS) in association with Apple Computers, Inc. who provided most of the computers. Now published by NGS, the Kids Network can accommodate thousands of

classrooms in each experiment and will eventually consist of more than twelve instructional units for grades 4-9 each requiring 6-8 weeks of class time and focusing on one topic such as acid rain. Each unit involves making measurements and sharing those measurements through the Kids Network. For each unit there is a participating scientist who is professionally involved in the topic and cares about the kids' results. Other units involve experiments from air and water pollution, weather, land use, epidemiology and fitness.

The Promise of Telecomputing

The Kids Network is an example of what can be expected from the application of telecomputing to education. Telecommunications is a very general term that properly applies to any form of communication over distance, including, presumably, shouting, smoke signals, semaphores, whale songs, and television. Recently, telecommunications has come to have two very different meanings in education: interactive TV and digital communication between computers. Interactive TV, or distance education, is not a technology that will solve many of the pressing problems of education since it is expensive, only slightly interactive and, at best, basically a lecture format. To distinguish from that technology, we have started using the term "telecomputing", that means "distant computing", for computer-based communication, a technology that holds real promise for education, as we will see in this section.

The idea of educational telecomputing is quite compelling and has many applications in science education that support teachers and students in the kind of student-centered, collaborative, project-oriented activities that are so greatly needed. It can provide:

- **Communications that supports teachers.** Teachers can find others who share interests and concerns. This has proven to be particularly valuable for teachers with interests not shared by local colleagues, such as the one chemistry teacher at a small school. Teacher workshops can be extended with post-workshop contact with colleagues and presenters. Teaching interns and new teachers can share their experiences with former students and faculty.
- **Access to data, images, and reference material.** Huge libraries are available on-line giving students and teachers access to a richness of research, data and current events unavailable in all but the largest libraries.
- **Support for collaborative student research projects.** Bulletin boards and conferences can create a community for students and teachers involved in project activities. Participants can share ideas, observations and data. Global-scale environmental measurements can be planned and coordinated through a network and the results shared and analyzed.
- **A convenient way for scientists and businesses to help educators.** Practicing scientists and engineers represent a potential resource for science education that might be tapped through telecommunications, because these busy professionals could communicate primarily through telecomputing at times and places at their convenience.

Given these potential advantages to education, it might seem surprising that telecomputing is not more widely used and that so many projects that have adopted telecomputing with great enthusiasm have not flourished. Why is telecomputing not an integral part of teacher support networks? Why is it not widely used in student projects and research?

The fundamental problem is the poor quality of the present technology. Most telecomputing technology available to educators is anachronistic, unfriendly, too expensive, and insufficiently powerful, making the act of telecomputing unpleasant and unnecessarily restrictive. When telecomputing is difficult, limited and frustrating, busy educators and students will tend to delay using it, get behind in answering mail, and withdraw from any on-going activities. Most available technology has not reached the point at which the benefits networking offers are outweighed by the petty difficulties of using the technology. We hope to change this situation in the near future.

Network Science

The Kids Network approach can easily be generalized to any level of education by changing the topics and their level of treatment. The idea of involving students in collaborative research was first applied at the elementary level because elementary science is in such bad shape, and because collaborators and funding were available. But now, the idea, that has become known as “network science”, has been broadened to encompass middle, high school and college students in all the sciences and mathematics. For example, the Global Laboratory project is building an international network of students working on global climate change research, involving students in a wide range of measurements and projects such as establishing monitoring programs observing temperature, trace gasses, and biological indicators. In another network science project, The Global Rivers Environmental Education Network (GREEN) has students throughout a watershed make simultaneous water quality measurements that are shared and analyzed over a network. This has proven to be motivating and a good way to spot polluters.

At TERC, we experimented with various implementations of the network science idea in our Star Schools project during the 1989-90 academic year. It combined project activities, cooperative learning, and network science into a powerful experience that seemed to work well with all students (in over half the classrooms a majority of the students were from families below the poverty line). Some of the student comments follow:

What captured my interest most was working with the computer, sending out messages. ...We usually don't have any communication with other schools, especially in other states, that's like way out in left field, that never happens. We did a lot more outside work, just outside the school in the community.

Overall I think this [project] was something I would never forget. It was a great experience. I learned about other schools and what questions they have been wanting to ask us. This gave us a chance to learn about other schools all around us. This also gave us a chance to get to know people in our class better. We got better acquainted with other people.

I think communicating with other kids, you know, like other states. They would tell us how they did them, their projects, and we'd tell them how we did...Well it was helpful cause we were able to work on our project. They told us what they did and it was able to help us.....they would tell, cause we had our own ideas and they gave us some helpful cues so [we] were able to learn even more, cause sometimes like we had a teacher who would forget about things and they would send them and she would be able to teach us about that. (Wier, et. al., 1990)

The network science idea makes it easier to offer collaborative student projects by providing some of the expertise, organization, and collaborators over the network. As telecomputing gets easier and less expensive, this approach will offer a very attractive stimulus for collaborative student projects.

Thought Experiment Set 4

- If possible, experiment with one of the MBL setups that measure distance with an ultrasonic motion detector, such as the IBM Personal Science Laboratory interface and its associated Explorer software. By walking toward and away from the detector, try to create velocity-time graphs like those in Ron Thornton's test. Discuss in a group why activities of this sort are such powerful stimuli for learning.
- Imagine you could have free communications with any school or set of schools in the world. What kinds of collaborative work would you like to undertake? Think about the intercultural issues to which you and your students would have to be sensitive.

•Suppose a scientist volunteered to help you offer project activities. How, exactly, would you use the scientist? How would you break him or her in on the realities of the classroom? Would telecommunications be helpful in your communications?

CONCLUSION

I dream of making science exciting for all students. In a typical school students will be alternating between meaningful projects and eager assimilation of new material that will qualify them to take on more projects. Computers will be ubiquitous and general-purpose MBL devices widely used for sensing and controlling. Students will be networked to others with similar interests worldwide, and scientists will come to the better-qualified students for help in making global environmental measurements.

There is no reason this could not happen. It will, when more educators stand firm against the pressures to cover more topics superficially, when more teachers teach deeply using constructivist principles and turn to science for their inspiration, thinking of themselves and their students as amateur scientists.

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Answers to the Halloun and Hestenes problems:

(8) (a) The ball would describe a parabolic path influenced only by gravity.

(9) (b) The ball will slow down as it rises, but it will continue to travel to the right, so its speed will never reach zero. Once past the top, the speed increases as the ball falls.

Answers to Painting-the-House Problems:

1) 3.75 hours 2) 15 minutes

Answers to Thornton's velocity questions (the most common wrong answer is shown in parenthesis).

1. C (A) 2. G (C) 3. D (B) 4. F (E) 5. A (D)