

Emerging Influences of Information Technology on School Curriculum

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Abstract

Just as information technology has improved effectiveness in medicine, finance, manufacturing, and numerous other sectors of society, advanced computing and telecommunications have the potential to help students master complex 21st century skills. Research-based curriculum projects are developing technologies that enable online virtual communities of practice using advanced tools to solve real world problems. Learners engage in guided, reflective inquiry through extended projects that inculcate sophisticated concepts and skills and generate complex products. Pupils act as partners in developing learning experiences and generating knowledge, and students' collaborative construction of meaning is enhanced via different perspectives on shared experiences. Simulation and visualisation tools help students recognise patterns, reason qualitatively about physical processes, translate among frames of reference, and envision dynamic models. These curricular approaches improve success for all types of learners and may differentially enhance the performance of at-risk students.

Introduction

In developed countries, sophisticated computers and telecommunications are on the verge of reshaping the mission, objectives, content, and processes of schooling. This is part of a larger change in those nations from loosely coupled, mature industrial economies to a profoundly interconnected, knowledge-based global marketplace (Dertouzos & Gates 1998). Driven by advances in information technology, this economic evolution is the largest leap from yesterday's workplace to tomorrow's in the last two centuries, since the dawn of the industrial revolution (Thurow 1999). In response, all forms of societal institutions are altering slowly, but radically—even schools. Since one of education's goals is to prepare students for work and citizenship, schools are attempting to change their policies, practices, and curriculum to meet the challenge of making pupils ready for a future quite different than the immediate past (Tucker & Codding 1998).

The issue is not simply aiding more students to reach a higher standard of achievement in today's curriculum (e.g. having all pupils take algebra rather than some, or raising everyone's scores on standardised tests by fifty points). While these goals are desirable, such improvements in traditional educational outcomes are inadequate to prepare pupils for 21st century civilisation (Dede 1998a). Students also need to master

higher-order cognitive, affective, and social skills not central to mature industrial societies, but vital in a knowledge based economy (Drucker 1994). These include 'thriving on chaos' (making rapid decisions based on incomplete information to resolve novel situations); the ability to collaborate with a diverse team—face-to-face or across distance—to accomplish a task; and creating, sharing, and mastering knowledge through filtering a sea of quasi-accurate information (Peters 1997).

Just as information technology has improved effectiveness in medicine, finance, manufacturing, and numerous other sectors of society, advanced computing and telecommunications have the potential to help students master these complex 21st century skills (President's Committee of Advisors in Science and Technology 1997). However, technology is not a 'vitamin' whose mere presence in schools catalyses better educational outcomes; nor are new media just another subject in the curriculum, suited primarily for teaching technical literacy with business applications students may encounter as adults. Instead, emerging interactive media are tools in service of richer curricula, enhanced pedagogies, more effective organisational structures, stronger links between schools and society, and the empowerment of disenfranchised learners (Trotter 1998).

Sophisticated computers and telecommunications have unique capabilities for enhancing learning. These include:

- centring the curriculum on 'authentic' problems parallel to those adults face in real-world settings (Cognition and Technology Group at Vanderbilt 1997)
- involving students in virtual communities-of-practice, using advanced tools similar to those in today's high-tech workplaces (Linn 1997)
- facilitating guided, reflective inquiry through extended projects that inculcate sophisticated concepts and skills and generate complex products (Schank, Fano, Bell, & Jona 1994).
- utilising modeling and visualisation as powerful means of bridging between experience and abstraction (Gordin & Pea 1995)
- enhancing students' collaborative construction of meaning via different perspectives on shared experiences (Chan, Burtis, & Bereiter 1997)
- including pupils as partners in developing learning experiences and generating knowledge (Scardamalia & Bereiter 1994)
- fostering success for all students through special measures to aid the disabled and the disenfranchised (Behrmann 1998)

However, realising these capabilities requires a complex implementation process that includes sustained, large-scale, simultaneous innovations in curriculum; pedagogy; assessment; professional development; administration; organisational structures;

strategies for equity; and partnerships for learning among schools, businesses, homes, and community settings (Dede 1998b).

