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SCIENCE FOR KIDS:

THE PROMISE OF TECHNOLOGY[1]

Robert F. Tinker

INTRODUCTION

> *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, p. 131)*

Technology offers new options for participatory education. Some of these options can improve the learning environment, many others can harm it. To select among technologies and apply them intelligently to science education, one must have an accurate fix on why science education is in trouble and what strategies are needed to improve it. Because many of the problems of science education can be traced to inappropriate educational goals and learning models, more appropriate goals based on a better understanding of how students learn are needed. The better approaches are significantly aided by technologies that offer flexible, economical tools and communications.

The unspoken goal of most science education is to stock students' intellectual storehouse with miscellaneous fragments of knowledge stored away for future contingencies. The unspoken model of learning used when filling this storehouse is to train students in facts and operations hoping this will lead to an understand the underlying science. Both this goal and method of achieving it are ineffective and

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need to be replaced by approaches that are of more immediate concern to students and closer to real science.

Using technology to simply increase the stock of intellectual fragments or to train students in more facts and operations is counter-productive. But microcomputers and computer-based telecommunications offer flexible tools for communication, data acquisition, instrumentation, computation, analysis, and visualization. These tools empower students to do science, to undertake investigations of immediate interest and to build a durable understanding of the underlying science. This argues for a project-based approach to science and for the development of technological tools to support student project work.

Storehouse Education

> *I believe that education, therefore, is a process of living and not a preparation for future living. (Dewey, 1897)*

Science education is usually based on a storehouse model: we ask kids to store away facts, formulas, and definitions against some day in the future when they will need to draw from their hoard. The act of filling this storehouse has become a goal in itself, and the role of science education has become to cram as much as possible of just the right stuff into this storehouse. The first phase of Project 2061 can be seen as a major effort to ensure that when Haley’s comet returns in the year 2061, just the right selection of condiments will be found when that storehouse is finally opened.

It is this storehouse model for science education that has led us to a dead end that finds students turned off, poorly prepared, and dropping out. It may have worked for some kids when education was clearly the only way to escape poverty or boredom, and it still does for the few students who are sufficiently motivated and imaginative to draw occasionally from the storehouse to make the jars found there “a process of living” for themselves.

Perhaps the most devastating description of storehouse educational philosophy is Dewey’s sarcastic definition:

> *Subdivide each topic into studies; each study into lessons; each lesson into specific facts and formulae. Let the child proceed step by step to master each one of these separate parts, and at last he will have covered the entire ground. The road which looks so long when viewed in its entirety, is easily traveled, considered as a series of particular steps. Thus emphasis is put upon the logical subdivisions and consecutions of the subject-matter. Problems of instruction are problems of procuring texts giving logical parts and sequences, and of presenting these portions in a similar definite and graded way. Subject-matter furnishes the end, and it determines method. The child is simply the immature being who is to be matured; he is the superficial being who is to be deepened; his is narrow experience which is to be widened. It is his to receive, to accept. His part is fulfilled when he is ductile and docile. (Dewey, 1902)*

Horrible as that atomistic description is, almost a century later, it remains the dominant model for teaching and curriculum design. Much educational "research" and curriculum development is devoted to subdividing the world into manageable chunks which will then be poured into passive students. When this fails to make an improvement, some other subdivision scheme is tried, perhaps dressed up with some currently-popular slogan like "discovery learning", "school reform" or "layer cake".

Of course, few science educators want to think of themselves as storehouse teachers. They have learned to identify with better-sounding ideas like "higher-order thinking skills", or "problem solving", or even "hands on". But it matters how the implied valuable but illusive goals are achieved; too often these good phrases are undermined with regressive deeds still based on the storehouse model. If, for instance, "problem solving" represents just another shelf in the storehouse which needs to be filled with a certain number of problem types, kids will not really learn, and the problems of science education are perpetuated under the guise these respectable concepts.

Performance Is Not Understanding

It has been seriously proposed that an undergraduate education at MIT consists of learning 400 problem types; a high school physics teacher insists that his students be able to perform 35 problem types in his course. I am sure that the theory of education on which these appalling ideas are based would feature problem-solving and higher-order thinking skills, but this approach really rests on the mistaken assumption that there is a necessary relation between performance and understanding.

