Using new technologies to increase learning in mathematics and science

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ABSTRACT

To a surprising extent, what we teach is dictated by what we have been teaching, even when far better strategies and resources are available than are currently used. There are many reasons for this innate conservatism. Texts, tests, standards, unions, and poor teacher preparation all resist change while there are few incentives for change. In math and science, there is another factor that is seldom mentioned, an over-reliance on formalism. There is an incorrect assumption underlying much of what is taught that understanding can only be based on formal knowledge.

Information technologies challenge us to re-examine what is possible to teach, because they can bring new resources and approaches into teaching that are not conceivable without technology. For instance, it is possible for nine-year olds to interpret graphs they generate through interactions with sensors. Eleven-year old learners can gain an intuitive understanding of basic calculus concepts by using a position sensor with a computer that generates a real-time graph of the learner's motion and velocity. Genetics can be learned through interactive simulations. The nature of chemical bonds can be understood through real-time orbitals visualized in 3D. Middle school learners can make quantitative projections of the world population under various assumptions.

This paper defines a series of technology-enhanced curriculum strands that would begin to realize the potential of technology. These strands could be easily integrated into schools without major disruption.

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THE NEED

The full realization of the promise of information technologies for greatly increased math, science, and technology (MST) learning will require a new K-14 curriculum that incorporates interdependent technology-based advantages. For instance, if technology helps fourth grade students gain an understanding of graphs and decimals, then the entire MST curriculum thereafter should build on that understanding. If calculus ideas are introduced in middle grades, then high school students could be applying calculus to interesting real-world problems. The research community has hardly begun to explore interdependencies of this sort. Yet until we understand these interdependencies, we cannot even begin to create alternative curricula that exploit the power of modern learning technologies.

Historians of science have revised their view of the progress of science to account for the huge impact of instrumentation and what could be measured (Latour, et al, 1986). Perhaps what we teach and what grades we teach it in has been similarly influenced by what can and cannot be measured, represented, and visualized. Without computers, for instance, it is difficult to measure and record many kinds of change. Perhaps it is not accidental, then, that a range of topics involving change are missing from the curriculum or unnecessarily delayed. The “technology” that has been universally available has been the use of theory and abstractions. While powerful, this technology may make many MST concepts available to only a few abstract thinkers. New technologies relying on visualizations, interactions, and kinesthetic experiences can make the key ideas of MST more widely accessible.

Our initial experience of research on graphing and probes illustrates the importance of beginning by re-assessing the implicit assumptions of science education in light of the new possibilities that technology affords. In 1980, our first research with students on probes used a Compucolor computer interfaced with temperature probes. Our software graphed the history of the temperature of the probe and displayed the current temperature to a tenth of a degree. Inexperienced in classroom research, we selected a fourth-grade class for observation and tape recording. Conventional wisdom, of which we were unaware, said that average students of this age would fail to correctly interpret decimals and graphs. Our results indicated exactly the opposite. Although these students had never been exposed to these topics, they quickly figured out both decimals and graphs through interactions with the probes and discussions of their observations. Subsequent research has confirmed that as a result of brief encounters with temperature or motion sensors and real-time displays of their output, students as early as first grade can learn to interpret graphs (Mokros & Tinker, 1987; Adams & Shrum, 1990; Beichner, 1994; Brassell, 1987; Thornton & Sokoloff, 1990). This experience suggests that highly interactive environments can easily convey an understanding of topics traditionally viewed as difficult by avoiding formalism and giving the learner a rich set of experiences in which concepts can be embedded.

We will soon have student access to technology that could revolutionize learning in mathematics, science, and technology. Today, five or more students share a school computer that is unlikely to have network access, and only the most affluent third of students have computers at home. The available computers sometimes do not work and too often lack a full suite of software. This low and unreliable access to technology means that students do not get enough experience to master complex software tools and teachers cannot assign homework that assumes ready computer availability. Important, technology-rich curricula materials are rarely implemented, if at all, because there is insufficient access to technology and schools are unable to rearrange the curriculum to exploit the advantages of these materials. In this environment, the potential of information technologies on MST education cannot be realized.