Too often, discussions of technology by pundits in education centre on comparisons to standard approaches for teaching conventional content (Tyack & Cuban 1997). However, the issue is not whether instructional tools are more efficient at accomplishing current goals with conventional methods, but instead how emerging media can provide an effective means of reaching essential educational objectives in the technology-driven evolution of a knowledge-based economy. Just as medical practice has shifted dramatically because of antibiotics, anesthetics, and immunisations, so the skills and knowledge required of educators are rapidly changing. Computers and telecommunications enable all students to master more complex subjects via rich interactions with resources outside of classroom walls just as geographically distributed workers create, share, and master knowledge. This article does not include applications that automate the presentation of conventional curricular content, but instead focuses on exemplary projects that illustrate the potential of computers and telecommunications to convey higher-order skills and knowledge.

Knowledge Networking: Involving Learners in Virtual Communities of Practice

In the United States, its National Science Foundation (NSF) has instituted a new multidisciplinary funding program to examine the potential of emerging information technologies in fostering 'Knowledge and Distributed Intelligence' (KDI). This initiative [<http://www.ehr.nsf.gov/kdi/default.htm>] was prompted by fundamental shifts that sophisticated computers and telecommunications are creating in the process of science (Dede 1999). Scientists are moving away from investigative strategies based on reading others' research results in journal publications as a means of informing and guiding one's own scholarship. Instead, many scientists are engaged in online virtual communities for creating, sharing, and mastering knowledge: exchanging real-time data, deliberating alternative interpretations of that information, using collaboration tools to discuss the meaning of findings, and collectively evolving new conceptual frameworks.

NSF calls this process 'knowledge networking' and is funding a series of KDI investigations to study these online virtual communities of practice both in the context of science and as a generalisable process that could enhance many forms of reflective human activity. Also, through knowledge networking, an 'emergent intelligence' appears in which the virtual community develops a communal memory and wisdom that surpasses the individual contributions of each participant¹.

Project SCOPE (Science Controversies Online: Partnerships in Education) at the University of California-Berkeley promotes knowledge networking among scientists and

learners exploring current scientific controversies that connect to citizens' interests (such as the reasons deformations are appearing in frogs across many regions of the world). The project's research combines expertise in natural science, pedagogy, technology, and classroom instruction from the University of California-Berkeley, the University of Washington, and the American Association for the Advancement of Science's *Science* magazine [<http://scope.educ.washington.edu/>]. Both national and international partners are involved in the distributed learning experiences (Linn, Shear, Bell, & Slotta 1999).

Using sophisticated telecommunications, knowledge networking in online virtual communities of practice using advanced tools to solve real world problems is practical and sustainable for many curricular topics. Learners engage in guided, reflective inquiry through extended projects that inculcate sophisticated concepts and skills and generate complex products. Pupils act as partners in developing learning experiences and generating knowledge, and their collaborative construction of meaning is enhanced via different perspectives on shared experiences. Two illustrations of such technology-based learning environments are described below using science curricula funded by the U.S. National Science Foundation. (The curricular examples that follow centre on domains in science and mathematics not because these fields are uniquely suited to educational technologies, but because large-scale funding for developing sophisticated learning tools has focused on technical areas rather than the social sciences, history, literature, and the arts. Ways are discussed to generalise the tools described for knowledge networking in science and mathematics to these other curricular domains.)

With NSF funding, the Centre for Highly-Interactive Computing in Education at the University of Michigan developed a suite of tools and a curriculum, ScienceWare, to support students as they investigate water quality issues in their community and link those data to national scientific investigations (Jackson, Stratford, Krajcik, & Soloway 1996). ScienceWare has tools that support all phases of the students' investigation: data gathering (RiverBank); data visualisation (Viz-It); modeling (Model-It); project planning for students (PlanIt-Out); publishing findings on the Internet (Web-It); and project planning for teachers (PIViT). Of these, the Model-It tool best illustrates the unique contributions technology can make to learning and the ways a tool can generalise across a wide variety of curricular subjects.

[insert figure 1 about here]

Figure 1 depicts the World View, one of the two main representations provided by Model-It. In this example, the World View's background is an actual photo of Traver Creek, a stream behind a high school in Ann Arbor, Michigan at which a 9th grade science class explored the creek's water quality. The icons at the bottom of the window are objects that can be inserted into the World View (e.g. 'weather', a 'people' icon representing humans fertilising the park that borders on the stream). When it rains,

fertiliser from the park gets washed into the stream, changing its levels of nitrates, dissolved oxygen, water quality, etc.

