Reinventing the Role of Information and Communications Technologies in Education

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This is a pivotal time for reinventing the role of information and communications technologies (ICT) in teaching and learning, because emerging tools, applications, media, and infrastructures are reshaping three aspects of education simultaneously:

- The knowledge and skills society wants from the graduates of education are shifting, due to the evolution of a global, knowledge-based economy and a "flat" world (Friedman, 2005).
- Methods of research, teaching, and learning are expanding, as new interactive media support innovative forms of pedagogy (Dede, in press-a).
- The characteristics of students are changing, as their usage of technology outside of academic settings shapes their learning styles, strengths, and preferences (Dede, 2005).

Combined, these trends suggest that – beyond implementing at scale the types of educational computers and telecommunications research and experience have proven effective – we should also develop alternative models of education that use emerging technologies to reinvent many aspects of teaching, learning, and schooling. If we were to redesign education not to make historic models of schooling more efficient, but instead to prepare students for the 21st century – simultaneously transforming teaching in light of our current knowledge about the mind – what types of learning environments might sophisticated ICT enable us to create?

<u>Three Observations about the Impacts of ICT on Society</u>

The rethinking of conventional educational models I advocate in this chapter is based on three fundamental observations about the impact of ICT on society. The first observation is that the definition of what computers and related technologies can accomplish has repeatedly expanded since these devices were first developed in the 1940s: from numerical calculators to data processors, to productivity enhancers, to information managers, to communications channels, to pervasive media for individual and collective expression, experience, and interpretation. Past visions of technology in teaching and learning largely reflect using ICT as a means of increasing the effectiveness of traditional instructional approaches: enhancing productivity through tools such as word processors, aiding communication by channels such as email and threaded asychronous discussions, and expanding access to information via Web-browsers and streaming video. All these have proven worthy in conventional schooling; however, as discussed later, none draw on the full power of ICT for individual and collective expression, experience, and interpretation – core life-skills for the 21st century.

The second observation about the impact of ICT on society is that cognition is now distributed across human minds, tools/media, groups of people, and space/time (Salomon, 1993; Hutchins, 1995; Engeström & Middleton, 1996; Dede, in press-b). Because of sophisticated computers and telecommunications, the process of individual and collective thought in civilization is increasingly dispersed symbolically, socially, and physically. For better or for worse, entertainment and human interaction are delocalizing as well. People who share the same dwelling may have very different personal communities as their major sources of sociability, support, information, a sense of belonging, and social identity, as contrasted to the historic pattern of lifestyles centered on face-to-face groups interacting with local resources (Rheingold, 2002). Our great-grandparents would see our lifestyle as bizarre – "electronic nomads wandering among virtual campfires" (Mitchell, 2003) – yet in counterpoint many youth today see prior generations as hapless prisoners of geography, trapped in the limits of a single physical location. Given that distributed thought, action, and sociability show no signs of receding, formal education should prepare people to achieve their full potential in this emerging, novel context, avoiding its weaknesses and traps while maximizing its strengths and opportunities.

The third observation about the impacts of ICT on society is that the types of work done by people as opposed to the kinds of labor done by machines are continually shifting. Economists Frank Levy and Richard Murnane (2004) have documented a very important aspect of about how the skills society needs from graduates of schooling are changing:

> Declining portions of the labor force are engaged in jobs that consist primarily of routine cognitive work and routine manual labor—the types of tasks that are easiest to program computers to do. Growing proportions of the nation's labor force are engaged in jobs that emphasize expert thinking or complex communication—tasks that computers cannot do. (pp. 53–54)

These economists go on to explain that "expert thinking [involves] effective pattern matching based on detailed knowledge; and metacognition, the set of skills used by the stumped expert to decide when to give up on one strategy and what to try next" (Levy & Murnane, 2004, p. 75). "Complex communication requires the exchange of vast amounts of verbal and nonverbal information. The information flow is constantly adjusted as the communication evolves unpredictably" (Levy & Munane, 2004, p. 94). Education should prepare students for a world in which almost all types of routine cognitive tasks are done by computers and in which expert thinking and complex communications are the core intellectual skills for prosperity. These higher order skills are based on fundamental knowledge about how to do simpler tasks, so the shift needed is not to remove the learning of routine cognitive performances from the curriculum. Rather, the fundamental change involves deemphasizing fluency in simple procedures as an end-goal of preparation for work and life, instead using these routine skills as a substrate for mastering complex mental performances.