The next decade is certain to see the basic costs of computation and networking drop dramatically; the underlying costs will drop by a factor of ten if Moore’s “Law” continues to apply as expected. This will continue to cause major changes throughout society, as all institutions are reorganized to fully exploit technology, creating a new “Knowledge Society.” The ubiquitous availability of computation and networking could have a profound impact on education as well, making it possible for every student to have full-time access to portable networked computational resources. With these tools, the ability of students to pursue their interests, learn important concepts, and undertake serious investigations will be greatly expanded. Technology utilization patterns in schools could change dramatically from today’s occasional use of simple applications to essentially continuous use of a suite of powerful tools. This could cause advances in learning that will, however, require changes in the structure of curricula. This change mirrors the changes technology has stimulated in other sectors of society. This is unlikely to happen soon in schools, because education currently lacks the research base to make the needed change.

As learning technologies become ubiquitous over the next few years, the disparity between what could be taught making full use of technology and what is actually taught in most classrooms will be increasingly obvious and intolerable. The problem is that creating a new sequence for teaching MST is a massive effort that requires a better research base and extensive experience. One cannot experiment casually with what students should learn for fear of missing critical concepts or undermining student motivation. Yet, the research community that has created the possibility of vastly improved learning must undertake this work, or see its visions unrealized and the educational potential of technology unused.

Researchers exploring educational technologies have many examples of approaches that allow students to learn far more, better, and earlier in contexts that take advantage of the educational impact of information technologies. Students in early elementary grades can use probeware to learn decimals and to interpret graphs (Linn, Layman & Nachmias, 1987). Important concepts of rate and change can be learned at surprisingly early grades with SimCalc (Kaput, 1992), the motion detector, ThinkerTools (White, 1993), and other. Middle school students can create dynamic models using Model-It (Jackson et al, 1995) and spreadsheets. Graphing software, symbolic equation evaluators, Logo, image analysis, data analysis and statistical packages, CAD tools, 3D renderers, supercomputers serving computationally-intense results and visualizations, and GIS (Geographic Information Systems) all have demonstrated capacities to make important contributions to improved student understanding of MST (Thornton & Sokoloff, 1990; Tinker & Papert, 1989; Tinker, 1996).

While there are indications of the educational importance of these individual innovations, they are usually studied in isolation from each other and implemented within current curricula frameworks. Just as technology requires changes in the workplace to realize its full economic benefit, technology will require changes in the curriculum to exploit its full educational potential. Before we can confidently create curricula that exploit ubiquitous student access to computers and networking, curriculum research is urgently needed that will tell us where new material can be learned and how powerful computer-empowered units can be strung together into strands.

A curriculum is not only the topics taught, but also the interdependencies that allow concepts to build on what students have previously learned. Current implementations of technology-based educational innovations rarely build on the new learning options created by technology-based projects. For instance, the well-documented capacity of MBL to allow kids in elementary school to interpret graphs is seldom exploited to improve and rethink the teaching of algebra. To date, the major implementations of learning technologies have been **within** the traditional curriculum context: the graphing calculator is used when graphs are addressed in the curriculum, the geometry visualizers are used to improve geometry wherever students usually encounter it, MBL is used to improve conventional labs. These potentially revolutionary technologies have not been used to create fundamental improvements in the traditional sequence of MST topics.

Educators and policy-makers are demanding research-based alternative curricula that better exploit the investment in computers and networking. We desperately need research-based responses that are sufficiently reliable to use as a base of policies that might influence an entire generation of learners. The most important finding of the report on educational technology by the President’s Committee of Advisors on Science and Technology (1997) was that, while there were many exciting and promising examples of educational technologies, there were insufficient data on which to base a major, multi-billion dollar national effort. They called for “. . . early-stage research aimed at developing new forms of educational software, content, and technology-enabled pedagogy. . . .” (p. 9).

TECS: A STRATEGY FOR INTRODUCING RADICAL CHANGE

Technology-enhanced curriculum strands, or TECS could provide a mechanism for realizing the potential of technology within the constraints of school curricula. TECS are sequential technology-enabled learning activities spanning grades that substantially improve student learning of central MST concepts. There are three important characteristics of TECS:

Substantial improvement. The TECS are based on activities that use technology and result in greatly increased student learning.

Sequential. Learning activities are consecutive, growing in complexity as students mature. TECS activities should be designed to address concepts and skills that support a later activity. The sequence of learning activities might stretch across a year or multiple years.

