The Potential of Technologies For the Enhancement of Science and Mathematics Teaching and Learning

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Introduction

The integration of modern information and communication technologies (ICTs) into the teaching/learning process of science and mathematics has great potential. In fact, it could be the only way by which countries can meet their educational aspirations within reasonable time and resources. Although the focus of the document is on technology, the emphasis on the word "potential" reflects our understanding that technologies are tools, and their effectiveness depends on how they are employed.

Technologies allow materials to be presented in multiple media, enhance critical thinking and other higher levels of cognitive skills and processes, and provide for access to worldwide information resources. They also may be the most cost-effective (and in some cases the only) means for bringing the world into the classroom and performing simulations of science lab experiments using real data and model processes. More specifically, technologies have unique advantages in the following areas:

1 Motivating Students

The famous astronomer Carl Sagan used to say that all children start out as scientists, full of curiosity and questions about the world, but schools eventually destroy their curiosity. The first and probably most challenging task in an effective teaching/learning process is to motivate students to learn. For math and science teachers, this task can be even more daunting, since their subjects are highly abstract, complex, and appear disconnected from the students' reality. New pedagogic methods indicate that students are motivated when the learning activities are authentic, challenging, multidisciplinary and multisensorial. Authentic activities have a close relationship to the "real world," that is, to the students' surroundings. They build on experiences that are meaningful to the students and challenge their view of the world and their curiosity. Being authentic, these learning activities help to break the walls between different types of learning: language, arts, mathematics or science. Through the use of real-life stimuli, they cater to different types of learners - visual, auditory, sensorial, and psychomotor.

Videos, television, and computer multimedia software can be excellent instructional aides to engage students in the learning process. These technologies can provide students with examples of real-life situations where specific knowledge is required. In addition, sound, color and movements stimulate the students' sensorial apparatus and bring a sense of enjoyment to the learning process. For instance, to introduce a lesson on properties of ideal gases, the Brazilian ***Telecurso*** project prepared a video about the use of bottled gas for cooking – the most common kitchen fuel in the country.[1]

Technology can also expand students' reality. Through the use of videos and video clips, students can be present at events that they would never be able to attend. For instance, they can observe an Olympic competition as an introduction to the study of acceleration, or virtually climb the Everest to study the effect of altitude on blood cells. The technology also makes available to them findings obtained through the use of powerful scientific instruments that schools will never be able to afford. Through a video, or images on the Internet, students can examine changes in a cell membrane, as if they were looking through a potent electronic microscope, or study the planets through the lens of the most powerful telescope.

[1] For information on ***Telecurso***, see Castro (1999).

2 Introducing and Demonstrating a Concept or a Topic

An important challenge faced by mathematics and science teachers is the abstract nature of the subject they teach. It addition, many concepts go against immediate intuition and folk knowledge. Students arrive at school with established views of the world. Their misconceptions about how the universe works may not be apparent, but strongly influence the type of information that will be absorbed and how it will be absorbed. Therefore, to introduce the students to scientific concepts, the teachers must provide them with a variety of contexts and engage them in reconstructing their worldview.

Research suggests that the acquisition of scientific and mathematical concepts is similar to the acquisition of a new language. When confronted with verbal or written material that has unfamiliar vocabulary, most people tend to shy away or openly reject the material. A similar reaction occurs when students are confronted with strange concepts and symbols. Images (text, graphics, icons, etc) have the ability to decode the unfamiliar language into known representations, thus making the material more enjoyable and easier to apprehend.

Good-quality videos and multimedia software present a mix of text, images, sounds and movements. A teacher explaining the concept of acceleration can utilize a computer animation to help students visualize the behavior of an object in free fall. A motion detector connected to a computer (or simulated in the program) proves to the students that there is a pattern in the fall and that the object is accelerating at a constant rate – an observation that is not immediately apparent. Graphics and charts offer different representations of the object's behavior during the fall to reinforce the initial observation. This strategy places the abstract concept in a context familiar to the students, and circumvents initial misperceptions. How different would have been Galileo's fate if he could have shown to his prosecutors satellite images of the movement of planets around the sun!