Richard Feynman (1985, p 212-3) recounts an experience in Brazil that illustrates the futility of teaching problem types. He was amazed that college students appeared to have mastered advanced physics while failing to have any understanding of even its simplest applications. For example, one group of students was studying electromagnetic waves and the mathematics of what happens when such a wave encounters a medium with a different index of refraction. The students could perform complex derivations and calculations, but when Feynman asked his students to look at light reflected from water in a bay through a Polaroid filter, the students could give no explanation of what they saw. They were entranced to find the light to be polarized, but were completely unable to relate that observation to their calculations or to the derivation of Brewster's angle they had just performed. The students did not recognize light as an electromagnetic wave or the bay as a medium with a different index of refraction. Feynman reports that "After a lot of investigation, I finally figured out that the students had memorized everything, but that they didn't know what anything meant."; they were able to perform solutions without understanding the basic physical ideas on which these solutions are based.

What Feynman did not realize is that this problems is not confined to Brazil, it is endemic now having been observed at all grades throughout U. S. education.

A few years after the Brazil incident, Halloun & Hestenes (1983) thoroughly demonstrated the same problem in college physics. They gave students simple problems that required no calculations, just an understanding of basic physics concepts–the ideas behind the equations. Then, after a full year of introductory physics, the students were again given the same problems. In the intervening time, the students had solved far tougher problems based on the same concepts; problems involving extensive calculations and complex situations. The amazing thing is that students achieved no significant improvement on the simple problems, the problems that require basic understanding unencumbered with calculation! The students had learned to perform problem types, but did not understand the physics; "..they didn't know what anything meant."

This is not an isolated observation. Halloun & Hestenes obtained the same conclusions for good lecturers and bad, advanced and normal classes, courses where labs were emphasized and others where it was not. Most physics teachers are sufficiently confident of their own teaching that they dismiss these results as applying to only poor teachers at second-rate institutions. But the brave few who have offered Hestenes' tests (to be published in the March, 1992 Physics Teacher) have invariably found the same depressing results, even a well-known Harvard physicist who shall remain nameless (Thornton, 1992). Others have made similar findings in elementary grades, in other sciences, and in mathematics. It seems we have been fooling ourselves into thinking that teaching students to perform resulted in learning. (Clement & Lochhead, 1979; McCloskey, Caramazza, & Green, 1980; Minstrell, 1982; Trowbridge & McDermott, 1979).

The same comments go for most laboratory experiences. Labs should be important because they offer students the chance for 'hands-on' learning that can put them in touch with the experimental roots of science. But these lofty goals are usually undermined by a set of detailed instructions, special apparatus that can only be used in one way, and time constraints that require the lab to be finished quickly. The usual lab is really another problem type, with some numbers obtained from the experiment that are plugged into a formula or process to get an answer. What is the result, what have students learned? The students may have literally had their hands on some equipment, but their minds could well have been off. They did not have to think up the problem, come up with a hunch about how to attack it, invent a way to use some equipment to make the required measurements, think up the best way to analyze the data, or wonder whether their hunch contained some truth. Unless some of this mental work has happened, 'hands on' is just busy work and the result is, at best, another jar in the storehouse.

Storehouse teaching is a very easy trap for a teacher to fall into; it is easy (you stand up and deliver), glorifying (the lecturer is the center of attention and the font of wisdom), and in control. One can feel righteous about students' failure to learn

("How could they miss that problem, I told them how to do it?"), and it satisfies the demands for breadth ("I covered all the topics on the exam"). All the pressures for coverage, economizing, safety, control, and higher SAT scores conspire to favor storehouse teaching. Even increased emphasis on teacher evaluation can favor the storehouse model by focussing on charisma and favoring easy grading.