Central Concepts. The strands should address core MST foundational knowledge important to citizens of the Knowledge Society and future workers in MST fields.

Research is needed to define appropriate grade levels and prerequisite skills for TECS and to demonstrate experimentally sequences of these activities that build upon each other. A better understanding of TECS will be extremely helpful to both educators and policy planners. Because sequences of activities are more flexible than a complete curriculum, TECS will be able to be implemented many different ways within current curricula.

We have developed the following criteria for technology-enhanced curriculum strands:

Core, difficult MST topics. The topics should span math, technology, and the sciences, including the quantitative social sciences. In each area, they should address some important, deep issues of one or more disciplines. Student mastery of these strands should significantly advance understanding in many MST topic areas.

Exploits new capacities. The TECS should make good use of the tool, computational, and communications capacities of ubiquitous technologies. These tools may be more sophisticated than most current educational software, because learners will have greater access and, hence, more time to appropriate powerful tools.

Effective educational theory. The TECS should employ learning strategies that best exploit the power of technology to increase the capacity of students to undertake investigations and construct understandings based on their observations and experiences.

Feasible. There should be evidence that the planned activities will lead to important learning. The activities should use current technologies and not pre-suppose exotic technologies or expensive approaches.

AN EXAMPLE: THE MACRO/MICRO CONNECTION

One possible TECS that we call the Macro/Micro Connection, is based on the idea that technology can help make the microscopic world of atoms and molecules as familiar as the macroscopic world. This is a difficult connection for students. The AAAS staff found the following from an exhaustive review of the relevant research they undertook to help guide the Benchmarks.

> *Students of all ages show a wide range of beliefs about the nature and behavior of particles. They lack an appreciation of the very small size of particles; believe there must be something in the space between particles; have difficulty in appreciating the intrinsic motion of particles in solids, liquids and gases; and have problems in conceptualizing forces between particles (Children's Learning in Science, 1987). Despite these difficulties, there is some evidence that carefully designed instruction carried out over a long period of time may help middle-school students develop correct ideas about particles. (Lee et al., 1993)*
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> *… A clear picture has emerged of students' misunderstanding of the nature and behavior of matter. There is still a need, however, for detailed research on effective teaching strategies to correct this,* ***especially to identify ways of leading students from a macroscopic to a microscopic understanding of matter****. Although some likely precursors to a microscopic view have been suggested—for example, the notion of invisibly small constituents of substances (Millar, 1990)—they have not been formally evaluated. [Emphasis added.] (AAAS, Benchmarks, p 337)*

The microscopic world contradicts experiences gained at the macro level. Gravity is negligible and electrostatics dominates so much at short ranges that everything sticks to everything else. Events happen so fast that time has to be slowed down to see anything. Quantum effects are important, particularly for electrons (which usually appear as clouds unless they are very energetic) and light (which has to be represented as photons). There is little wonder that the connection between the macro and micro worlds is confusing and that the few attempts to bridge the two without interactive technologies have met with little success. If these worlds can be bridged, learners will have a powerful set of ideas, models, and associations that should make a wide range of science concepts far easier to learn and remember. The models might also raise questions about important concepts like quantum effects, biochemistry, and nano-technology that will motivate future learning.

A software environment could be created consisting of a visualization tool, haptic (force-feedback) mouse and a variety of simulated atoms, molecules and aggregates with which they can interact. Many copies of the molecules can be placed in a container to observe their interactions. The design for this software would build on work by Paul Horwitz (Horwitz, in press; Horwitz & Barowy, 1994) on computer-based manipulatives: rich, interactive visualizations that help students create mental models at the molecular level to aid in understanding, remembering, and predicting macroscopic properties and interactions. The haptic mouse is an inexpensive tethered mouse developed for games that gives programmable force feedback. With suitable simulation software, the haptic mouse allows the user to feel a force generated by the applications. Any two-dimensional force within the range of the device can be programmed. The forces are not large, but the high frequency response of the system combined with the exquisite sensitivity of the human hand makes this a very important, expressive medium. (Cohn, Lam, & Fearing, 1992; Minsky & Lederman, 1966)

The software environment would support a number of interactions on which student exploration could be based:

Bend or twist a molecule or pull it apart. One part of a molecule could be put in a vice and the force feedback mouse used to pull on another part. This would give a feel for the energy of bonding, conformation, rotation, and vibration.