[insert figure 2 about here]

To construct a model, students must create

- objects – “things” in the model, such as insects, streams, people;
- factors – variables related to the objects created; and
- relationships among objects’ factors.

In the Relationship Editor window, students build a relationship by constructing a sentence via selecting words from drop-down menus. For example, in figure 2 a student is building a relationship between the nitrates (a factor) in the stream (an object) and the stream’s water quality (a factor): ‘As Stream: Nitrates increase, the Stream: Water Quality increases, by more and more.’ Notice that the graph on the right-hand side is linked to the text expression, altering in response to any changes in the sentence. The graph can help students bridge qualitative and quantitative representations; Model-It’s underlying computational architecture uses differential equations to actualise the student’s qualitative, textually-expressed relationships.

Figure 1 also illustrates what students see as they run their model. Meters and graphs provide rich visualisations of the dynamics of the model. In addition, an independent variable’s meter (in this case the Weather Rainfall factor) can be used to change the simulation during run-time.

[insert figure 3 about here]

In a detailed study, Stratford, Krajcik, and Soloway (1997) analysed final models from 50 students, as well as videotaped conversations and interviews with 8 pairs of those students as they built models of stream ecology. Fully 75% of the models analysed were scientifically meaningful. Students created models that were coherent, accurate and well behaved; their models made sense and were non-trivial. For example, figure 3 shows a model created by 2 ninth grade students. These models indicated that the students knew what they were doing and were able to express what they knew about stream ecosystem phenomena in the form of a dynamic model.

Modeling is an important skill that underlies many topics in the curriculum beyond science and mathematics. For example, social scientists, historians, and economists use models to understand dynamic changes in their fields’ phenomena. While the rules underlying these models may not be as precise and well understood as scientific equations, qualitative modeling tools developed for learners can help students understand alternative ways of explaining complexity in the ‘human sciences’ and can aid their participation in virtual communities of practice. Also, the ‘concept maps’

exemplified in figure 3 can facilitate representations of interrelationships in many curricular areas, as illustrated by Landow's teaching of English literature (Landow 1992).

Often integral to knowledge networking curriculum projects that link students and scientists are computer-mediated communication (CMC) tools that enable shared design and collaborative argumentation across time and distance. For example, the NSF-funded Learning Through Collaborative Visualization (CoVis) project developed computational tools to involve high school students in a virtual community of practice for meteorological phenomena (Edelson, Pea, & Gomez 1996). This curriculum development initiative provided a wideband high-speed computer network, desktop video conferencing capabilities, structured groupware for collaboratively developing and conducting scientific inquiries, and scientific visualisation tools that provided access to wide-ranging data sets on climate, weather, and other global parameters [<http://www.covis.nwu.edu>].

[insert figure 4 about here]

Covis's groupware tool supports scientific inquiry by enabling students to record, carry out, and discuss their project work with distant collaborators (see figure 4). The Collaboratory Notebook is essentially a text-based asynchronous computer conferencing system, although multimedia capabilities are incorporated for the display of attached pictures or other documents. In addition, the Notebook is a hypertext authoring tool, allowing users to link pages of text and images together into a coherent structure. Internet connectivity allows students to communicate with a potentially global audience; students can use these tools to support cooperative activities within their classroom or to supplement local activities through communication with distant mentors and peers. Collaborative design and shared critical reflections are fundamental to constructivist pedagogy in many fields. CMC capabilities can generalise to a wide variety of curricular areas, such as the extensive use of hypertext in collaborative writing and in teaching about the historical context of literary works (Landow 1992).

Is knowledge networking using advanced tools to solve real world problems limited to gifted and talented students in its benefits? On the contrary, technology-enhanced curricular approaches improve success for all types of learners and may differentially enhance the performance of at-risk students. For example, researchers have suggested that activities-oriented ('hands-on') methods and materials are likely to promote more science mastery for learning disabled students than the textbook-oriented instruction they typically receive (Mastropieri & Scruggs 1992, 1994, Patton 1993). Students with learning disabilities typically exhibit problems with reading fluency, text comprehension skills, vocabulary learning, and abstract reasoning from text presentations. Because of these characteristics, students with learning disabilities are unlikely to learn best in science — or any other subject — when classrooms are textbook oriented.

