Information Technologies in Science and Mathematics Education[1]

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Information technologies[4] have the potential to support much-needed large scale change in mathematics and science education. Technology-rich curricula can help meet the demands of the new standards for more inquiry-based learning and new content and can support more sweeping change that goes far beyond what is envisioned in the standards. To fully realize the math and science potential of all students, we need to develop new and far more ambitious curricula for a quite different future that information technologies make possible.

We are in a period of acute self-doubt concerning our educational system. We know our students are not learning as much as they should, but it is difficult to identify the cause; teachers, schools of education, textbooks, school schedules, local funding, Federal policies, and larger societal trends have all been blamed. To many, large-scale reform, applied in a “systemic” manner, is the solution, but to date, the funding and commitment to large-scale change is completely inadequate and capable of no more than token change. Others hope for change by creating new standards that define tough core content, but it has proven very difficult to reach consensus about what core content is needed.[5]

Some look to technology to save the educational system. There is a widespread hope that new technology will by itself cause a revolution in learning. For instance, Perelman talks about “Hyperlearning” as though it were an accomplished fact or something that researchers will find when they figure out the right mixture of computers, networking, and multimedia.[6] Others talk of information technology as a Trojan Horse that, once let into schools to appease the call for the “technology,” will cause a revolution, because its good use requires reform of curricula and instructional strategies. These arguments ignore the fact that technology is essentially neutral and can be used in support of education that is regressive as well as progressive.

While technology is not a quick fix, it does represent the only major new resource education can draw on for reform Just as information technologies are changing the larger society, they *do* have the potential to support a major reform of education (see, for instance, Means, 1994). Information technologies, when used intelligently in combination with good curricula and good learning strategies, can result in learning that is much faster, deeper, and more lasting than we have come to expect is feasible. But it is important to realize that the technology is a necessary but not sufficient part of the resulting improvement. Used only in small doses, without thought to curricula or with poor learning strategies, information technologies have little educational value.

This paper presents a strategy for the wise use of information technologies to support significant improvements in school mathematics and science.[7] As a result, this article makes no attempt to cover the entire educational technology landscape with an even hand. What is attempted is to map out a balanced strategy that cash-strapped schools could pursue as part of a larger effort to make substantial improvements in teaching in these fields.

WHAT TECHNOLOGY CAN DO FOR EDUCATION

The most useful educational perspective on information technologies is to see them primarily as tools that help students accomplish more. The tool role is of primary importance, because it extends the capacity of students to undertake investigations, to attack computational problems, to communicate, and to access information resources. Secondarily, information technologies also can be used for interesting simulations students can learn about through exploration and interaction.

Information technologies offer new ways of structuring the curriculum to both support student inquiry and cover more content. A major commitment to using technological tools across the curriculum will permit more advanced mathematics and science concepts to be treated. Computational power frees mathematics students to explore both mathematical and real-world phenomena where in the past the computational complexity would have been a barrier. Computers can also mount brute force attacks on problems that previously required abstract formalisms far beyond the reach of most precollege students. With this power, students can investigate and understand topics that are beyond the current curriculum standards.

In the long run, the tool and simulation capacities of information technologies can have four different levels of impacts on the curriculum:

Level 1. Substitution. At the first level, information technologies are used to accomplish the existing curriculum goals but doing them better or to a higher level of student comprehension. For instance, labs based on probes connected to computers have the ability to reach very high levels of student comprehension of material previously mastered by few students.

Level 2. Addition. At this level, technology makes it possible to achieve new curriculum goals, usually by adding new material to an existing course. For instance, the TERC Global Lab project[8] adds to existing science courses the possibility of international collaboration and peer review by creating groups of schools linked through telecommunications.

Level 3. Disciplinary restructuring. At this level, the capacity of information technologies makes it possible to redesign a course or series of courses within a discipline. For instance, graphing can be introduced far earlier in the math sequence giving students skills that can help speed their understanding of many concepts that might have a graphical interpretation.

Level 4. Interdisciplinary restructuring. At this level, technology supports the redesign of courses across disciplines. For instance, if systems modeling was learned in ninth grade math, then subsequent science courses could use this capacity to address a broader range of science material at a deeper level.

These four levels involve increasing difficulty and educational payoff. Clearly, the first level is simplest to implement, because it is easy to substitute an improved, technology-based approach to a topic for a less effective one. This strategy has given rise to tens of thousands of small computer programs, far more than can be addressed in this article. The ease of implementation has often outweighed considerations of quality; just because the material is treated with technology does not guarantee that the learning is better.

Level two is more difficult to implement because curricula represent a zero-sum game: for every topic added, something must be dropped. Making curriculum changes and justifying them to all the concerned educators and parents takes time and effort. Still, there are many cases in which educators undertake this effort, understanding the importance that the new capacity of technology adds.

Levels three and four represent large-scale course changes that are largely untried and unstudied. Yet, these kinds of change promise the greatest rewards, providing students with far deeper understanding of much more content that is currently expected. Such large-scale changes are difficult for a single school or school district to implement, because their graduates might not have the familiar set of knowledge and because transfer students, in and out of the system, will face severe difficulties. As a result, such really large-scale change must await regional, state, or national consensus that is very difficult to achieve.

It is important, therefore, to begin our survey with the emerging national consensus about what curricula should be and what the role of information technology might be. The recently-promulgated national standards for mathematics and science are probably the most thoughtful compendia of what is needed, and so we begin by reviewing them.

STANDARDS AND INFORMATION TECHNOLOGY

The most significant new message to take away from the science[9] and mathematics[10] standards, is that student inquiry must be given much higher priority and must be at the core of instruction in these fields. The standards require that students must learn through inquiry, they must have opportunities for extended inquiry, and they must have the intellectual tools needed to make sense of their inquiries. Heavy reliance on information technologies is both implicit in this requirement and explicitly mentioned.

The NRC Content Standard A (Science as Inquiry) states that in grades 5-8, as an essential ingredient of inquiry “..developing spreadsheets .. should be part of the science education.” (p 144) It states that one of the “abilities necessary to do scientific inquiry” is to “Use appropriate tools and techniques to gather, analyze, and interpret data.” Thus, “The use of computers for the collection, summary, and display of evidence is part of this standard. Students should be able to access, gather, store, retrieve and organize data, using hardware and software designed for these purposes.” (p 143.) At the high school level, the inquiry content standard includes

"Use technology and mathematics to improve investigations and communications" as one of the necessary abilities. (p 175).