Many educators regret the failure of the storehouse model and cannot accept that it does not work. They pine: "If only kids were more disciplined..." "They have to work (suffer?) to learn science..." Others acknowledge that there is something fundamentally wrong with the current model of education but then propose alternative approaches which only fill the storehouse some other way: through additional dreary labs, reorganized curricula, or cooperative learning. For others, technology–using flashy videodiscs, computer tutors, or TV-mediated distance learning–offers the solution, but too often the result is storehouse education in another medium. While each of these approaches could help improve learning, to the extent that they are based on a storehouse model of teaching, they fail to get to the root of the problem and are doomed to make little measurable effect improving science education.

The Alternative: High Adventure

> *Better learning will not come from finding better ways for the teacher to instruct but from giving the learner better opportunities to construct. (Papert, 1991)*

The storehouse model must be rejected. Many thoughtful commentators have, at least for the last century, seen the need for something else. The popular alternative these days is "constructivism", learning based on the idea that each student must actively construct a personal mental framework. Papert prefers the term "constructionism" to emphasize the need for physical construction to parallel the mental.

Whatever the term, it is usually defined in opposition to the storehouse model: it is student-centered rather than teacher-centered; it requires active student thought rather than passive memorization; it focuses on activities rather than on texts; its motto is "less is more". This is clearly the right direction to explore, it feels right and there are indications from cognitive research that this is a sound way to learn. But there is a danger in this negative definition, it fails to give a positive direction, a positive vision to replace the strong attraction of the storehouse.

The needed vision for science education can be found in the original inspiration for teaching science, science **itself**. Science provides the ingredients missing in science education: the joy of discovery, the excitement that comes from deeper understanding, and the satisfaction of solving an important problem. It can also provide an organizing principle for student learning, the goal of which should be not to fill a storehouse for the future, but to do science today.

It is the very strangeness of nature that makes science engrossing, that keeps bright people at it, and that ought to be at the center of science teaching. There are more than seven times seven types of ambiguity in science, awaiting analysis. The poetry of Wallace Stevens is crystal-clear alongside the genetic code...

I believe that the worst thing that has happened to science education is that the great fun has gone out of it... Very few see science as the high adventure it really is, the wildest of all explorations ever taken by human beings, the chance to catch close views of things never seen before, the shrewdest maneuver for discovering how the world works. Instead, they become baffled early on, and they are misled into thinking that bafflement is simply the result of not having learned all the facts. They are not told, as they should be told, that everyone else–from the professor in his endowed chair down to the platoons of post-doctoral students in the laboratory all night–is baffled as well. (Thomas, 1981)

The practical way to introduce the bafflement of science into science education is through the the extensive use of student-based, collaborative projects in which students try to understand something they care about. There are many practical advantages of a project-oriented, constructionist educational strategy:

- **Adaptable.** Learners with different styles and abilities work comfortably together on projects and long-term activities.
- **Interdisciplinary.** Projects often require input from a variety of technical fields, use many forms of communication, and profit from the creative arts.
- **Integrative.** Students see how disciplinary studies fit together to solve problems and address issues.
- **Pre-professional.** The activities envisioned and their use of technology tend to mirror those of the adult world and thus give students an unusually accurate view of the professions.
- **Motivational.** Activities selected by students and pursued in depth can be extremely interesting for students and can call on skills and motivation that standard classroom instruction leaves untapped.
- **Effective.** Constructed knowledge that comes from self-selected topics and self-directed inquiry has unusual staying power.
- **Efficient.** The use of technology offers the many chances for major improvements in learning "efficiency" using a definition that honors the amount of deep learning and problem solving skills students acquire.

In the following, three examples of learning that are fun and baffling are illustrated from the work at TERC. Each shows students learning science while undertaking different kinds of projects.

Project-Oriented Instruction

> *...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)*

Student projects are most widely used in the very best schools and perhaps this is why project-oriented instruction has gained an unjustified reputation as being only for elite and academically advanced students. A study by Warren, Rosebery, and Conant (1989) of a seventh grade bilingual Haitian Creole class belies this view and clearly shows that a broad range of students can learn in through participation in projects. 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.