Based on these three interrelated shifts, this chapter advocates that we as a field develop a new, transformative vision for the evolution of education over the next fifteen years. In this enterprise of reinventing teaching, learning, and schooling, we would not need to rely on any major technological advances not yet achieved, such as a substantial leap forward in artificial intelligence. Instead, we could make full use of emerging, sophisticated technologies that are not creative or smart in comparison to humans, but are increasingly adept at accomplishing "routine" tasks. In our process of reconceptualization, we must first focus on what educational needs we are meeting with the increased power of emerging ICT, because centering new visions simply on recently expanded capabilities of computers and telecommunications will merely generate "solutions" in search of problems.

The Educational Challenges of the 21st Century

Numerous reports on the global, knowledge-based economy and the "flat" world document that tomorrow's workers must be prepared to shift jobs and careers more frequently, to be flexible and adaptable in acquiring job skills, and to integrate and focus a changing mix of job and education knowledge on business processes and problems (Friedman, 2005). The worker of the 21st century must have science and mathematics skills, creativity, fluency in information and communication technologies, and the ability to solve complex problems (Business-Higher Education Forum, 2005). And yet much of U.S. education is still based on the premise that economic processes and institutions will mirror those in the 20th century (Dede, Korte, Nelson, Valdez, & Ward, 2005). Students are prepared to be future employees of business organizations now rapidly becoming obsolete (Business Roundtable, 2005). Current trends suggest that more students will run their own businesses rather than work for others and as adults must constantly, quickly, and efficiently learn new skills and information to be effective entrepreneurs.

Unfortunately, at a time when sophisticated reasoning is becoming an entry level skills for a desirable job, the rate at which high school graduates are going on to postsecondary education is falling, not rising. Our country is losing vital talent because our current educational system neither engages many students nor helps them succeed. Failure to address our dropout crisis will lead to dismal economic results in the years ahead. Why are we throwing away so much human potential? A substantial part of the explanation is that we use far too narrow a range of pedagogies in schooling students.

Maximizing Human Potential Requires Accommodating Diversity in How People Learn

Learning is a human activity quite diverse in its manifestations from person to person (Dede, in press-a). Consider three activities in which all humans engage: sleeping, eating, and bonding. One can arrange these on a continuum from simple to complex, with sleeping towards the simple end of the continuum, eating in the middle, and bonding on the complex side of this scale. People sleep in roughly similar ways; if one is designing hotel rooms as settings for sleep, while styles of décor and artifacts vary somewhat, everyone needs more or less the same conditions to foster slumber.

Eating is more diverse in nature. Individuals like to eat different foods and often seek out a range of quite disparate cuisines. People also vary considerably in the conditions under which they prefer to dine, as the broad spectrum of restaurant types attests. Bonding as a human activity is more complex still. People bond to pets, to sports teams, to individuals of the same gender and of the other gender. They bond sexually or platonically, to others similar or opposite in nature, for short or long periods of time, to a single partner or to large groups. Fostering bonding and understanding its nature are incredibly complicated activities.

Educational research strongly suggests that individual learning is as diverse and as complex as bonding, or certainly as eating. Yet theories of learning and philosophies about how to use ICT for instruction tend to treat learning like sleeping, as a simple activity relatively invariant across people, subject areas, and educational objectives. Current, widely used instructional technology applications have less variety in approach than a low-end fast-food restaurant – small wonder that, even by middle school, so many children give up on our educational system and lose the belief that learning is motivating and possible for them.

As discussed above, a crucial challenge for U.S. education is to align curriculum and learning to a whole new economic model[1] based on an emerging global, knowledge-based workplace (Dede, Korte, Nelson, Valdez, & Ward, 2005). Linking economic development, educational evolution, workforce development, and strengthened social services is essential to meeting this challenge (National Academy of Science, 2006). Given the huge loss of human capacity from dysfunctions in our current systems of schooling, to compete successfully in a "flat" world we must transform children's learning processes in and out of school and engage student interest in gaining 21st century skills and knowledge. But what "21st century skills" are we neglecting to teach?