Activities-oriented materials typically place fewer demands on language and literacy abilities as well as verbal memory. Project-based instruction builds on real world situations to provide learning experiences and is engaging for at-risk students who are not accustomed to succeeding in school (Resnick & Rusk 1996). Such activities are associated with increased science achievement for girls (Burkam, Lee, & Smerdon 1997) and may aid and motivate all types of pupils who have doubts about their capability in science due to adverse cultural, ethnic, and environmental influences. Experiences with manipulatives also help learners who are not native speakers in the language of instruction or who are more comfortable with visual, auditory, or kinesthetic interactions rather than verbal or textual presentations. The types of technology-based learning experiences described above can foster these positive effects for all students. This is also true of the second major kind of technology-based curricular applications discussed below, interactive media for representation, modeling, and visualisation.

Using Multiple Representations, Modeling, and Visualisation to Enhance Learning

The ability to work with abstract and multidimensional information is a crucial skill (Salzman, Dede, & Loftin 1998). Increasingly, workers are required to navigate complex information to locate data, to identify patterns for problem solving, and to use sophisticated representations to communicate their ideas (Reiber 1994). In academic areas such as math, science, engineering, and statistics, students' success depends to a large extent upon their abilities to envision and manipulate abstract information (Gordin & Pea 1995). Participants in knowledge-based economies increasingly must grapple with important political, environmental, and social issues that can only be understood through the integration of and visualisation of multidimensional data.

Unfortunately, substantial research shows that visualisation is difficult for most people (McDermott 1991, West 1991, White 1993). Thus, techniques that can help people recognise patterns, reason qualitatively about physical processes, translate among frames of reference, and envision dynamic models are important (Lohse, Biolsi, Walker, & Rueter 1994). Below are described three projects funded by the U.S. National Science Foundation that use unique capabilities of advanced information technologies to develop learning experiences that help students master these crucial skills while also learning core curricular content.

The NSF-funded SimCalc project reconceptualises when and how calculus should be taught in the mathematics curriculum and has developed technology-based tools and physical manipulatives that enable middle school students to link qualitative and quantitative representations of change (Kaput & Roschelle 1997). In SimCalc, the underlying ideas of calculus (variable rates of changing quantities, the accumulation of

those quantities, connections between rates and accumulations, and approximations) are taught in the middle school as a precursor to algebra and are rooted in children's everyday experience, especially their kinesthetic experience. Computational media provide new notations, multiple representations, and actions upon these to make student-controllable simulations and the importing of physical data central to learning. A variety of tools and curricular activities are available at the project website [<http://www.simcalc.umassd.edu>]; a brief description of just one of these software applications is provided below.

In studying their own movement, students confront subtle relations among their kinesthetic sense of motion; interpretations of other objects' motions; and graphical, tabular and even algebraic notations. The SimCalc curriculum builds on students' own intuitive experiences with speed and motion by employing a technology through which graphical representations on a computer control physical devices. For example, Figures 5 and 6 illustrate how a sampled function from a motion sensor can drive an actor in a simulation - the "Froggie Dude" character at the right of the top image in figure 5. A student has created a motion physically by moving in front of the motion-sensor (figure 6), and this data has been uploaded to SimCalc's MathWorlds suite of representational tools and attached to Froggie Dude. Then, the student creates a series of 'Clown' characters and synthetic motions for each, using piecewise linear functions. In effect, the student is 'leading his own Clown Parade.' (Note that Figure 5 shows the parade in progress, so only the first part of the associated graphs is revealed.)

[insert figures 5 and 6 about here]

Curricular strategies and learning experiences such as these are not intended to eliminate the need for eventual use of formal notations for some students, and perhaps some formal notations for all students. Rather, SimCalc's purpose is to provide a substantial mathematical experience for the 90% of USA students who do not now have access to the mathematics of change and variation, as well as to supply a conceptual foundation for the approximately 10% who will need to learn more formal calculus. In addition, these instructional approaches lead into the mathematics of dynamical systems and its use in modeling nonlinear phenomena, a topic of importance for 21st century work and citizenship (Cohen & Stewart 1994).