3 Learning the Basics

Learning everything through individual inquiry and exploration takes more than a lifetime to achieve. Structured and organized disciplines of knowledge provide shortcuts. Moreover, scientists and mathematicians never start from scratch; they build on what others have constructed. Pedagogically, non-structured learning environments, based solely on open-ended investigation, can be confusing to some students, who require more structure and organization. For these reasons, there is a place for efficient learning of basic knowledge and skills. Also, drill and practice may be necessary strategies for retention and recall. Computer-aided instruction (CAI) utilizes three important characteristics of technology: speed, memory power, and the capability to repeat tasks without reducing performance. These programs offer students the opportunity to practice basic skills on their own time and pace.

CAI functions as automated tutors, presenting a hierarchic level of concepts and skills that the students need to master before they are allowed to proceed to the next level. Generally, the material is divided into modules of increasing difficulty. Students are evaluated at the end of each module, receiving an immediate feedback. If they respond correctly a determined percentage of questions, they can move to a more advanced module. Otherwise, they may either repeat the module, or enter remedial modules, until they have mastered the skill. Some programs integrate computer and textbook instruction. One of CAI advantages is to give students control over their learning.

Students who are struggling with a specific topic can practice the lesson as long as they need without the pressure of their more advanced peers. The program can keep a history of the students' performance: the lessons they have mastered, within how many attempts, the topics where they had more/less difficulty, etc. With this history, the teacher can design an individualized plan to help students attain their educational goals.

CAI was introduced for educational purposes more than fifty years ago, mostly for the teaching of basic mathematics skills. Currently, CAI is being used for different subject matters, including foreign language teaching. The Cognitive Tutor (www.carnegielearning.com), developed by Carnegie Mellon University, focuses on problem solving activities, rather than simple drill practices. The program integrates individual and group assignments and maintains a record of students' progress. Typically, students spend two days a week working with the computer, and three days working on small-group activities. At the secondary level, the Cognitive Tutor includes courses in Geometry, Algebra I and Algebra II.

Research shows that students using CAI learn faster and retention can be increased by 50 percent. These students are also more likely to complete their courses. The use of CAI for military training has shown to cut the training period by one third. CAI has been proven to be less costly than other measures that aim to improve student achievement, such as individual tutors and extra class time. Carnegie Mellon touts significant improvements in college admission tests and the Third International Mathematics and Science (TIMSS) tests by students using their Cognitive Tutor.

4 Applying the Knowledge

Understanding concepts and mastering basic skills are only part of the process. Students must be able to utilize the information acquired to solve problems, formulate new problems, and explain the world around them. Computer applications have the potential to store massive amounts of data, plot curves, conduct statistical tests, simulate real-life experiments, build mathematical models, and produce reports – all this with speed and accuracy. Computers also save classroom time. While computers are doing repetitive tasks and long calculations, teachers and students can concentrate their time on analytical activities that require higher order thinking skills.

In a chemistry class on acids and bases, students can use simple spreadsheets to store a series of pH measurements for posterior analysis. Spreadsheets, different from paper-pencil process, can store large amounts of data and provide immediate visualization as tables, charts and graphics. This fast response favors the visualization of errors and new lines worthy of inquiry. Datalogging is a type of software that enables the use of actual sensors and probes connected to the computer. Rather than feeding the information manually to the computer, the sensor directly uploads the measurement, thus reducing the margin of error, and reproducing a situation that is closer to an actual experiment.

ICT has also the potential to link what is learned in the classroom to contexts that are familiar to the students. Through videos and video clips, students can see scientists working in environments to which they cannot have access, such as nuclear plants. This strategy helps students to visualize how the concepts learned are employed in real-life situations. Computer simulations go a step further and enable teachers and students to virtually reproduce the scientists' work.

Computer simulations go a step further and enable teachers and students to virtually reproduce the scientists' work. Students can follow the menu of experiments in the software or create their own. They can also repeat the experiments as many times as necessary until the skills are mastered. Simulations mimic real-life experiments so that students can understand the challenges of doing science - without the risks attached to it. In addition, simulations may enhance a student's curiosity about a phenomenon or may challenge students' misconceptions, a process that has been proven successful in science teaching. For instance, before a class on respiratory systems, students can use simulations to test their ideas on gas exchange in the lungs. The teacher can use the results of their experiments to highlight discrepancies between students' beliefs and actual reactions of the organism in response to changes, such as feedback, bypass, etc (Hargrave & Kenton, 2000; Linn, Slotta & Baumgartner, 2000). Since no material is used or destroyed during virtual experiments, these programs offer a cost-effective tool for science education. Situations where computer simulations are particularly helpful for learning science include the following (Rodrigues, 1997):

- Experiments are too risky, expensive or time consuming to be conducted in a school laboratory, such as those involving volatile gases;
- "Tidy" experiments that require precision so that students can see patterns and trends; students may not be able to achieve the necessary precision without simulation tools;
- Experiments that break the laws of nature, such as exploring kinematics collisions that violate conservation of momentum law;
- When ethical issues are at stake, such as in the case of some biology experiments;
- Instrumental data capturing and display; and
- Mathematical modeling, where students alter existing laws.