[1] Education has many responsibilities other than aiding economic development, and this chapter does not attempt to portray the full range of educational missions or the instructional strategies needed for success across this spectrum of goals. However, all those other responsibilities are possible only if education succeeds in providing the foundation for a prosperous future. This does not mean that education for economic development is privileged more than other objectives. Nonetheless, those who want education to succeed in resolving major concerns (e.g., equity, moral citizenship, self-realization) need to incorporate perspectives about preparation for 21st century work into their planning.

Crucial, Neglected 21st Century Skills

If we apply the three observations about impacts of sophisticated ICT on society (individual and collective expression, experience, and interpretation; distributed cognition and action; erosion of routine tasks in favor of expert decision making and complex communications skills) to predictions about the emerging global, knowledge-based economy, what insights emerge about the 21st century skills today's students should acquire in school (Dede, in press-c)?

In current instructional practice, the most neglected cluster of 21st century skills is *collective problem resolution via mediated interaction*. In 21st century work, knowledge is grounded in a setting and distributed across a community, rather than abstract and isolated within individuals. Problem *finding* (the front-end of the inquiry process: making observations and inferences, developing hypotheses, and conducting experiments to test alternative interpretations of the situation) is crucial to reaching a point where the work team can do problem solving. Individual and collective metacognitive strategies for making meaning out of complexity (such as making judgments about the value of alternative problem formulations) are vital.

Each person involved has strong skills in effective pattern matching based on detailed knowledge and in judging when to give up on a particular problem solving strategy and what to try next. Individuals on the work team are adept at manipulating sophisticated ICT applications and representations utilized within the complementary perspectives they bring to bear (e.g., using a spreadsheet to examine financial hypotheticals). They also are skilled in expressing core insights from their knowledge to others who have different backgrounds and experiences. Richly interactive complex communication among team members is not limited to face-to-face dialogue, but frequently relies on mediated interaction across distance in which the team co-constructs and negotiates shared interpretive understandings and a problem resolution strategy.

Unfortunately, the interrelated 21st Century Skills delineated above are largely absent in current pedagogical and assessment practices. The next section describes the strengths and limits of current ICT-based instructional design approaches in helping students attain this cluster of 21st century knowledge and skills. Then, the subsequent section delineates how emerging technologies such as multi-user virtual environments and augmented realities enable new types of pedagogical strategies that meet a broader spectrum of learning styles and enable mastering more sophisticated kinds of skills, complementing current teaching methods to more effectively prepare students for the 21st century.

How Well Do Current ICT for Learning Meet 21st Century Educational Challenges?

Three competing schools of thought on how people learn – behaviorism, cognitivism, and constructivism – have strongly influenced the design of instructional technologies (Dede, in press-a). Behaviorists believe that, since learning is based on experience, pedagogy centers on manipulating environmental factors to create instructional events inculcating content and procedures in ways that alter students' behaviors. Cognitivists posit that, since learning involves both experience and thinking, instruction centers on helping learners develop interrelated, symbolic mental constructs that form the basis of knowledge and skills. Constructivists believe that, since learning involves constructing one's own knowledge in a context richly shaped by interactions with others, instruction centers on helping learners to actively invent individual meaning from experiences. At times, a collective cultural setting may influence this interpretive process.

Each school of thought is not a single, unified theory, but rather a collection of theories distinct from each other, but loosely related by a common set of fundamental assumptions. Further, any given pedagogical tool, application, medium, or environment may incorporate perspectives from more than one of these intellectual positions.

In the behaviorist school of thought (Dabbagh, 2006), the purpose of education is for students to acquire skills of discrimination (recalling facts), generalization (defining and illustrating concepts), association (applying explanations), and chaining (automatically performing a specified procedure). The learner must know how to execute the proper response as well as the conditions under which the response is made. Computer-assisted instruction (CAI) and drill-and-skill learner management systems (LMS) are the two types of instructional technologies most closely associated with this school of thought, although many other ICT tools and applications utilize some aspects of behaviorist design.