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 felt was the wrong result–the first floor water tasted better! Convinced that this was wrong, the students then decided to do what any reasonable researcher would, they repeated the experiment more carefully with a larger sample. This time, they decided to use other students’ opinions, so they picked a day to test water at lunch time in the cafeteria using an improved 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 interesting science lurks behind almost anything. Even with faith that the science could be found, no publisher would make a drinking fountain project 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. It is the project orientation that leads to the observed learning, because the project grows out of student interests and involves real-life, complex situations.

This kind of excitement and learning stimulated through student projects is not an isolated phenomenon. Warren and Rosebery have worked extensively with Hatian Creole students at all grade levels and have seen project oriented science reliably excite and motivate these students. One of the most significant aspects of this work is that after reviewing their success, no one could possibly maintain that students who are performing poorly and who are at risk would fail to respond to a project orientation.

But, of course, the project approach has applications far more broadly than simply in the language minority population studied by Warren and Rosebery. For contrast, take another example of project-based learning at the other end of the educational spectrum: in the physics courses at MIT.

At MIT twenty-five years ago the faculty realized the standard mass-production 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 MIT students without a laboratory, but any serious science major is urged to take one of the alternative laboratory courses which are offered. One is Professor 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, 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.

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.

Telecomputing[2]

> *Normally we're given...how passive solar heating works and stuff, but [in this project] 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 [using a project approach] you understood in your own way. It wasn't like somebody trying something and you just memorizing it. (TERC Star School participating student quote in Weir, et. al., 1990)*

The NGS Kids Network[3] is a revolutionary series of seven units designed for students in grades four through six. Each unit features student participation in science through some measurement they make and share over a digital telecommunications network with other students and scientists. The units cover

[2] I am advocating the use of the term "telecomputing" to refer to computer-based telecommunications. This more precise term distinguishes this form of telecommunications from TV, voice telephone, and radio.

[3] The NGS Kids Network was conceived and developed at TERC and is published and supported by the National Geographic Society (NGS). The project was funded by the NSF with matching funding and in-kind contributions from NGS. The NGS Kids Network and the National Geographic Kids Network are registered trademarks of the National Geographic Society.

background information necessary to set the measurement in a context and make it meaningful. They also cover the interpretation of the amassed data and address the social implications of what the students discover.

The Acid Rain unit was the first we developed and has been the most studied. In a typical year the unit might be offered once in the fall and again in the spring, each time involving thousands of classrooms and tens of thousands of student scientists. After a standard introduction to acid-base chemistry, and some practice at determining pH, students look at the effects of solutions of different pH values. Students design their own rain collectors and evaluate their designs against some important criteria: they better not blow over and they should not collect water dripping off something else.

At the same time, they have been using the telecomputing network, discovering that they are part of an international working group, and getting to know their colleagues in the group. Just to get a feel for the system, they exchange some exploratory data within their group. Then, at a pre-set time, the tens of thousands of participating students begin collecting rain and measuring its pH. At the end of the week values are sent to a central computer where they are collected, analyzed by an expert scientist, and returned to the students. This process is repeated over three weeks, in part to give every class a high probability of contributing some data.

The unit regularly generates excitement and serious participation among its student-scientists. The kids sense that what they do matters; that this is not just another silly exercise or cookbook lab. The act of sending off the data is taken seriously because they understand that someone–other classes and the participating scientist–will look at their work and that this work will contribute to a pattern that they will all have a chance analyze. The effect on the class is palpable: kids come in on weekends if there was rain because it is important to measure the pH soon after the storm; sometimes learning disabled kids shine; teachers report students exhibit talents they never knew lay dormant; other teachers revise their whole instructional strategy as a result of what they learn about student learning in this unit..