5 Inquiry and Exploration

Inquiry and exploration are at the core of scientific work. The major skill of a scientist is the ability to ask good questions and develop appropriate strategies to pursue the answers. The inquiry process is a source of affective and intellectual enjoyment and a main reason that many are drawn to science. This sense of adventure is taken away in a traditional classroom, where questions and answers are established a priori and are unrelated to students' interests, and where research is reduced to a word in the textbook. The problem for many educators is that "doing science" requires resources that are unavailable in traditional classrooms, such as large databases and well-equipped laboratories.

ICT have the potential to let students explore the world in cost effective and safe ways. Videos and computer animations can bring movement to static textbook lessons. As described before, spreadsheets can store and analyze data, while computer simulations enable vicarious experiences in safe environments. Using these tools, students can initiate their own inquiry process, develop hypotheses and test them. In a virtual reality setting, students can manipulate parameters, contexts and environments, and can try different scenarios. In the process, they learn science and about science, that is, they learn the content but also the reasoning behind the content and the methods utilized to reach scientific conclusions. Most of all, they have the opportunity to move from a role of passive receptors of information to builders of knowledge.

The Internet is an even more powerful teaching tool than videos and software, because it provides access to real databases and connections with large learning communities. Exploring the Internet can be a fun and enriching experience, or a waste of time. Teachers have a major role as guides and facilitators. They need to provide some background material and guidelines before the students start the search. They also need to monitor the process, since research shows that students tend to browse the web, rather than follow structured search plans. The teacher is also instrumental in helping students to make sense of the large amount of information they may find, and weed unreliable from reliable sources (Kuechler, 1999; Sivin-Kachala, Bialo & Rosso, 2000).

The Internet has a vast potential to offer teacher and students opportunities for real-life scientific exploration. For instance, middle school students on the western coast of the United States study linear and exponential patterns of growth by experimenting with population simulation programs that are stored in an eastern coast university 3,000 miles away. Based on their findings, the students prepare reports for state and foreign governments on how the expected population changes may impact demand for public services. In the process, the students learn science and public policy. Most of all, they become scientists (The Benton Foundation, 1999).

The Internet provides access to real databases and connections with large learning communities, thus becoming a powerful source of inquiry and exploration. For instance, the National Center for Health Statistics web page (http://www.cdc.gov/nchswww) has information on numbers of births and deaths in the United States. The National Geophysical Data Center (http://www.ngdc.noaa.gov) and the National Oceanic and Atmospheric Administration (http://www.noaa.gov) have data on tides, planetary orbits, and average monthly temperatures. The information is presented numerically and graphically and is continuously updated. Students can use the information to understand concepts of percentage variation, slope, functions, sine curves, correlation, and more.

The WISE Project is an example of the Internet potential to enrich well-planned science activities (http://wise.berkeley.edu/). WISE is a free online learning environment where students examine real world evidence and analyze current scientific controversies. Projects are designed to meet standards and complement current science curriculum. Students can work on exciting inquiry topics such as global climate change, population genetics, hybrid cars, and recycling. They learn about and respond to contemporary scientific controversies through designing, debating and critiquing solutions.

6 Beyond the Classroom Walls

Science and mathematics are universal disciplines of knowledge that have no national barriers and can be applied to all areas of life. However, the limited resources of traditional classrooms create a false impression that the fields of science and mathematics are self-contained and have little relationship with life outside school. Moreover, science and mathematics teaching tends to be theoretical and "bookish".

ICT has the potential to expand the walls of the classroom so that students may experience science and mathematics "in the field." Videos, free-standing or broadcast, provide exciting opportunities to learn about plants, animals and habitats from all over the world - and these are available in abundance. Moreover, students can take virtual field trips to deserts, zoos, and rain forests, as well as to outer space. Even if their schools do not have a telescope, the students can explore the space through NASA web page (http://www.nasa.gov).