Conducting scientific inquiry requires that "students have easy, equitable, and frequent opportunities to use a wide range of equipment, materials, supplies, and other resources for experimental and direct investigations of phenomena." Along with microscopes, this includes "tools for data analysis, and computers with software for supporting investigations." (p 220) Also, "good science programs require access to the world beyond the classroom." This includes field trips, museums, and "communications technology that should be easily accessible to students." (p 220-1)

The AAAS advocates a similar approach. They emphasize scientific and mathematical inquiry and see information technologies as essential to student inquiry. For instance, they state that by the end of the eighth grade, students should be able to use a spreadsheet for calculation and use computers for data storage. By graduation, students need to "use computer spreadsheet, graphing and database programs to assist in quantitative analysis." and to "use computers for producing table and graphs and for making spreadsheet calculations." (p. 291 and p. 294)

The NCTM is even more specific about the role of computers, seeing them as having expanded the content of mathematics as well as offering numerous opportunities to support and expand mathematics instruction. The standards state that "Students should learn to use the computer as a tool for processing information and performing calculations to investigate and solve problems." Computers permit a broadening of both content and focus of traditional algebra to include data analysis, statistics, probability, and discrete mathematics. The NCTM calls for more integration across these topics at all grade levels and "for increased attention to real-world applications, matrices, and the use of emerging calculator and computer technologies as tools for problem solving and conceptual development." Calculators and computers are seen as "tools for learning and doing mathematics," and this is essential because mathematical exploration is something that students must experience. Computation power permits students to study equations in meaningful contexts, rather than as mathematical objects symbolically manipulated and "stripped of other meaning."

Thus, taken together, the standards advocate increased reliance on student investigations as an educational strategy and on information technologies to support this through general-purpose tools. These tools are important, because when mastered by students they greatly extend the range and depth of investigations students can undertake. This is an exciting vision that must be taken seriously by schools and will require a major reorientation of curricula and reassessment of the role of information technologies.

In terms of the analysis above, the standards advocate information technology use primarily at level two, adding increased inquiry and relying, in part, on information technologies to make this feasible.[11] The mathematics standard ventures a bit into level three, suggesting ways mathematics could be rearranged across grades to include a variety of computational capacities to support new material or old material earlier in the curriculum. In contrast, neither of the science standards address this possibility.

While these standards are a useful starting point, it is important to look at them critically and ask whether their recommendations are adequate. Out of concerns for equity and the lack of teacher preparation, the standards have avoided too great a reliance on information technologies and therefore are not able to build consensus for the thorough-going change possible at level three. Because the standards were discipline-oriented, none had the mandate to consider the interdisciplinary synergy that is possible at level four. Therefore, the standards should be seen as rather cautious about information technologies, unwilling to advocate the kind of radical curriculum changes that information technologies make feasible.

INVESTING IN FAMILIARITY

Even with the best user interface, information technologies take time to master because they usually embody new concepts that take time to appreciate. This requires a substantial investment in time. Students need time to learn how to operate generalized tools and then more time to master them with sufficient skill to appreciate their generality. It is not sufficient to simply expose students once or twice to a tool like a spreadsheet. Depending on how prescriptive that exposure was, students might learn almost nothing about how they might apply a spreadsheet to their own questions. It takes repeated exposure and time to make mistakes before students become familiar with general tools.

Schools have great difficulty making this kind of investment in familiarity. The time devoted to learning the tool is always in competition with limited instructional time for “real content.” In the beginning of the process of learning a new tool, the technology can actually be an impediment.[12] Then there is the huge problem of transfer students who have not learned the tool and enter a curriculum at a point where the tool is assumed to be available.

In the past, these kinds of impediments have discouraged educators from investing in programming languages, and they will operate to make the investment in other information technology tools equally problematical. It has proven simpler to ignore information technologies and hope that they would go away. But information technologies have only increased in importance over time, so it is time that every school should have a strategy for substantial intellectual investment in these tools.

Spreadsheets

For both mathematics and science, the single, most valuable information technology tool is the graphing spreadsheet. Almost every conceivable calculation, graph, model, or analysis can be done with a graphing spreadsheet. Spreadsheets can make mathematical abstractions very concrete and help students understand both the details and large picture.

Spreadsheets have a number of attributes that make them important in education. Any spreadsheet cell can contain a number that is the result of a computation based on other cells, and the user can view either the resulting number or the formula.

The formulae for entire arrays of cells can be entered through a process of duplication that makes the role of constants and variables explicit. In these ways, spreadsheets facilitate the critical transition from arithmetic to algebraic functional thinking. In addition, learning spreadsheets is a valuable commercial and vocational skill.

Spreadsheet concepts are transferable between specific programs, so time invested in learning ClarisWorks is not wasted when only Excel is available. Spreadsheet data can easily be imported and exported between programs, so that if specialized software is needed for some reason, its data can easily be used with spreadsheets. Spreadsheets can easily be linked to computer networks, so both data and the calculations can be easily shared. For all these reasons, spreadsheets should be taught and used throughout the mathematics and science curriculum.

Readers not familiar with the incredible versatility of spreadsheets should look at the box “You Can Do Anything With Spreadsheets.” Starting with a simple addition table, it illustrates graphing, data analysis, and modeling, spanning content from first grade through graduate school. One application shown is a challenging learning game that is equivalent to a popular commercial product. This flexibility means that spreadsheets have the capacity to reach students who are functioning at a very wide range of mathematical or scientific levels of sophistication.

One important class of applications illustrated in the box is that of dynamic modeling. This is the mathematics behind many branches of science, feedback and control, system dynamics, and chaos. Increasingly, predictions about the future that demand public decisions are based on dynamic models. In order to understand the nature of science, mathematical models, and their role in society, it is important that students learn to use, modify, and build their own models. So, while not widely recognized as important, any school striving for excellence in mathematics and science should incorporate dynamic modeling in its curriculum.[13]

Without computers, dynamic modeling has been outside the reach of high school students, because their mathematical formalism requires several years of calculus. With computers, however, students with only an introduction to algebra can build and use dynamic models. There are specialized software packages to help students create such models[14], Stella being the most widely used.[15] However, research with students has convinced the author that using spreadsheets represents a better educational strategy for learning how to construct dynamic models, because the calculations are more visible and the relationships between numbers, functional relationships, and variables are clearer (Tinker, 1993).