Qualitatively understanding the mathematics of change and variation is important for many topics in the curriculum beyond algebra and calculus. As discussed earlier, the social sciences, economics, and history increasingly rely on dynamic models to understand complex phenomena. Interactive media that simultaneously present qualitative and quantitative representations are potentially useful in many fields for helping learners bridge between experience and abstraction.

Another NSF-funded curriculum development project centred on modeling and visualisation is GenScope, which provides a tool enabling students to investigate biological concepts through simulation and experimentation (Horwitz, Schwartz,

Kindfeld, Yessis, Hickey, Heidenberg, & Wolfe 1998). Using GenScope, students and teachers can manipulate the processes of genetic inheritance on six different, but interrelated levels of representation: DNA, chromosome, cell, organism, pedigree, and population. As a complement to text-based instruction, the computer allows students not only to read about genetics, but also to observe and manipulate processes at one biological level and observe the effects on multiple other levels.

In GenScope, students accomplish this analysis of biological interrelationships by studying an imaginary species of dragons. For instance, they can make an alteration at the chromosome level (figure 7) of a gene that codes for a specific trait (such as colour or the number of legs) and can then observe the effects of this alteration reflected at other levels. At the organism level (figure 8), they see how many legs each dragon has (four, two, or none). At the cell level (figure 9), they can initiate and observe meiosis. Which gametes have the dominant allele? Can they follow the allele through the process of crossover? What happens at the pedigree level (figure 10)? When a father who has no legs has babies with a mother who has two legs, what percentage of babies has two legs? four? none? At the DNA level (figure 11), students can see how the dominant and recessive alleles differ. Is one base pair affected or several? At the population level (figure 12), students can examine if a genetic trait confers differential survivability within an environmental context.

[insert figures 7 through 12 about here]

GenScope gives students the ability to create dynamic models for manipulating a number of dragon species characteristics, such as horns, wings, legs, colour, sex, and the ability to breath fire. Simplified models of other species (e.g. horse, human, dog) are also available; the project website is <http://genscope.concord.org>. The power of GenScope stems in part from interrelating phenomena that differ greatly in time scale (seconds to centuries) and physical scale (molecular to entire populations of organisms in an ecosystem). Its developers are now extending the tools underlying Genscope into a Bioscope curriculum that will cover a broader range of topics.

Similar activities could underlie comparable visualisation tools in other curriculum domains. As one illustration, economics deals with many situations in which micro-level events create macro-level outcomes, as does history. In the visual and performing arts, small-scale organising principles can invoke large-scale patterns in space and time not easily understood without representations that link levels of scale. To aid in understanding fields such as history, economics, and sociology, students could conduct investigative, analytic, expressive, and inventive activities with visualisations of demographic data. Also, comparisons of style in literature, linguistics, and the arts can utilise visualisations to exemplify similarities and differences. Interactive media such as GenScope aid learning by enabling two-dimensional visual comparisons; next generation technologies such as virtual reality carry this analytic strategy several steps farther.

As a third example of NSF-funded curricular applications involving modelling and visualisation, the author and his colleagues are exploring the potential of virtual reality to enhance learning complex scientific concepts [Dede, Salzman, & Loftin 1996]. Project ScienceSpace consists of two virtual worlds (NewtonWorld and MaxwellWorld) we have designed to assess the potential utility of physical immersion and multisensory perception to improve science education.

[insert figures 13 and 14 about here]

For example, one of our virtual reality learning environment, MaxwellWorld (MW), allows students to explore electrostatic forces and fields, learn about the concept of electric potential, and ‘discover’ the nature of electric flux. Using a virtual hand, students can place both positive and negative charges of various relative magnitudes into the world (figure 13). Once a charge configuration is established, learners can instantiate, observe, and interactively control model-based scientific representations of the force on a positive test charge, electric field lines, potentials, surfaces of equipotential, and lines of electric flux through surfaces. For example, a small, positive test charge can be attached to the tip of the virtual hand. A force meter associated with the charge then depicts both the magnitude and direction of the force of the test charge (and, hence, the electric field) at any point in the workspace. A series of test charges can be ‘dropped’ and used to visualise the nature of the electric field throughout a region. In our most recent version of MaxwellWorld, learners can also release a test charge and watch its dynamics as it moves through the fieldspace (figure 14), then ‘become’ the test charge and travel with it as it moves through the electric field.