Behaviorist instructional technologies are limited both in what they can teach and in the types of engagement they offer to learners, but have proven useful for tasks involving learning facts and simple procedural skills (National Research Council, 2000). What the diverse subject areas taught by CAI and LMS have in common is an emphasis on factual knowledge and recipe-like procedures: material with a few correct ways of accomplishing tasks. So, for example, behaviorist instructional technologies can teach simple skills such as alternative algorithms for division, in which number of permissible variants is small and the end result is always the same. Factual knowledge, such as the year Columbus discovered America, is similar in its cognitive attributes: one right answer, basic mental processes primarily involving assimilation into memory. A contrasting illustration of knowledge and skills not well taught by CAI and LMS is learning how to write an evocative essay on "My

Summer Vacation." Behaviorist instruction can help with the spelling and grammar aspects of this task, but effective literary style is not reducible to a narrow range of "correct" rhetorical and narrative processes.

In contrast to behaviorist objectives for teaching, goals for instruction characteristic of the cognitivist school of thought include (National Research Council, 2005):

- providing a deep foundation of factual knowledge and procedural skills;
- linking facts, skills, and ideas via conceptual frameworks – organizing domain knowledge as experts in that field do, in ways that facilitate retrieval and application; and
- helping students develop skills that involve improving their own thinking processes, such as setting their own learning goals and monitoring progress in reaching these.

Although a wide variety of instructional technologies incorporate some principles from cognitivism, intelligent tutoring systems (ITS) are veridical examples of pedagogical media based on this school of thought.

The Andes Physics Tutoring System illustrates the cognitivist instructional design underlying an ITS (VanLehn et al, 2005). Andes aids college students with physics homework problems. Its screen simultaneously presents each problem and provides specialized workspaces for learners to draw vectors and coordinate axes, define variables, and enter equations. Unlike pencil and paper representations, Andes generates immediate feedback on the correctness of each step a student takes. In addition, Andes includes a mathematics package for equation solving and provides three kinds of tutorial help customized to each specific process in a task. As the student solves a problem, Andes computes and displays a score that is a complex function of degree of correctness, number of hints, and good problem solving strategies.

Scholars disagree on how broad a range of knowledge and skills cognitivist instructional technologies can teach (Dede, in press-a). What the diverse subject areas now taught by pedagogical media like ITS have in common is well-defined content and skills, material with a few correct ways of accomplishing tasks. Proponents of cognitivist approaches believe that eventually ITS-like educational devices, coupled with human instructors, will teach most of the curriculum, including less-well-defined skills such as the rhetoric of writing an evocative essay. However, three decades of work towards this ambitious goal have yielded limited progress to date.

The constructivist school of thought is characterized by goals for instruction that include (Dabbagh, 2006):

- Instruction is a process of supporting knowledge construction rather than communicating knowledge.
- The role of the teacher is a guide, rather than an expert transferring knowledge to novices' "blank slates."
- Learning activities are authentic and center on learners' puzzlement as their faulty or incomplete knowledge and skills fail to predict what they are experiencing.
- Teachers encourage students in reflecting on experiences, seeking alternative viewpoints, and testing viability of ideas.

Student motivation to achieve these goals is determined by factors such as challenge, curiosity, choice, fantasy, and social recognition (Pintrich & Schunk, 2001).

Constructivist pedagogical media span a wide range. An example that illustrates many aspects of this approach is the Jasper Woodbury mathematics curriculum. Middle-school students in math class view fifteen minute video adventures that embed mathematical reasoning problems in complex, engaging real world situations. One episode depicts how architects work to solve community problems, such as designing safe places for children to play. This video ends with this challenge to spend the next week of class meetings designing a neighborhood playground (National Research Council, 2000, page 208):

> Students in the classroom help Christina and Marcus by designing swingsets, slides, and sandboxes; then building models of their playground. As they work through this problem, they confront various issues of arithmetic, geometry, measurement, and other subjects: How do you draw to scale? How do you measure angles? How much pea gravel do we need? What are the safety requirements?

Contrasting this example to the two schools of thought depicted earlier provides a sense of the differences in pedagogical media developed by these differing theories of learning and teaching. In particular, note that these students are learning simpler skills in the context of a complex task, in sharp contrast to Behaviorist instructional design.