The most important implication of the versatility of spreadsheets is that students, using their own prior knowledge can quickly learn to modify and create their own spreadsheets to apply to their own projects. Some of the spreadsheets illustrated are more complex than one would expect typical teachers or students to generate, but that is not a problem because there is a rich literature of applications and help available online.[16] The idea is not that every teacher or school must invent its own spreadsheet applications, but that everyone be sufficiently invested in spreadsheets to be aware of what has already been invented and sufficiently creative to see how these can be modified and used in the curriculum.

Productivity Packages

What spreadsheets are to mathematics and science education, word processors are to language and communications, and, to a lesser extent, databases are to the social sciences and graphics packages are to the creative arts. This suggests that so-called “productivity packages” that combine all four — spreadsheet, word processor, database, and graphics — would be the best choices for a cross-disciplinary curriculum strategy of information technology use. Such a choice would be valuable for mathematics and science education, as well.

The ability to write, draw, and perform database functions is essential to mathematics and science. All the standards point out that communication is as much a part of mathematics and science as collecting data and calculating. The most important understanding about math and science a student can come away with is that “I can do it,” because she or he actually has. The “it” in this case is science and mathematics in their fullest sense, and this includes reporting, peer review, and communications.[17] Collaborations over digital networks help support this by giving students an audience for their writing as well as providing the motivation implicit in important, large-scale research.

Digital networks need computer-based tools, the most common of which is the word processor. To communicate ideas, explain the reasoning behind a calculation, and share half-developed concepts requires a medium in which students can be expressive. Pure text is not this medium for most kids; they need software that supports compound documents that include text, drawings, tables, graphs, and photographs. Thus, a productivity package that is “networkable,” software that allows documents including all four kinds of applications to be combined into single, compound documents and sent over networks, represents the best information technology investment for schools.

Specific Packages

In this section, three packages will be discussed: ClarisWorks, Microsoft Works, and Alice. All are widely used in schools and all run on both the Macintosh and Wintel[18] computer platforms. This covers all the computers schools are currently purchasing. Schools with a large backlog of older computers need not despair, however, since perfectly good productivity packages are available for every computer ever made and the skills learned with one package are easily transferred to others.

ClarisWorks is a productivity package that many schools have adopted.[19] It is inexpensive and limited but provides adequate performance for many school applications and is easy to learn. Most importantly, it is easy to create compound documents within ClarisWorks. This means, for instance, that a spreadsheet can be embedded in a formatted text document that also includes drawings, databases, and other objects. The embedded spreadsheet is not just a picture of the state of a spreadsheet, but a live application that can be opened, used, modified, and saved. This supports collaboration both within a class and over networks.

Microsoft Works[20] is a close second as an inexpensive productivity package. But, to get the best general spreadsheet, you a better choice is the Microsoft Excel spreadsheet .[21] It has more options, more cells, more functions, and all kinds of formatting features. The latest version of Excel has the BASIC programming language just under the surface, so when students need additional horsepower in their spreadsheets, they are ready to learn some new programming concepts. It is important to teach programming, and a problem students need to solve can provide the context and motivation for learning this skill.

Alice is a software package that shares some features with productivity packages, but was developed specifically for schools.[22] Alice was designed to simplify sharing data over networks and was kept simple to use in order to make it accessible to beginning users. It has tables that are a bit like spreadsheets but do not have different calculations for each cell; instead, its calculations are done on entire columns. While this limits its flexibility, having the same rule for every number in a column is clearer and more intuitive for neophytes. It also makes it easy to use built-in database functions since each row can be treated as a record. Alice's graphing capacity is better in some important respects than most spreadsheets, and if the data include latitude and longitude columns, they can be plotted on a zoom-able map. In networking applications, Alice table data can be sent off to a database where it is combined with data from others and downloaded. This is ideal for collecting and sharing environmental data collected by students. Best of all, Alice is free.

A system-wide strategy for spreadsheets might start students in early elementary grades simply using spreadsheets to explore patterns such as indicated in the addition table example. Ironically, an advanced spreadsheet like Excel might be best for this level because applications built from it can have a user interface that is easier to use and relatively bullet-proof. In the upper elementary grades, students will be ready to go "behind" the user interface and need the simplest package. Alice might be a good choice here, particularly if it were introduced in the context of an environmental data sharing project. Middle grade students might begin using a simple spreadsheet like ClarisWorks in both mathematics and science while learning its other applications in arts, communications, and social science classes. At this level, student projects could begin to exploit the power of these tools. By high school, students might need to graduate to the additional power of Excel that would be used extensively in mathematics, science, technology, and social science courses.

OTHER TOOL SOFTWARE

While spreadsheets are underrated and should be central to any school's information technology strategy, they cannot do everything, and there are additional software tools that should be part of any precollege mathematics and science program. This is especially true in biology, where spreadsheets prove a less felicitous match for methods and explorations typical of the life sciences.

In the following, seven additional kinds of more specific applications will be recommended each of which represents an important kind computational capacity. The educational justification for each of these is the same as that for spreadsheets: students need to master powerful general tools that can be applied to their own investigations, and they need a basic understanding of the capacities of this technology that is transforming so much of science, technology, and society.

Microcomputer Based Labs

Computers are a routine part of most science research laboratories, where they control experimental conditions and automate the collection and display of data. In the 1980s, I made the observation that if this were so important in science, it would also be in science education. In order to capture both the technology and a constructivist educational use of the technology into a single package, I coined the term Microcomputer Based Labs (MBL) to apply to the educational applications of computers used for data acquisition and analysis.[23]

It turns out that, properly implemented, MBL frees students from the drudgery of labs and allows them to think more clearly about the phenomena. Seeing massed data summarized in graphs or other symbolic forms while still in the lab helps strengthen the relationship between the experiment and abstract representations and gives the opportunity to make additional explorations under different conditions.[24] The use of probes does not automatically result in improved learning, but, when combined with good educational strategies, it can result in learning that is difficult to achieve through any other combination of lecture, problem sets, and traditional labs.[25]

MBL is an important counterbalance to the tendency of information technologies to divorce learning from reality. Although simulations are available for every common teaching lab, they can never be as good as the real thing. Simulations have their role for labs that cannot be offered for reasons of safety, scale, or cost, but every effort must be made to increase the amount of exposure students have to real experimental situations. MBL harnesses the power of information technologies to make labs a better learning environment and to increase the range of investigations students can undertake.