How do these experiences of physical immersion and multisensory perception aid learning? By themselves becoming part of a phenomenon (e.g. a student becomes a point-mass undergoing collisions in an immersive virtual environment without gravity or friction), learners gain direct experiential intuitions about how the natural world operates. In particular, those aspects of virtual environments that are useful in understanding scientific principles become salient to learners' senses. For example, in two-dimensional Newtonian microworlds students often ignore objects' velocities, instead focusing on position. In our comparable immersive environment, NewtonWorld, learners ‘inside’ a moving object are themselves moving; this three-dimensional, personalised frame of reference centres attention on velocity as a variable. Our research studies on learning in MaxwellWorld document statistically and educationally significant learning gains in our virtual reality worlds over comparable experiences in two-dimensional, visual educational simulations. More detailed descriptions and research findings are available at the project website [<http://www.virtual.gmu.edu>].

Virtual reality research is important in part because information technology is developing powerful capabilities for creating shared virtual contexts. Within the next decade, via the videogame industry, devices capable of multisensory immersion will be

ubiquitous in rich and poor homes, urban and rural areas. To compete with the captivating, but mindless types of entertainment that will draw on this power, educators will need beautiful, fantastic, intriguing environments for learning. Project ScienceSpace is beginning to chart these frontiers for curriculum development, as well as revealing which parts of VR's promise for education are genuine, which parts are hype.

As discussed earlier, activities-oriented science is beneficial to students with learning disabilities, particularly in the elementary grades (Mastropieri & Scruggs 1992). However, as students move into secondary level science, reliance upon manipulative activities to enhance learning becomes more problematic, for several reasons:

- Some phenomena that are studied in secondary science classes (e.g. weightlessness) cannot easily be directly 'manipulated' in classroom activities.
- Some phenomena can neither be directly observed nor physically manipulated in classroom activities (e.g. quantum effects).
- Although static representations of abstract phenomena are often presented (e.g. textbook illustrations showing lines of electromagnetic force), students viewing these images lack the sense of active participation with these scientific phenomena that they may have achieved with foundational science activities.

Emerging interactive media that enable visualisation and simulation experiences with complex scientific phenomena provide all students, especially learning disabled and at-risk pupils, an increased opportunity for success.

Reasons of space preclude a discussion of additional research-based curriculum projects that provide intriguing ways of using technology:

- The Classroom Tool for Mathematical Investigations Using Digital Video (CamMotion) project supports the use of student-created digital video for classroom investigations. [http://teaparty.terc.edu/cam/cam_homepage.html]
- The Kids Interactive Design Studio project builds on young students' informal science knowledge and helps them to program (i.e. design) interactive multimedia resources to teach science concepts in either physics (magnetism/electricity) or life sciences (ocean habitats) to even younger pupils. [<http://www.gseis.ucla.edu/faculty/kafai/KafaiIntro.html>]
- The Epistemology and Learning group at the Massachusetts Institute of Technology Media Lab is creating 'smart' toys and interactive contexts that children can use to aid their thinking and understanding of science and mathematics. [<http://el.www.media.mit.edu/groups/el/elprojects.html>]
- MOOSE Crossing is a shared virtual environment in which students ages 13 and under can build digital architectural spaces, design and program interactive objects, and collaborate on learning activities. [<http://www.cc.gatech.edu/fac/Amy.Bruckman/moose-crossing/>]

- The Virtual High School is a nationwide collaboration of secondary schools that offer a unique collection of Internet-based courses [<http://vhs.concord.org/home.htm>]
All these illustrate various capabilities by which sophisticated computers and telecommunications can shape and enhance curricula.