Pick up and move an atom or molecule relative to another. This would give a feel for the hydrogen bond, the van der Waals and electrostatic forces between molecules and how molecules might fit together.

Turn on temperature to both see and feel thermal motions. Pressure, thermal conductivity, equilibration, energy distributions, ionization, and photon emission could be observed.

Bombard an atom or molecule with electrons, photons, or other atoms. The force feedback could be used to feel and display the energy (force integrated over distance) given to the bombarding particle by a "particle launcher." The user could also feel the energy in any particles released.

Move a test charge around to see what the fields are. This way learners can feel where there are charged or polar parts of molecules.

Explore water and solutions. Collections of water molecules would exhibit hydrogen bonding, surface tension, and phase change. Other molecules in water would illustrate solubility, pH, and hydrophilic or hydrophobic properties.

The following is a possible way of using this technology across a number of grade levels. In each case, this content would be embedded in a project or anchoring situation as described. The suggested sequence of concepts is made possible primarily by this software but other activities, some using technologies would be useful as well. For instance, probes could be used with experiments in the temperature and water quality activities. A grapher and standard productivity tools would find use in several units. Networking could prove useful for sharing ideas when implemented in classrooms. Non-computer resources and activities would, of course, also be used as needed.

Size and shape. This introductory unit would establish the incredibly small scale of atoms and molecules while introducing learners to the visualization software. The activities would emphasize the size, shape, appearance, and alternative representations of molecules. These topics will be embedded in a problem for students to debate: whether we can see atoms and molecules. To answer this meaningfully, students will have to learn how devices like scanning tunneling microscopes create images and whether these images qualify as “seeing.” They will also have to consider how to interpret various software representations of molecules and what “seeing” an electron cloud means.

Temperature and states of matter. This unit would address temperature at the atomic level, using the software to simulate, in slow motion, the random motion associated with temperature. Software tools would permit students to quantify the random energy of various motions and the equipartition of energy across all degrees of freedom. Energy units appropriate at the micro level would be used, including kT, and electron volts. The model would exhibit phase changes for collections of different molecules between solid, liquid, gas, and ionized gas. This content would be anchored in the problem of finding life on other planets and moons.

Properties of matter. This unit would relate the macroscopic physical properties of matter to microscopic forces and properties that learners would discover through exploring the software with the haptic mouse. Rock climbing and its need for strong rope, good friction, and competent rock would provide the context. This would motivate the exploration of crystals, determinants of the strength of solids, tearing of solids, surface friction, elasticity, composites, and the effect of temperature extremes. These explorations would help students predict improvements in rock climbing gear and technique.

Molecules and reactions. This unit would introduce covalent and ionic bonds and some of their macroscopic consequences, particularly energy release and color. Light, photons, spectra, photon emission and absorption, and photon energy would be addressed. The anchoring topic would be how a fireworks display is related to chemical reactions, temperature, and the color of light. These would be related to laboratory explorations using a flame test and hand spectroscopes.

Water. This unit would introduce hydrogen bonding as the major factor that explains many of the unusual properties of water, including its high boiling and melting temperatures, low solid density, high surface tension, and solubility properties. Mental models of acids, bases, and pH would follow naturally from an understanding of the high solubility of ions. The context would be set by water quality measurements using probes and collaboration software.

Big molecules. This unit would address a cluster of topics related to large molecules like biological polymers and plastics that can be made from smaller units. This relates to biological molecules such as proteins, DNA, and lipids. Hydrogen bonds help explain their structure and interactions. Van der Waals forces need to be introduced to understand the mutual attraction of non-polar molecules. These topics would be anchored in the story of sickle cell anemia and its relationship to a point DNA substitution.

It will take time and multiple exposures for learners to have sufficient experiences in the odd micro world to develop rich intuitions, associations, and mental frameworks about particle behavior. Experiences at the simulated micro level need to be linked with multiple learner observations about the macroscopic world, such as color, crystal shape, light spectra, strength of materials, solubility, combustion, surfactants, membranes, rust, plating, and batteries, to name just a few. These experiences also have to be embedded in good instruction that fosters exploration and problem-solving that is anchored by interesting, rich contexts. With these experiences at the microscopic level and meaningful links between them and the macroscopic world, the resulting understandings should help students remember and predict phenomena and concepts at the macroscopic level.