In spite of its proven importance, the implementation of MBL has been slow. The major impediment is the cost of equipping lab stations with computers and the additional hardware required. Many science teachers are solving the computer problem by going after older computers that are declared surplus as newer ones are moved in. Many MBL applications require minimal computational power and run perfectly well on old Apple II, Commodore 64, Mac, and IBM computers. To meet the variety of interfacing challenges created by these computers, most MBL vendors provide interfaces that plug into the standard serial port that all computers have. This means that a science lab can invest in one line of interfacing hardware that can be used between different computers as well as any future computers that might appear. The difficulty of learning about the technology has slowed the implementation of MBL, too, although there are a number of workshops[26] and discussion groups available to support teachers.

There are a wide range of vendors of MBL interfaces and probes.[27] Probes are available for position, speed, acceleration, force, pressure, rotation, pH, conductivity, temperature, light, magnetic field, colorimetery, and much more. Lab activities, which tend to be specific to a vendor’s combination of hardware and software, are available from most vendors. The best are a combination of fairly-specific cookbook instructions designed to get students started with the apparatus doing a familiar lab and some open-ended extensions that can challenge even the most creative student and explore science far beyond what is possible in the traditional lab.

Databases, Statistics, and Tabletop

Graphing software and databases are, in many respects, complementary. Like graphers, databases are tools that help students build theories and understand observations and are particularly important when there are lots of observations. Databases are particularly useful when the data are categorical, when there are many possible variables only some of which might be related, and when statistics is important due to high variability in the data. Databases are under-utilized in schools, in part because the fear so many have of statistics.

There are software tools that help students understand categorical data and make inferences without needing formal statistics even when the data has considerable random variability. Perhaps the most general and accessible are Tabletop and Tabletop Junior.[28] In Tabletop, each data record is represented by an icon that can be interrogated by clicking. The icons can be sorted by the values of their variables using logical functions or axes. As the sorting conditions change, the icons move smoothly into their new positions. The results are appealing and very revealing. Scatter diagrams, Venn diagrams, and cross-tabulations all seem quite natural and comprehensible in this environment.

Many experiments can be compared to a theory by a fitting straight line to the experimental data. For instance, absolute zero can be estimated by measuring the volume of a fixed quantity of gas at different temperatures around room temperature and extrapolating the observed trend to zero volume. To do this accurately, you need to determine what straight line best fits the data. There is a statistical procedure for determining the “best-fit” straight line, but this seems like magic to anyone unfamiliar with the rather complex formalism. One package lets the user try different fits, while showing the data, the straight line, and the amount of error displayed in a thermometer-like bar.[29] This gives the user a feeling for how the best fit is determined as well as its reliability or how sensitive the errors are as the straight line is altered.

Image Analysis

A great deal of information can be extracted directly from photographic images. You can count rings in a tree stump, colonies on a Petri dish, the area of a leaf and the percent infected, the area of damaged trees on a satellite image, the size of a paramecium in a photomicrograph, or the number of galaxies. By analyzing successive images of a video, one can measure the velocity of a dancer’s arm, the speed of a planet, or the growth of a seedling. Working from images is appealing to students and, especially if they photographed the images, motivating and inherently interesting.

All these tasks can be automated with one standard image analysis software package called NIH Image that has the particularly appealing property of being free.[30] The disadvantage of Image is that it is aimed at the professional, so it is packed with more features than the beginner wants or needs. This creates a bit of a hurdle, but one well worth the investment of some time for any application that starts with images. The Center for Image Processing in Education provides workshops, curricula, and CD-ROMs filled with images, software, and information that help educators master Image and apply it to the curriculum.[31]

One kind of image analysis that has proven very useful in physics, and has applications in other fields as well, involves extracting position information from successive frames of a video. A student dancing, successive frames of a flower growing, and slow-motion of a diver each generate video input that students can analyze to help understand the underlying science. NIH Image supports macros that do this[32], but specialized software for students that simplifies the process of extracting and graphing the data is also available.[33]

Internet Browsing

The hottest things in information technology right now are Internet Web pages and their access through browsers. Investors are throwing money at this technology, and it has even penetrated the comic pages.[34] Because the commercial interest is attracting new and inexperienced people to education, there is a great deal of hype about the educational value of this that must be discounted. However, the international frenzy will continue to drive the development of capacity and resources that will have important educational implications. While it is risky to make any predictions in this fast-moving area, it seems as though three classes of applications have the greatest potential to support core mathematics and science educational goals:

Access to data and information. The Internet is a vast and growing library that students can access for all kinds of material no school could afford to acquire for its library. A sample of interesting material would include seismic traces showing today's earthquake,[35] census track data for your town,[36] global methane production,[37] a field guide to lichens,[38] photos of Shoemaker-Levy 9,[39] and a description of the significance of the top quark.[40] Of course, the user must beware; some of the information on the Net is wrong or misleading, much is undigested, and there will be bias; hardly a new problem, but one to which students must be alerted.

Professional development. There are many online resources for teacher professional development. Currently, the most valuable are relatively informal discussions groups, but soon, large numbers of more organized courses of various kinds and lengths will be available, some bearing graduate credit. The kind of assistance teachers will need to take advantage of the educational opportunities generated by information technologies will be available in the form of network-based courses offered by world experts and accessible at any time at home or school.[41]

Collaboration. Eventually, it will become common to see genuine collaboration between students with similar mathematical and scientific interests. Students working together can attack big problems and contribute significantly to our understanding of pressing environmental and social problems. Now this is seen only in some funded projects,[42] because the connectivity has not reached many students and the need to communicate in text hampers expressiveness. Eventually we will see the development of network-based communities of student-scientists with their own conferences, meetings, working groups, professional societies, publications, peer review, and grant-making groups. Participation in these communities will give students an invaluable working understanding of how science is organized as well as unprecedented opportunities to learn science concepts.