Moving from Research-based Curriculum Development to Large Scale Implementation

Without extraordinary resources or heroic efforts, successfully implementing new educational approaches in typical classrooms has proven quite difficult. This is particularly true for technology-based innovations, in which the cost of computers and telecommunications, their rapid evolution, and the special knowledge and skills required of their users pose additional challenges in effective utilisation (Dede 1998b). Many research-based curriculum development projects foster a few isolated innovation sites, then disappear. Needed are clinical, applied studies on adapting exemplary innovations via reflective interplay between basic research and practice, a bi-directional process that helps both sides evolve toward increasingly sophisticated objectives. In such a relationship, implementation is not the blind adoption of recipes and materials for innovation developed by others, but instead the reflective adaptation of a process that enabled a similar group to succeed in improvements actualised somewhere else (Dede 1999).

Widespread implementation of technology-based curricular innovations cannot be accomplished via one-way transmission of best practices, but instead requires and is enhanced by reflective, interpretive dialogue in a knowledge-building community (Cohen 1996). As an illustration in the USA, Union City, New Jersey, is an example of a school district that has implemented a very effective series of educational reforms, reshaping its curriculum, pedagogy, assessments, technology usage, and links to the community [<http://www.union-city.k12.nj.us/>]. Information technology has played an important role in not only enabling new types of curriculum, but also aiding dissemination, adaptation, and community acceptance. Impacts on student learning are very positive and impressive, especially since this district has a weak tax base and many challenges associated with a diverse population. Other schools have much to learn from this district's successes, which have been studied in depth (Chang et al. 1998).

To accomplish such transfer of successful curricular strategies, a process of 'mutual adaptation' is necessary, in which external innovations are adapted to fit local conditions and local conditions are adapted to fit the innovations (McLaughlin 1990, Ball & Cohen 1996). But what distinguishes 'mutual adaptation' from what Brown & Campione (1996) have called 'lethal mutations' in evolved implementations? Why is it

and how it is that, in the process of adapting reform to local conditions, the spirit of reform is frequently lost and the result is practice as usual?

One important reason for this shortfall is that not enough dialogue to enable reflective adaptation takes place between those attempting to implement an exemplary practice and the original innovators. To explore a curriculum dissemination strategy that uses technology to foster such a dialogue, an NSF-funded Centre for Learning Technologies in Urban Schools has been recently created with four partners: the Detroit Public Schools, the Chicago Public Schools, the University of Michigan, and Northwestern University [<http://www.letus.nwu.edu>]. The focus of the Centre is on developing and implementing strategies for embedding learning technologies in the middle school science curriculum, building on the ScienceWare and CoVis curricula described earlier. These learning technologies provide the critical support students need to engage in the complex scientific inquiry central to new national and state curriculum standards. The collaboration of the four partners provides a unique opportunity to study how to support the scaling-up of technology integration into the curriculum of urban classrooms. The Centre is developing a 'Living Curriculum' collaborative relationship between developers and teachers, initially through face-to-face interaction, but increasingly through new interactive media and the formation of virtual communities for innovation. This evolution into knowledge networking is crucial for the widespread scaling-up of best practices.

To meet this challenge, conventional strategies for dissemination must evolve toward facilitating the adaptation rather than the adoption of reform-based innovations. Through empowering rich forms of knowledge networking and emergent intelligence that provide intellectual, emotional, and social support, new interactive media can greatly aid this process of adaptation. Parallel to exemplary practices with learning technologies in classrooms, the real power of these media comes not from automating information transmission, but from enabling students' collaborative, guided construction of meaning. Information technology is the only practical means we have of making such rich human experiences affordable and scaleable across the full population of educators.

Conclusion: Emerging Interactive Media as A Moving Target

The evolution of the Internet is fostering the continuing creation and proliferation of emerging interactive media, such as the WorldWide Web and shared virtual environments. A medium is in part a channel for conveying content; as the Internet increasingly pervades society, educators can readily reach extensive, remote resources and audiences on-demand, just-in-time. Just as important, however, a medium is a representational container enabling new types of messages (e.g. sometimes a picture is

worth a thousand words). Since expression and communication are based on representations such as language and imagery, the process of learning is enhanced by broadening the types of instructional messages students and teachers can exchange (Dede 1996).

Below is a list of devices, media, and virtual contexts enabled by sophisticated information technologies, along with the author's estimates of a conservative timeframe for their technological and economic feasibility.