The latest analysis of the Kids Network comes from an independent evaluation by the North Central Regional Educational Laboratory. The following summarizes a detailed study of 49 teachers in 26 Iowa schools funded by the Roy J. Carver Charitable Trust:

> *The National Geographic Society states that seven elements of Kids Network make the network "special" (Teacher's Guide). They are investigation, collaboration, geography, computer skills, interdisciplinary approach, cooperative learning, and critical thinking. The findings of this evaluation confirm this assertion and the overall success of the program. (Fein, et al, 1991, pp 4-5)*

While a project-oriented instructional strategy does not require telecomputing, the technology can support it in many ways, making interesting projects easily implemented and feasible in a broad range of classrooms, as demonstrated in the Kids Network. In support of student projects, telecomputing can:

- Provide student collaborators worldwide.
- Enable gathering and distributing data in a timely manner between many sites.
- Give assess to databases of data and research in support of projects
- Be the medium for student discussion and publication of project results.
- Be a medium for the development and publication of project-based curriculum materials.
- Provide easy access to scientists and others to assist student projects.
- Support teacher enhancement activities.

At TERC we have been exploring various ways of supporting student projects with the use of telecomputing. The Kids Network is the most mature of these projects and has generated considerable interest. However, it lacks one critical feature of scientific research, having students determine what research they will undertake. With later TERC projects oriented toward older students we have experimented with relaxing that constraint. The problem one immediately encounters is that by encouraging students to do their own thing, communication on a common topic becomes much more difficult. Instead of having a fixed and known subject to share with other users as we do in the Kids Network, telecommunications are needed to help forge group discussions about what to study and how to do it. Since this is difficult and potentially embarrassing material for students, this kind of discussion is difficult to have, especially using a technology which is not as friendly as it could be.

As a result of several projects, we have found students are more comfortable collaborating much the way most scientists do–not by all doing experiments together, but by building on results from other groups. For instance, in the fall of 1991, out of a concern of reports of over-fertilization, Russian students in the Global Laboratory network became interested in measuring nitrate ion concentrations in fruit and vegetables. Their subsequent impressive electronic report was picked up in Wellesley high school where students, in the course of extending the Russian work, discovered alarming nitrate levels in hydoponically-grown lettuce. The final report of this potentially important discovery has now inspired new Russian student research which is underway at this writing.

While much remains to be discovered about educational applications of telecomputing, it seems that it can support impressive student research and should be considered an essential tool for the near future. As a recent TERC conference concluded:

- ***Educational telecomputing can make an important contribution to improving education.*** *It provides low-cost access to communities of teachers and students, to data, and to other resources, all of which could help make important improvements in education.*

- ***ALL teachers and students should have ready access to inexpensive and easy-to-use telecomputing resources as soon as possible.*** *Universal access is an achievable goal over the next five years and a necessary prerequisite for unlocking the potential of educational telecomputing.*

- ***A substantial body of information and experience on educational telecomputing is available now.*** *The educators represented at the Conference have the experience needed to implement large-scale, effective educational telecomputing programs. However, this knowledge needs to be made more widely available through compiling information and undertaking and publishing additional research.. (Tinker, 1992)*

Microcomputer Based Labs

> *...I am speaking for ... a laboratory involvement which may be painfully slow, which "doesn't get anywhere." You don't "cover the material," but you spend a good many hours of the week doing something [projects]... It is not impossible that they [the students] could find something that nobody else knows (Morrison, 1963).*

For some time the staff at TERC has been exploring educational applications of computer-based, real-time data acquisition, an application TERC named microcomputer-based labs (MBL). This work was motivated by the dream of developing a series of low-cost probes that could be used by students to measure the widest possible range of variables: temperature, humidity, distance, velocity, acceleration, force, pressure, pH, light, air flow, rotation, radiation, etc. These should be able to be measured in time scales ranging from microseconds to years, singly and in arbitrary groupings. In the same ways that this instrumentation has increased the efficiency and scope of practicing scientists and engineers, it should also improve student learning in experimental settings, making learning more effective and providing a more accurate view of the conduct of science.

Perhaps an example can help illustrate the power of this approach. One of the sensors we developed is an ultrasonic motion detector using the electronics developed by Polaroid for their autofocus cameras. Jim Pengra, a physicist on leave at TERC from Whitman College, first connected the Polaroid sensor to a computer. He programmed the computer to tell the sensor to emit a "chirp" consisting of a few cycles of ultrasonic sound. This sound can reflect back to the sensor which detects the returning signal. Jim programmed the computer to measure the time between emitting and detecting the signal and, using the known speed of sound, to convert it to the distance between the two. By repeating this process up to 40 times per second, the computer can have detailed, accurate, and instantaneous data about the location of whatever is closest to the sensor. Jim programmed the computer to graph this distance as people, pendula, and carts moved around in front of the sensor. We quickly realized that we could compute and graph in real time velocity and acceleration from these data.