Constructivist approaches can potentially teach a very broad spectrum of knowledge and skills (Dede, in press-a). However, in practice constructivist instruction has proven quite difficult to implement in conventional school settings, for a variety of reasons discussed in the other chapters in this volume. Also, the efficiency of constructivist learning technologies for material that these other two schools of thought can teach is questionable. Content and skills that are relatively invariant regardless of individual perspective (e.g., arithmetic operations) are learned more quickly when taught as “truths” than when found through exploration that, in extreme unguided forms, involves students slowly reinventing civilization (Kirschner, Sweller, & Clark, 2006).

Of all the pedagogies sketched above, the closest to preparing students for collective problem resolution is guided social constructivism (Duffy & Cunningham, 1996; Kafai & Ching, 2001). Guided constructivism is defined as students actively constructing their knowledge with instructional support, as opposed to being passive recipients assimilating information communicated by the teacher (Jonassen, 1996). In social constructivism, students construct knowledge as a result of their interactions with their community (Edelson, Pea, & Gomez, 1996). Some scholars (Pear & Crone-Todd, 2001; Simpson, 2002) identify the scientific research community as an example of social constructivism, since researchers construct their own ideas, share those with peers, and through these interactions reformulate their knowledge.

Unfortunately, many forms of "project-based" or "problem-based learning" [frequently used synonyms for both strong and weak forms of guided social constructivist pedagogy] make little use of ICT (Krajcik & Blumenfeld, 2006). Also, as other chapters in this Yearbook describe, successfully implementing innovative curricula based on guided social constructivism in the era of No Child Left Behind is difficult for a myriad of reasons (Wiske, Franz, & Breit, 2004).

Shortfalls in Current Approaches Using ICT to Aid Learning

When comparing all these current uses of ICT in the design of instruction to the types of 21st century skills graduates of schooling need, serious shortfalls are evident (Dede, in press-c). Conventional K-12 instruction, particularly behaviorist and cognitivist approaches, emphasizes manipulating pre-digested information to build fluency in routine problem solving, rather than filtering data derived from experiences in complex settings to develop skills in sophisticated problem finding. Also, problem solving skills are presented in an abstract form that makes transfer to other academic disciplines (inside of schools) and real world situations (outside of schools) difficult. In all three types of instructional designs, the ultimate objective of education is often presented as learning a specific problem solving routine to match every work situation, rather than developing expert decision making and metacognitive strategies that indicate how to proceed when no standard approach seems applicable.

Little time is spent on building capabilities in group interpretation, negotiation of shared meaning, and co-construction of problem resolutions, particularly in behaviorist and cognitivist instructional strategies. The communication skills stressed are those of simple presentation, rather than the capacity to engage in richly structured interactions that articulate perspectives unfamiliar to the audience. As discussed earlier, ICT applications and representations are largely used to automate traditional methods of teaching and learning, rather to model complexity and express insights to others. In all three types of learning theories, face-to-face communication and assessment based on pencil and paper tests are seen as the "gold standard," so students develop few skills in mediated dialogue and in shared design within a common virtual workspace.

Conventional assessments and tests focus on measuring students' fluency in various abstract, routine skills, but typically do not assess their capabilities for expert decision making when no standard approach seems applicable. Essays emphasize simple presentation rather than sophisticated forms of rhetorical interaction. Students' abilities to transfer their skills to real world situations are not assessed, nor are capabilities related to various aspects of teamwork. The use of ICT applications and representations is generally banned from testing, rather than measuring students' capacities to use tools, applications, and media effectively. Abilities to effectively utilize various forms of mediated interaction are typically not assessed. In other words, the *effects from* technology usage (what one can accomplish without tools) are measured, but the *effects with* technologies essential to effective practice of a skill are not (Salomon, 1993).

None of this analysis is meant to imply that behaviorist, cognitivist, and constructivist pedagogical approaches do not play a valuable role in schooling. On the contrary, learning technologies based on all three types of instructional designs are important in developing foundational knowledge and cognitive skills that serve as a necessary substrate for mastering complex mental performances, such as collective problem resolution via mediated interaction. However, to prepare students for 21st century work and citizenship, the usage of sophisticated ICT based on a complementary pedagogical theory, situated learning, is a vital supplement to current educational technologies. In particular, situated forms of instructional design are better suited than behaviorist, cognitivist, or constructivist approaches to teaching sophisticated "problem finding" as the front-end of the inquiry process for making meaning out of complexity.