<u>Functionality</u>	<u>Uses</u>	<u>Time Frame</u>
Hypermedia (nonlinear traversal of multimedia information)	Interlinking of diverse subject matter; easier conceptual exploration, multiple simultaneous representations for learning	Current
Cognitive audit trails (automatic recording of user actions)	Support for finding patterns of sub-optimal performance	Current
Computer-supported cooperative work (design, problem solving, decision support)	Facilitation of team task performance	Current
Intelligent tutors and coaches for restricted domains	Models of embedded expertise for greater individualization	Current
Optical-disc systems with multiple read/ write and mixed-media capabilities	Support of large databases; cheap secondary storage; shared distributed virtual environments	Current
Standardization of computer and telecommunications protocols	Easy connectivity, compatibility; lower costs	Current

User-specific, limited-vocabulary voice recognition	Restricted natural language input	Current
High quality voice synthesis	Auditory natural language output	Current
Sophisticated authoring and user interface management systems	Easier development of applications; reduced time for novices to master a program	Current
Widespread high-bandwidth fiber-optic networks	Massive real time data exchange	3-5 years
Fusion of computers, telecommunications	Easy interconnection; universal “information appliances”	3-5 years
Information “utilities” (synthesis of media, databases, and communications)	Access to integrated sources of data and tools for assimilation	3-5 years
Microworlds (limited, alternate realities with user control over rules)	Experience in applying theoretical information in practical situations	3-5 years
Semi-intelligent computational agents embedded in applications	Support for user-defined independent actions	5-7 years
Advanced manipulatory input devices (e.g., gesture gloves with tactile feedback)	Mimetic learning which builds on real world experience	5-7 years
Artificial Realities	Intensely motivating	7-10 years

(immersive, multisensory virtual worlds)	simulation and virtual experience	
“Information appliance” performance equivalent to current supercomputers	Sufficient power for simultaneous advanced functionalities	7-10 years
Consciousness sensors (input of user biofeedback into computer)	Monitoring of mood, state of mind	7-10 years
Artifacts with embedded semi-intelligence and wireless interconnections	Inclusion of smart devices in real world settings	2010+

Thus, information technology is a moving target, still rapidly evolving. This makes attempts to assess the full extent of its influences on the school curriculum quite difficult. Also, even though no financial or technical barriers exist, note that many current capabilities are not yet widely used instructionally. The primary barriers to altering curricular, pedagogical, and assessment practices are not technical or economic, but psychological, political, and cultural (Fullan 1993, Means 1994).

The important issue for the evolution of school curriculum is not the availability and affordability of sophisticated computers and telecommunications, but the ways these devices enable powerful learning situations that aid students in extracting meaning out of complexity. New forms of representation (e.g. interactive models that utilise visualisation and other means of making abstractions tangible and sensory) make possible a broader, more powerful repertoire of pedagogical strategies. Also, emerging interactive media empower novel types of learning experiences; for example, interpersonal interactions across networks can lead to the formation of virtual communities. The innovative kinds of pedagogy enabled by these novel media empower moving instruction beyond synchronous, group, presentation-centred forms of education and enable preparing students for the complexities of a 21st century knowledge based global marketplace.

NOTES

1 NSF is supporting studies of this process through its ‘Learning and Intelligent Systems’ (LIS) initiative within KDI.

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BIONOTE

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Figure and Table Captions

figure 1: Model-It's multiple linked representations exploring water quality

figure 2: Constructing a dynamic relationship without differential equations

figure 3: A representative model built by 2 ninth graders

figure 4: ClimateWatcher visualization tool

figure 5: Collaboratory Notebook groupware tool

figure 6: MBL Dude leads a clown parade

figure 7: Mixing kinesthetic experience with simulations

figure 8: Chromosome view in Genscope

figure 9: Organism view in Genscope

figure 10: Cell view in Genscope

figure 11: Pedigree view in Genscope

figure 12: DNA view in Genscope

figure 13: Population view in Genscope

figure 14: Above the NW corridor, showing cameras, balls with shadows, and the far wall

figure 15: After launch, illustrating NW's spring-based launching mechanism

figure 16: User exploring a field with test charges and field lines

figure 17: Bipole with moving test charge.

table 1: The likely evolution of interactive educational media