These units should be appropriate for late elementary through high school students. Mathematics, often a barrier to scientific understanding, is not widely used in this TECS. The most complex mathematics would involve decimals and scientific notation to quantify the small sizes and unit conversions to express the relationships between different measures of distance, time, and energy. Both of these concepts could be introduced within the units and supported with simple software tools.

RESEARCH ON TECHNOLOGY-ENHANCED CURRICULUM STRANDS

There are many other possible sequences of technology-enhanced units that could greatly accelerate MST learning. The following are just a few possible candidates:

Design. Technology intuitions and skills can be fostered through models, visualizations, CAD, Logo, Crickets, electronics, and probes. This is not an updated variety of vocational education, but an exploration of the intersections of technology, math, and science. We might start with the idea that many things have associated numbers that we can measure to introduce the technology of measurement, including decimals, scientific notation, errors, standards, calibration, and probes. The idea that functional modules can be used to build things could be illustrated in programming, electronics, and building. Design challenges could be based on designing apparatus for science experiments. This strand could address important topics in technology, mathematics, and science.

Inquiry. Probes interfaced to good software, sensors with logging electronics, image and video analysis tools, and network databases provide unprecedented opportunities for students to learn how scientists explore the world. A host of important investigative skills such as experiment design, data analysis, treatment of deviations, data interpretation, error analysis, peer collaboration, and communication of results all become important and increasingly familiar as students have more opportunities to experiment using networking and technology-based tools. This strand could address important topics in the nature of all sciences.

Projecting the Future. Student fascination with themselves can be expanded to include their future and the future of society. With appropriate software tools, learners can investigate population growth, economics, resource limitations, planning, environmental changes, sustainability, and other trends that seem hidden given the scale of the students' age and experience. . By compressing time and permitting many futures to be explored, simulations, visualizations, and online gaming, can give students an intuitive understanding of these issues. This strand could address important topics in the quantitative social sciences.

Math of Change. Early experiences, as Kaput and Rochelle (Kaput, 1992) are exploring, with a variety of rates and flows can lead students to an early understanding of key calculus concepts. Since calculus is fundamental to much of science, ideas that are central to most science disciplines could be understood at an intuitive level far earlier by students who understand the mathematics of change. This would give students access to dynamics in physics, dynamical systems in the chaos sense, formal calculus, electronics, and more. This strand could address important topics in mathematics, physics, and technology.

Modeling. Increasingly, computer-generated models frame public debates, determine investments, and report scientific discoveries. Students need an understanding of how to use, evaluate, test, modify, and create different kinds of models. This strand could address important topics in mathematics, technology, and all sciences.

A major effort is needed to define and study TECS. We could start by developing TECS blueprints based on assumptions about what students can learn with technology tools, when in their development they can learn these topics, and how much time it takes. The blueprints will identify the most important and least studied of these assumptions and suggest focal questions that could be answered through additional research, such as:

Unit comprehension. What do students at different levels learn in a unit? To what extent are the unit's learning objectives achieved with typical students at different grades? How robust and accurate are students' mental models of the micro world? Can students use their models of the micro world to reason about the new relationships between micro and macro worlds?

Unit interrelationships. Does one unit provide the essential understanding for subsequent units? Do students retain these understanding for significant times? What are the prerequisites for each unit? How can these prerequisites be mastered for students who missed or forgot content in earlier units? Do students integrate new concepts into their mental models of the micro world?

Transference. To what extent do learners apply the knowledge and tools they acquire within a strand to other topics? Does a rich mental model of the micro world help students acquire new knowledge about either the micro or macro world?

The definition and study of TECS could begin to realize the potential of technology. It starts by asking what technology can add to learning and how to build on that learning in subsequent instruction. It creates strands of activities that can easily be inserted into existing curricula without requiring wholesale change. This permits schools to proceed carefully and incrementally. As they see improvements they can increase their commitment. Since the technology is likely to change quickly, this flexibility also leaves room for curriculum change as better research and implementations become available.

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