Situated Learning as a Vehicle for Developing "Problem Finding" Capabilities

The seminal works of Brown, Collins, & Duguid (1989) and Lave & Wenger (1991) define *situated learning* as embedded within and inseparable from participating in a system of activity deeply determined by a particular physical and cultural setting. The unit of analysis is neither the individual nor the setting, but instead the relationship between the two, as indicated by the student's level of participation in the setting (Barab & Plucker, 2002).

Studies of apprenticeship in “communities of practice” (moving from newcomer to expert within a sociocultural structure of practices) are a central construct for situated learning (Wenger, McDermott, & Snyder, 2002).

In essence, situated learning requires authentic contexts, activities, and assessment coupled with guidance from expert modeling, situated mentoring, and legitimate peripheral participation (Lave & Wenger, 1991). Brown, Collins and Duguid (1989) proffer the graduate student experience as an example of apprenticeship in a community of practice. As part of their academic program, graduate students evolve from pupils to researchers through a series of learning activities embedded within a scholarly mileau. For example, graduate students may work within the laboratories of expert researchers, who model the practice of scholarship. These students will interact with experts in research as well as with other members of the research team who understand the complex processes of scholarship to varying degrees. While in these laboratories, studentsgradually move from novice researchers to more advanced roles, with the skills and expectations for them evolving (legitimate peripheral participation). In contrast to courses, students learn the knowledge and skills expected of them in their future research careers through modeling, mentoring and legitimate peripheral participation.

While powerful and prevalent in life settings, situated instructional designs are seldom utilized in academic contexts, especially pre-college. Greeno et al (1997) indicates that the power of situated learning is derived from a person learning to solve problems as part of a community in the authentic context confronting these challenges, a difficult environment to develop in a K-12 classroom. Previous attempts to evaluate situated theory in school settings have encountered severe limits in authenticity, legitimate peripheral participation, and developing problem-solving communities with participants at different levels, from novice through expert. For example, Griffin (1996) conducted a research study to develop mapping skills through methods leveraging situated learning theory. However, in this study students were first taught in a school type environment and then were provided an expert from whom to learn. This approach lacked a means to create and evaluate classroom-based situated learning because no multi-leveled community of learning was involved.

Fortunately, emerging ICT that enable immersive, collaborative simulation now offer the capability to implement situated learning environments in classroom settings. This potentially provides the missing piece in the puzzle of how to teach 21st century skills of problem finding in academic contexts remote from real world communities of practice engaging in collective problem resolution via mediated interaction.

How Can Emerging ICT Aid in Meeting 21st Century Educational Challenges?

Three complementary technological interfaces are currently shaping how people learn, with multiple implications for K-12 education:

- The familiar *"world- to- the- desktop"* interface provides access to distributed knowledge and expertise across space and time through networked media. Sitting at their laptop or workstation, students can access distant experts and archives, communicate with peers, and participate in mentoring relationships and virtual communities-of practice. This interface provides the models for learning that now underlie most tools, applications, and media in K-12 education.
- Emerging *multi-user virtual environment (MUVE)* interfaces offer students an engaging "Alice in Wonderland" experience in which their digital emissaries in a graphical virtual context actively engage in experiences with the avatars of other

participants and with computerized agents. MUVEs provide rich environments in which participants interact with digital objects and tools, such as historical photographs or virtual microscopes. Moreover, this interface facilitates novel forms of communication among avatars, using media such as text chat and virtual gestures. This type of "mediated immersion" (pervasive experiences within a digitally enhanced context), intermediate in complexity between the real world and paint-by-numbers exercises in K-12 classrooms, allows instructional designers to construct shared simulated experiences otherwise impossible in school settings. Researchers are exploring the affordances of such models for learning in K-12 education (Clarke et al, 2006; Barab et al, 2004).

- *Augmented reality (AR)* interfaces enable "ubiquitous computing" models. Students carrying mobile wireless devices through real world contexts engage with virtual information superimposed on physical landscapes (such as a tree describing its botanical characteristics or an historic photograph offering a contrast with the present scene). This type of mediated immersion infuses digital resources throughout the real world, augmenting students' experiences and interactions. Researchers are starting to study how these models for learning aid students' engagement and understanding (Klopfer et al, 2004; Klopfer & Squire, in press).