Right now, the best Internet browser is Netscape 2.0[43] although other browsers will soon to be available that will be at least as good. At this writing, the most exciting development is Java and its enhancements. Java is a programming language in which supports little applications, called applets, that can be downloaded by one of these browsers and executed, regardless of which computer you are using. Before applets, essentially all you got when you browsed the Internet was static pages.[44] Applets make it possible for any common computer to run a simulation, graph data, and do anything else computers do, but as part of a Web page. This will probably lead to the development of free applications that increase capacity and decrease the need for large, expensive software packages.

Everything Else

In this brief review of information technologies, there is insufficient room to mention many other valuable information technology capacities that have a role in mathematics and science education. No review would be complete, however, without at least mentioning three other categories of tools:

Lego Logo and Logo. While the focus of MBL is getting data into the computer, there are many applications where the computer is used for control, often in conjunction with sensors. The most thoughtful approach to this combination of control and sensing is the Lego Logo system.[45] Using extensions of the Logo language, this flexible hardware and software system is an ideal introduction to computer control at the middle grades. It also gives the student-experimenter a valuable set of tools for controlling experiments. The Logo programming language is, by itself, worth learning, because it is simple, logical, but quite powerful and gives students a tool with unlimited potential to attack any problem.[46]

Proof Explorers. There is a tiny group of applications[47] that help students explore geometry and algebra and develop proofs in these areas. Formal mathematical logic is an important part of mathematics and one many students find completely inaccessible. These packages help by formalizing the operations and permitting the user to explore many instances to see whether a particular result is general. This lets students gain an intuitive understanding while simplifying the process of building formal proofs based on their growing intuitions.

Interactive Physics. The Knowledge Revolution[48] produces a remarkable simulation environment for physics. At first glance, it looks like a graphics package that allows one to draw the usual circles, squares, and polygons. Rods, springs, strings, motors, and other oddities can also be added to the drawing. But the amazing thing is that the result can be "run" in a two-dimensional world that obeys the laws of physics. Objects fall, collide, bounce, and vibrate just as they would in the lab. This is an outstanding simulation environment and playground to couple with real experiments.

This survey has attempted to keep the recommended software list short and focused entirely on general-purpose tools. There are many, many additional programs, and their absence from this list does not mean that they are without value. The reason for concentration on tools is that they offer the greatest potential educational payoff.

PUTTING IT ALL TOGETHER

Information technologies are only one of three ingredients needed for large-scale improvement in education; the other two are good curricula and revised course content.

Information Technologies and Instructional Strategies

Information technologies must be embedded in excellent curricula that take advantage of the new opportunities for learning created by the technology. We have seen a well-tested explorative MBL lab rendered meaningless to students by a teacher who could not foster student exploration. Marcia Linn has conclusively demonstrated the role of curriculum in a remarkable series of classroom experiments.[49] Starting with 3% of the students able to distinguish accurately between heat and temperature, students reached only 10% using the first curriculum. But after eight iterations with the same apparatus, they reached 50%.

In over a decade of research and refinement of the hardware, software, and curriculum, Ron Thornton has shown that exploration with MBL can improve student qualitative understanding of mechanics dramatically better than any combination of traditional labs, lectures, and homework (see, for instance, Thornton and Sokoloff, 1990). Then, using interactive MBL demonstrations with a large display that a whole class can see, combined with good instructional strategies that engage every student, he can achieve a stable increase in understanding that verges on complete comprehension for all students (Thornton, 1996).

In both these cases, MBL technology was necessary but not sufficient to achieve the educational goals; excellent curricula, consisting of quality instructional strategies, materials, and learning goals, were equally necessary. It is the importance of excellent curricula and the difficulty of developing it that needs to be underscored. Too many technology advocates assume that access to information technologies will drive reform; "Just give them access to the Internet" is their rallying call. But it is never that simple.

These examples demonstrate how much effort is required to craft an excellent curriculum; that multiple cycles of in-class testing and revision are needed before the greatest learning is achieved. Unfortunately, there is little curriculum material that takes good advantage of technology and is available to schools. Two of the best are discussed next.

Voyages of the Mimi

The Voyage of the Mimi curricula was developed in the 1980's by Sam Gibbons under the leadership of Dick Ruopp who was then president of Bank Street College. Each of its two "Voyages" is a complete year-long science curriculum for grades 4-6 that makes full use of video, software, and MBL. In the videos, students see young researchers studying whales and an archeological dig using a full range of software tools. Then the students are given similar tools they can use for their own, similar, explorations. In this way, students identify with scientists and see for themselves that they can "do" science.[50]

The NGS Kids Network

The largest network-based educational curriculum is the NGS Kids Network, developed at my initiative by Candice Julyan and others at TERC. It is now published by the National Geographic Society and reaches over a quarter-million children annually. Each of the eight-week modules that comprise the materials involves taking some environmental data, sharing it across the network, and analyzing the resulting combined data. This experience is embedded in a carefully-tested curriculum that addresses related science and math topics.[51] Along the way, students use a word processor, a grapher, and networking using a general-purpose software tool like Alice.

The Need for More IT-Rich Curricula

It is no accident that the Voyages and the Kids Network are excellent, because they were carefully developed over five to ten years by highly creative teams of experts. They each required multiple iterations of testing and revision in a wide range classrooms; the Kids Network was tested in 200 classrooms. The total development cost of each curriculum was between five to ten million dollars.[52] In terms of a single school's budget or other educational projects, these are huge expenses; they are, however, comparable to what a publisher invests in a new text or series of texts, and infinitesimal compared to the billions invested nation-wide in texts, computers, or sports equipment.

What is tragic is that both these projects were designed over a decade ago and that there are no comparable projects underway that fully exploit the substantial curriculum advances possible with the better technology now available. Very few technology-driven projects are able to invest the level of funding available for curriculum development of the Kids Network and the Voyage of the Mimi. As a direct result, there are very few excellent technology-rich curricula. In fact, the high cost of developing curricula leads curriculum developers away from information technologies, because they want to reach the largest number of students possible.

Placing any restrictions on who can use the new curriculum, such as they must have Internet access or use MBL, runs counter to the desire to reach every student.