The resulting system is dramatic: you can walk up to the sensor and see a graph of your motion as you are moving. Misconceptions about the graphs melt away. For instance, one of the negative velocity is a tough problem for most anyone. But if you are watching the velocity-time graph as you walk, you see very quickly that movement away from the sensor generates a positive velocity and movement towards it generates a similar negative one. While initially confusing, most users are quickly convinced of the logic of this, since the distance is getting smaller as you walk toward the sensor. In a few minutes, users at all grade levels quickly learn to interpret the graphs and relate them to their motion.

Thornton and Sokoloff (1990) have shown that the motion probe, used appropriately, can produce large gains in students' intuition of just the sort tested by Halloun and Hestenes. These gains are impressive and cannot be achieved by any combination of lecture, traditional labs, and homework alone, but are only observed when MBL is used. Similar differential gains are observed with high school and college students in advanced, average, and below-average classes.

One remarkable result of the motion probe system is how well it works at all grade levels. The motion detector has been used with students from grades one through college. All can quickly grasp the graphical representation of their motion and interpret the graphs. Most can experiment with the system and learn something from it. For instance, if you try to walk at a constant speed, you will see a slight variation in the resulting velocity graph which reflects the way we walk–a series of arrested forward falls. Many students observe this and learn something about how we walk as a result. With some guidance, students quickly learn the relation between position and velocity graphs and learn to estimate one given the other.

This is all the more surprising because most people have great difficulty interpreting line graphs. Graphs are not usually introduced until grades 4-6 and even college students in pre-engineering physics courses stumble on simple graph interpretation tasks (Clement and Lochhead, 1979). Furthermore, most college professors will tell you understanding the relation between position and velocity graphs requires a good grasp of calculus concepts and is difficult for most of their students in introductory calculus courses. How is it possible that elementary grade students using the motion detector can construct an understanding of the essentials of graphing and calculus without instruction in graphing and calculus? The answer demonstrates the comparative power of constructivist educational strategies.

There is a tremendous difference between the ability to *perform* the production of graphs and the derivation of calculus results and to *understand* graphs and calculus relationships. The hidden assumption in most instructional strategies is that by teaching students to perform, their understanding of the material will follow automatically. The result of extensive research in MBL environments is that performance and understanding are quite independent; most students can learn to perform without understanding but in an MBL situation it is possible to gain an understanding without even knowing the rules for producing results. This is important because we can teach for understanding long before students have amassed the skills required for performances; in fact, a good understanding greatly helps students later master the formalism.

It is important to note that use of MBL does not automatically result in increased learning. The greatest gains occur in an environment where students are using the technology to solve problems of interest; in other words, they are doing science. We once studied a classroom that shall remain nameless, where the teacher introduced an MBL lab through a careful, detailed lecture, showing in an overhead screen every step of the experiment, every detail of computer software, and every keystroke expected of the students. In other words, the teacher had grafted a traditional instructional education strategy onto this new technology. The message was clear–to get a good result, do not mess around, just follow these instructions. The result was predictable–there were no measurable learning gains. In similar situations where teachers use a project-oriented instructional strategy with good MBL tools at students' disposal, substantial gains are registered (Linn and Songer, 1991).

Lessons From the Examples

These are but three of many examples that illustrate the power of organizing science education around science. The hallmark of this approach is student research. That sounds too formal and out of reach--in most people's mind, research is what you are certified to do after a PhD. Research should not be such an intimidating term; after all, research is what anyone does when searching for the answer to a problem. A first grader who plants a seed to see what will happen is performing science research. But, to soften the image, I propose the term "science project" should be substituted, with the caveat that I am not talking about simply be any project—like decorating the gym for a party–but really science research.