Videos and online virtual exhibits enable students in rural schools anywhere in the world to have guided tours of museums located in large cities that they would never visited otherwise. Moreover, the Internet now provides any connected school with the opportunity to visit the most sophisticated interactive science and technology museums without leaving the building. Examples are the Yokohama Science Center (www.city.yokohama.jp/yhspot/ysc/ysc/e-menu.html) in Japan, and the Exploratorium (www.exploratorium.edu) in San Francisco, California.

ICT restores the universal meaning and purpose of science and mathematics, and helps students in remote schools of developing nations to live experiences similar to those lived by their peers in more developed nations. The *Global Learning and Observations to Benefit the Environment* (GLOBE) (http://www.globe.gov) is an international network that offers teachers and students an Internet-based collaborative learning environment through which they communicate with experienced scientists and help in their research. It involves Kindergarten to high school students, teachers and scientists interested in earth science. GLOBE focuses mostly on mapping and understanding patterns and changes in three major areas: atmosphere/climate, hydrology/water chemistry, and land cover/biology. The project, launched on Earth Day 1994, is administered by an interagency partnership that includes some of the most renowned scientific organizations in the United States, including the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the National Science Foundation (NSF).

The project has three main objectives: improve mathematics and science education across the globe, raise environmental awareness, and contribute to a worldwide scientific database about Earth. To attain these objectives, GLOBE scientists help teachers and students develop projects such as measurements of pH in the water, analyses of temperature readings to observe changing patterns, etc. GLOBE can be implemented in different ways: as part of a science class, a separate class, a club, a lunch group, etc. In Kindergarten and grades 1-3, GLOBE teachers work in a project with 10 or fewer students, but as the children advance, the groups can be much larger. The students conduct measurements and analyze the data that are then sent to be stored in a central database. Scientists utilize the data for their research. Data and findings are available to all participants in numeric and graphic representation, and ongoing communication between schools and scientists is maintained. To ensure that the data collected is compatible, participant schools must use the same software and measurement tools and must obey the project's scientific protocol. Approximately 9,500 schools in more than 90 countries participate in GLOBE, including schools in Benin, Burkina Faso, Cameroon, Chad, Gambia, Ghana, Kenya, Mali, Namibia, Senegal, South Africa and Uganda.

An evaluation of GLOBE shows that participating students perform better than their peers in activities that require understanding of science, including ability to interpret data and apply science concepts. They also showed a greater appreciation of science. The project also instills in the students pride for their work, which is taken seriously by scientists and community members. For instance, GLOBE students in a North-American school were asked by the local fire company to examine the reason for a foul smell in their station. The students' pH measurements of the local water supply helped government scientists to find a gas tank leak in the vicinity. The gas was infiltrating the soil and causing health problems. The students' participation was instrumental to solve the problem, and was the best possible lesson on the pragmatic importance of science.

7 Creating Collaborative Environments

Scientific work has always been dependent on communication. The scientific community has been quite creative in maintaining open channels where they can discuss different perspectives on a common topic, obtain information, work on similar or complementary projects, replicate experiments, and share breakthroughs. It is not surprising that e-mail was the product of a scientist's need to communicate with colleagues. The modern workplace, having destroyed the production line, is a collaborative environment, where workers must share knowledge and cooperate to accomplish a common goal. This reality deeply contrasts with traditional classroom organizations, where students tend to work in isolation through tasks that boost competition, rather than cooperation. Students leave the school not used to share ideas, divide tasks and collaborate.

Information and communication technologies, as the name indicates, expand the power of individuals and communities to acquire and exchange information. In addition, ICTs provide the tools for communication even among geographically distant partners. Fax, one-way interactive video and e-mail enable fast and asynchronous contact and exchange of information. Videoconferencing and Internet-based chat rooms ensure conversations regardless of distance. The Computer Supported Intentional Learning Environment (CSILE) (http://csile.oise.utoronto.ca) is an Internet-based collaborative environment that offers a shared database for students who want to place a question or raise a hypothesis. Other project participants access this information and make comments and suggestions. The system notifies the author when comments are received. The author can use the comments to refine ideas, research responses and advance the inquiry. The process motivates students' curiosity, and learning becomes an adventure worthy of pursuit. It also gives the students the confidence that science is not a mystery too complex for them to understand.

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