As a consequence, a gulf has opened between people creating new curricula and those advocating information technologies; the curriculum developers are shy of technology and the technology promoters are forced to downplay the importance of curricula and advocate doing without. Until there is adequate recognition of this problem by funders able to cover the high costs of developing technology-rich curricula, new projects will tend to either ignore information technologies or treat them as optional add-ons. Unfortunately, this confines most new material to level one (substitution) or two (addition), making it impossible to find fundamentally new courses based on information technology.

Revised Course Content

The real payoff from school investment in information technologies will come when information technologies are utilized at levels three and four where course content can be substantially changed and upgraded. The following is a highly speculative picture of what could result in information-rich schools of the future:

Elementary Levels

Information technologies will have supported a full integration of experimental science with mathematics around beginning student projects and investigations. Starting at six years old, kids will be introduced to the idea that many phenomena have numbers associated with them, because they will have portable measuring tools that can detect temperature, force, light level, and much more. This capacity will lead kids to design their own investigations, gaining experience with materials, design, measurement, sources of error, and interpretation. This will be followed by the introduction of graphing and graphing analysis, starting when kids are about ten, using data gathered from MBL and digital images. We will also see far earlier introduction of decimals in the context of experimental measurement at the expense of fractions (which will be treated as an anachronistic novelty in one week in the middle level.)

Experimental probability will be introduced with the earliest experiments, and then treated graphically beginning around age eleven. The resulting measurement and analytic skills will enable eleven- to thirteen-year-olds to explore a range of scientific areas through observation and measurement. These explorations, some as part of networked groups, some with MBL and digital cameras, will have given students a broad exposure to examples of categories, change, regularity, and cause and effect in the natural world.

Middle Years

Because of the new elementary content, mathematics at middle levels will be freed from much of the beginning algebra abstractions and will, instead, concentrate on numerical modeling, estimation, and, later, the use of algebraic formalism, particularly with the help of graphing spreadsheets and symbolic manipulators. Transcendental functions will emerge incidentally from dynamic models as *particularly simple systems. Feedback and control will be central themes introduced in design problems and formulated into the dynamic models.*

The concentration on modeling, particularly dynamic modeling, will provide a key underpinning for a range of scientific theorizing, since dynamic models with feedback help students predict the future of everything from astronomy to the stock market, global warming to school demographics. This will give kids a technique to move between quantitative observations to theory that they will find powerful and general. Experimental investigations will continue to mature as the students mature. They will enable students increasingly to coordinate multiple variables in various disciplines using increasingly sophisticated measurement techniques supported with network materials rich in images and video. With increasing exposure to measurements in various fields of science and technology, kids will be able to design their first extended investigations and share their thinking and results with others with similar interests throughout the world using programs that involve global data collection and sharing with students and scientists who are interested in their results. Technology and design challenges will be plentiful, but not separated from the experimental design and information technology skills these learners will develop as part of their investigations.

High School

The prior treatment of algebra, graphical analysis, and dynamics will free new space in the precollege curriculum for a pure mathematics sequence where the goal is the exploration of mathematical reasoning for its own sake. This sequence will combine experimental axiomatic geometry and algebra with the formalism of calculus, all making extensive use of computer tools, and network collaboration based on specialized interests. Some learners will, for instance, join a hyperbolic geometry forum to share problems and proofs. There will also be an applied mathematics sequence that advances student ability to deal with computer-based numerical methods, statistics, multivariate data visualization, image analysis, and geographic information systems. Many of these topics will draw on real data from the network and from student investigations.

In science, students will find support on the Net for increasingly sophisticated challenges. Many of these will require considerable background study which will be provided as needed through a rich set of modularized, just-in-time units which will be available. Opportunities for original work using networked telescopes, seismographs, scanning microscopes, and supercomputers will be commonplace. Students will contribute to and analyze global environmental datasets, polls, and other network science projects. Learners will collect their best work and evidence for skill mastery into portfolios that will be available on the network to teams of evaluators. These external evaluations will change the relation between students and their teachers who will increasingly be seen as allies and guides. These evaluated portfolios will become the primary evidence used in college admissions and job applications.

The kind of advances sketched above results in a kind of non-liner growth in educational payoff in technology, because investments in new material based on technology early in the curriculum yield returns at multiple points in later courses. Students not only learn more when the technology-rich content is first covered (a linear effect), but they then exploit this new knowledge to learn more later (a non-linear effect).

It is important to note that radical changes of the sort described above are largely untried. Several of the ideas are supported by research (for instance students can build dynamic models from spreadsheets at least as early as ninth grade) but no individual schools have undertaken such major revisions (Tinker, 1990). There are many reasons for the absence of significant case studies:

Risk. The fact that these more radical changes are untried makes them difficult to justify to parents and educators.

Scale. Such changes would need to be undertaken across an entire district and over many years.

Costs. The development of good curriculum is expensive, and this would require a great deal of new material.

Population shifts. Once in place, students transferring into and out of the system would be at a great disadvantage.

Staff knowledge. Teacher preparation at all levels is so thin in mathematics and science that few teachers are able to adopt more advanced content without substantial inservice support.

To overcome these problems, there needs to be funding, presumably at the Federal level, to explore and study the benefits of this kind of systemic change. “The nation, through its government, needs to undertake appropriate experimentation and evaluation to understand how to produce in education the ‘economies of scale’ and ‘economies of scope’ that technology has produced in the world of practice” (Sabelli, 1995).