Student projects should be designed to engage students in active, collaborative real science project activities, increasingly having students undertake all aspects of scientific problem solving: defining the problem, developing a solution strategy, making predictions, defining procedures, collecting data, analyzing results, and acting on their conclusions. Students who have never experienced project-oriented science cannot be expected to do all these activities at once, so a good strategy is to introduce different aspects of the scientific process gradually. For instance, in the Cheche Konnen project, students undertake whole-class projects with a great deal of guidance from the teacher. In the Kids Network, collection and analysis of data of potential scientific interest is featured. In the MBL activities, instrumentation, measurement, prediction, and problem-solving are emphasized.

Science education should be structured around increasing students' ability to undertake increasingly larger and more significant projects. Our goal in science education research should be to determine what kinds of projects are appropriate at different educational levels and what kind of experiences, skills, and understandings are necessary for students to undertake research at these levels. Our goal in curriculum development should be to design feasible, interesting student projects at various levels and to create lessons and fashion experiences which prepare students for these projects.

Each school and each teacher must work out how to make a transition from more to less structure, from less to greater student involvement and responsibility. In this light, the Kids Network and MBL described above should be seen as first steps teachers can take toward a student-centered project orientation. They provide some structure, they introduce essential elements of student project work, and illustrate powerful technologies which support student projects. The next step needs to be less structured and depends more on teacher initiative. Projects like the Cheche Konnen experience described above require teachers to draw from students ideas, interests, and concerns which can be converted into full-scale investigations. No two student groups will have the same set of interests, the same background, and the same resources. Hence, the best projects will have to be fashioned anew for each class and will not be found in textbooks.

THE ROLE OF TECHNOLOGY

The most important product of the past two decades of work on educational technology has been the emergence of a vision of what information technology has to offer science education. Earlier thinking focused on technology as supporting the more rote and mechanical aspects of learning. The new vision focuses on using technology to support excellence in learning. In this vision, students tackle much harder problems, they work on larger-scale, more meaningful projects, they have a greater and more reflective responsibility for their own learning and they are able to work in a variety of styles whose differences reflect gender, ethnicity or simply individual personality. Much of the earlier thinking saw the computer as replacing at least some of the functions of the teacher. The new vision sees the technology as supporting excellence in science teaching; it enhances, rather than replacing, the teacher.

The project-oriented approach to education is not new, but the advent of inexpensive microcomputers and telecommunications adds new dimensions to the concept, allowing it to be a more powerful learning strategy while simplifying its implementation. Technology has something to offer for every aspect of student projects; it can expand the range of possible projects, offer new opportunities for collaboration and communication, simplify acquiring and displaying data, provide mechanisms to control experiments, increase the sophistication of the theory-building, modeling and data analysis students perform, provide new outlets for creative expression, and grant access to vast databases of information. Furthermore, the limitations imposed by one teacher's imagination and background can be removed through mentors and collaborators on networks.

While technological tools are available on the microcomputers found in schools, their systematic use to empower students has not been widely explored nor followed to the conclusions that will inevitably alter and expand the definition of science education. Technology can play an critical role in enabling, simplifying, or amplifying all aspects of student projects in science–engaging, collaborating, measuring, analyzing, revising and communicating. Without the technology, practical issues of classroom management, limitations in the scope of potential projects, and teacher style and background all make student-centered activities difficult to offer and sustain. Technological tools give students a capacity they can apply to their investigations and new collaborators with whom to communicate and learn.

The history of technology adoption in all areas is the same: innovative technology is first used to support the current way things are done, and only later is the way things are done modified to really take advantage of the technology. The first use of steam in boats was to power a sailboat only when it was becalmed; only later was sailing abandoned and the desirability of metal-hulled steamboats recognized. Similarly, the first use of microcomputers and telecommunications in education has been to do the old style of education slightly better.

But someday these technological tools will be used not to reinforce current educational modalities but to support better ways of learning. The most significant change this could induce in science education at all levels will be to enable collaborative student projects. Perhaps we can look forward to the day when students will have the technological tools to undertake serious science research as part of an international community of student researchers.

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