SUMMARY

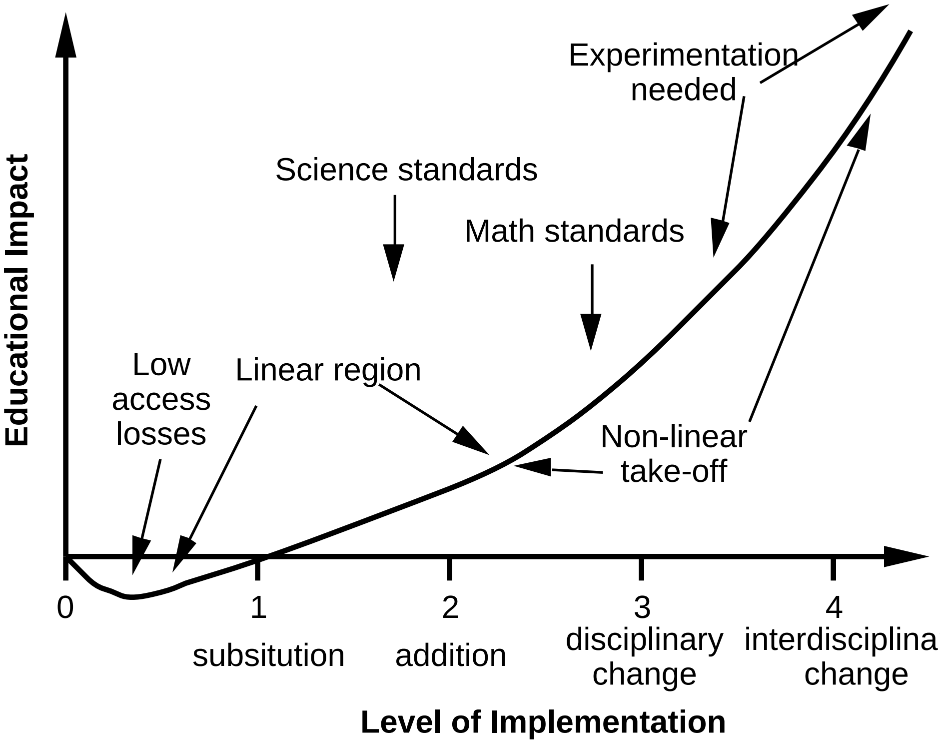

Figure 1: A summary of the possible impact of information technologies on learning in mathematics and science.

The qualitative graph in Figure 1 summarizes several important points concerning the impact of information technologies implementation on education. At low levels, it shows a net loss because students not familiar with the technology find it gets in the way. After this loss, increasing levels of substitution of better, technology-rich additions to the curriculum result in linear gains. The gains realized when the curriculum is changed through higher information technology use are shown as non-linear, because students not only learn the material taught with technology, but the improved curriculum lets them use the resulting knowledge to learn other new material as well. The science standards do not envision any disciplinary change due to information technologies whereas the math standards begin to realize some of the possible improvements within math of information technology use. Neither standard assumes information technology-supported changes will cross disciplinary lines. Experimentation is needed in this non-linear region where the greatest gains can be expected.

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[1] This paper is based in part on research of the Science Learning in Context project at the Concord Consortium funded by the National Science Foundation grant REC 9553639. Any opinions, findings, or recommendations expressed herein are those of the author and do not necessarily reflect the views of the Foundation.

[2] The author would like to thank George Collison for thoughtful suggestions and substantive additions to this article.

[3] For additional information on the Concord Consortium, see <http://www.concord.org> or write <info@concord.org>

[4] The term "information technology" is more accurate than the more common "technology" which can apply to any technology from arrowheads to Zambonnis. More importantly, using the modifier "information" provides a clue to what makes these technologies unique and important to education. The term "information technology" is, however, often inconveniently long, so the shorter "technology" will be used in its stead throughout this article.

[5] Paul Gagon, (1995) an official at the U.S. Department of Education feels that the national standards effort has been thwarted by academics unwilling to make hard choices.

[6] Perelman (1992) claims technology will support "hyperlearning," a form of learning that will so completely undermine schools that they will cease to exist. His critique of the current educational system and its low investment in research and development is important, but there is no evidence that any amount of research could greatly accelerate the learning process with or without technology. Nevertheless, his point that schools will have to improve in the face of competition from technology is valid. If courses can be offered on networks that are even as good as average instruction, all those schools falling below average will have to get better or their communities will turn to networked alternatives.

[7] Other good general references to the role of information technologies in science education include Ellis, 1989; Sheingold, Roberts, and Malcom, 1992; and Ruopp, 1993. The Ellis and AAAS books, although seven and four years old respectively, are thoughtful, forceful, and quite relevant. The Ruopp book is an excellent documentation on the use of information technologies to support student projects in physics teaching.

[8] This project engages students throughout the world in environmental research. For further information, see http://hub.terc.edu/terc/gl/global-lab.htm

[9] There are two important national standards for science, one from the American Association for the Advancement of Science (AAAS, 1993) and one from the National Research Council (NRC, 1995). The AAAS makes a very broad interpretation of science that includes mathematics, engineering, social studies, agriculture, and the history of science. Regardless of one's view of the importance of these fields, there are very few precollege teachers prepared to teach these topics. The AAAS standards document is also rather detailed, including an unrealistic one benchmark per hour of instruction in math and science K-12. The NRC standards are more general, fewer in number, and more focused on the traditional content of the quantitative sciences.

[10] The National Council of Teachers of Mathematics (NCTM) has published three standards documents: the Curriculum and Evaluation Standards for School Mathematics (1989) available at <http://www.enc.org/online/NCTM/280dtoc1.html>, The Professional Standards for Teaching Mathematics (1991) and The Assessment Standards (1995).

[11] Level 1 was ignored because the standards do not address how to teach, just what the outcomes of instruction should be. Thus, the question of where information technology might be used to do a better job in achieving an objective that is part of the standard is an instructional issue outside the scope of the standards.

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[12] This could account for the lack mixed successes that have been reported for initial implementations of computers. (Henry Becker, personal communication.)

[13] While not mentioning dynamic modeling specifically, both the NRC and AAAS call for applying mathematics to understand science, one possible definition of modeling. “Much of the work of mathematicians involves a modeling cycle which involves..” abstracting, calculation, and checking the match between prediction and reality. (AAAS, p 38)

[14] Model-it is a qualitative modeling package that helps get at the basics while minimizing the details. See http://krusty.eecs.umich.edu/highc/projects/sw/model/modelit.html

[15] Stella has grown out of the work of Jay Forrester at the System Dynamics Lab at MIT; see http://sysdyn.mit.edu/ For information from the software vendor, see http://www.hps-inc.com/.

[16] For an excellent set of spreadsheet referenes and pointers, see http://www.smc.univie.ac.at/~neuwirth/spreaded/spreaded.html An archive of spreadsheets is starting at http://192.239.146.18/SS/Spreadsheets.html. A short introduction to using spreadsheets is online at http://forum.swarthmore.edu/sum95/math_and/spreadsheets/intro.html A listserver devoted to using spreadsheets can be joined by sending email to listserv@miamiu.acs.muohio.edu with the single word “help” in the body of the message.

[17] The importance of communication in science is discussed in the NRC standard on p. 175-6 and in the AAAS on pp. 295-7.

[18] That is, computers based on an Intel microprocessor running one of the Microsoft Windows operating systems.

[19] See http://www.claris.com/Products/ClarisWorks/Index.html or call (800) 544-8554, extension 311.

[20] See http://www.microsoft.com/works/

[21] See http://www.microsoft.com/msoffice/msexcel/prodinfo/index.map?79,75

[22] Alice development was spearheaded by the author at TERC starting with funding from the U.S. Department of Education Star Schools project in 1988. The National Science Foundation has funded Alice through several grants of which the author was a principal investigator.

[23] The terms “probeware,” “computer as a lab partner,” “CLP,” and “lab interfacing” have also been applied to this approach. Now that calculators can be used to gather data, Texas Instruments has created the term Calculator Based Labs (CBL) as an obvious extension of MBL.

[24] A good overview to MBL techniques and related research is contained in Tinker, 1996.

[25] Ron Thornton has shown this quite convincingly for mechanics; see Thornton, 1996.

[26] See for instance, http://ac4.jjc.cc.il.us/tyc/tyc.html

[27] Vernier Software was started by a physics teacher and has stayed close to its roots while offering a broad line of interfaces, software, materials and the CBL system that uses the TI-82 computer. http://www.teleport.com/~vernier/ or call 503-297-5317. LOGAL has an excellent set of MBL hardware. See http://server.logal.com/home.html. Sunburst has an MBL package called Whales and their Environment developed as part of the Voyage of the Mimi. See http://www.nysunburst.com/ or call 1-800-321-7511. Tel-Atomic has Kis and Champ II interfaces with lots of probes. 1-800-622-2866. Pulse Metric has a cardiovascular monitoring package. 1-800-92-PULSE. Quantum Technology has a “LEAP” interface and materials coordinated with BSCS Biology. 1-303-674-9651. The Accu-Labs Products Group has a system they call SensorNet with a range of probes. Call 1-209-522-8874. TERC teamed up with IBM to generate the Personal Science Lab (PSL) interface with lots of probes and teaching units now available through Team Labs at 1-800-PSL-HELP. PASCO has an excellent physics-oriented interface with lots probes. Call 1-800-772-7800.

[28] Tabletop was developed by Chris Hancock at Harvard and TERC. Tabletop Junior is a simplified version developed with funding from Brøderbund. Both programs are available form Brøderbund. See

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http://www.broder.com:80/education/programs/science/tabletop/ or call 1-800-521-6263

[29] The Statistics Workshop from Sunburst. See http://www.nysunburst.com/ or call 1-800-321-7511.

[30] This software is available by anonymous ftp at zippy.nimh.nih.gov/pub/nih-image

[31] Contact LuAnn Dahlman (Dahlman@aol.com) for information about the Center. They have produced and are producing CDs that contain images, ideas, software, and information concerning the application of image analysis in various fields. Their CDs are distributed at their workshops and from Tom Synder Productions (call 800-342-0236). Only physics is currently available through TSP (as Hands on Image Processing Physics or HIP Physics), but biology and others are planned.

[32] Included in HIP Physics (see prevsious footnote).

[33] CamMotion is one such software package under development at TERC. See http://hub.terc.edu/terc/view/view_homepage.html Similar software is available from Learning in Motion Inc. called Measurement in Motion; see http://www.learn.motion.com/lim/mim/mim1 or call 800/560-5670

[34] http://www.doonesbury.com and scottadams@aol.com (Dilbert)

[35] The Princeton Earth Physics Project at http://lasker.princeton.edu/pepp.shtml

[36] http://www.census.gov

[37] http://bigmac.civil.mtu.edu/public_html/classes/ce459/projects/t19/intro.html

[38] http://hub.terc.edu/terc/gl/LICHENS/LICHEN-13.html

[39] http://nssdc.gsfc.nasa.gov/planetary/comet.html The NASA web page that includes photos of the Shoemaker-Levy 9 collision with Jupiter has attracted over 5.3 million visits!

[40] http://fnnews.fnal.gov/top95/top_news_release.html

[41] For more information about courses for teachers on the net see http://www.concord.org Canada has a major program described at http://fas.sfu.ca/telelearn/overview.html An outstanding NSF project for science teachers is described at http://www.montana.edu/~wwwxs/index.html#Topics

[42] There are a number of important projects that involved students in world-wide environmental research including GLOBE (http://globe.fsl.noaa.gov/), the Global Lab (http://www.hub.terc.edu/terc/gl/global-lab.html), the NGS Kids Network (call (202) 775-6701 and look at http://www.nationalgeographic.com:80/ngs/geo_ed/geoed29.html), the Global Schoolhouse (http://www.gsn.org/), and Kids as Global Scientists (http://www-kgs.colorado.edu/).

[43] Netscape can be obtained at http://home.netscape.com/

[44] This is not quite true, because you can submit information that a remote computer uses to generate a Web page on the fly. This is used, for instance, in computing Mandlebrot sets of arbitrary location and magnification.

[45] Contact Lego Dacta Lego Systems Inc. 655 Taylor Road P.O. Box 1600 Enfield, CT 06083-1600 (800) 527-8339 For examples of student work with Lego Logo, http://bear.blake.pvt.k12.mn.us/campus/projects/lower/lego/index.html and http://lisa.ee.nd.edu/~lego/

[46] For a discussion group on Logo, see http://www.gsn.org/archives/logo-l/

[47] Geometric Supposer, the Geometer's Sketchpad, and Cabri. These are discussed at http://forum.swarthmore.edu/dynamic.html The Geometer's Sketchpad is available from Key Curriculum Press (1-800-338-7638) http://www.keypress.com/product_info/sketchpad3.html

[48] The product is called Interactive Physics II. Look at http://204.247.119.2/ipinfo.htm or call 800 766-6615

[49] This research is accessible at http://www.clp.berkeley.edu/CLP.html#top

[50] The Voyages are available through Sunburst. See http://www.nysunburst.com/ or call 1-800-321-

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7511.

[51] Six elementary-level modules are currently available from the NGS. Additional middle-grade modules are currently being readied for publication. See footnote 42 for further information.

[52] The U. S. Department of Education provided the initial funding of the Voyages and the National Science Foundation funded the Kids Network; significant additional funding and in-kind materials and services came from the NGS, Apple Computer, and many other sources.