As emerging forms of ICT for learning, MUVEs empower creating contexts inaccessible in the real world, while AR enables the infusion of virtual contexts within physical locations.

My colleagues and I are conducting design-based research on one such MUVE-based learning experience, River City (http://muve.gse.harvard.edu/rivercityproject/), a project funded by the National Science Foundation to enhance middle school students' educational outcomes in science (Clarke et al, 2006). Students virtually immerse themselves inside a simulated, historically accurate 19th century city. Collaborating in teams of three or four participants, they try to figure out why people are getting sick and what actions can remove sources of illness. They talk to various residents in this simulated setting, such as children and adults who have fallen ill, hospital employees, merchants, and university scientists. Participants go to different places in the town and collect data on changes over time, acting in gradually more purposeful ways as they develop and test hypotheses. They help each other and also find experts and archives to guide them. Further, students use virtual scientific instruments, such as microscopes to test water for bacteria.

This immersive simulation allows them to conduct an experiment by changing an independent variable they select based on a legitimate research question, then collecting data in the city to test their hypothesis. Students not only hypothesize what would happen if, for example, a sanitation system were built—they can actually visit the city with a sanitation system added and see how this change affects the patterns of illness. Our research results indicate students are deeply engaged by this immersive experiential curriculum and are developing sophisticated problem finding skills.

If we examine students' technology use outside of school, we see widespread use of MUVE interfaces occurring in their informal, voluntary educational activities. For example, while one child sitting in front of a console game is still prevalent, collaborative, mediated gameplay is rising. The latest generation of console systems (Xbox 360, PS3, and Wii) have hardware architectures that encourage "connected" playing right out of the box, encouraging interaction across distance and space. Massively multi-user online environments (MMO), such as Second Life (Linden Lab), the World of Warcraft (Blizzard Entertainment) and Everquest (Sony Online Entertainment), bring participants together online where they can interact in a virtual collaborative context. Emerging communities such as "modding," in which users create new content for games (often contributing to a shared database of models), and "machinima," in which users create new content via video capturing techniques, are further shaping how kids now express themselves via collaborative digital experiences. Youth are forming networked communities around games and movies, in which they share codes and strategies and build collaborative clans working together to fulfill quests.

My colleagues and I are also in the early stages of developing an AR designed to promote skills in collective problem resolution via mediated interaction (Clarke, Dede, & Dieterle, in press). Alien Contact! is part of a project funded by the U.S. Department of Education Star Schools program (http://education.mit.edu/arworkshop/) and is designed to teach math and literacy skills to middle school students. Students work in teams of four to figure out why aliens have landed and whether they are friend or foe. Each student on a team plays one of four complementary roles (chemist, computer expert, linguist, or FBI agent), which determines the information and experiences provided to that learner. Each team member has access to different data, so team members must collaborate to solve the problems they encounter (jigsaw pedagogy, in which each learner is provided only part of the information needed to understand the situation). Prior results from AR research indicate the promise of this instructional design strategy for teaching problem finding and for supporting a wide range of students' "neomillennial" learning styles and strengths (Dieterle, Dede, & Schrier, in press).

As with MUVEs, youth increasingly have access outside of school to a new generation of wireless handheld devices (WHDs) that combine the affordances of personal information managers, telephony, wireless Internet connectivity, and Global Positioning Systems (GPS) – all the capabilities needed to support educational AR. Two of the most common WHDs utilized by school-aged children are cell phones and handheld gaming devices. Among U.S. teenagers, as Lenhart, Madden, and Hitlin (2005) have found, almost half report owning a cell phone, with a greater percentage of older teens owning a phone (nearly 3 in 5 teens aged 15-17) than younger teens (nearly 1 in 3 teens aged 12-14). Roberts, Foehr, and Rideout (2005) have found that more than half of U.S. students aged 8 to 18 own at least one handheld gaming device. Wireless mobile devices can support social interactivity, are sensitive to shifts in context, enable individualized scaffolding, and can facilitate cognition distributed among people, tools, and contexts (Klopfer & Squire, in press).

In their learning processes, many of the distributed communities among youth based on AR and MUVE interfaces parallel the activities of 21st century professionals in knowledge-based workplaces. In both MUVEs and AR, knowledge is grounded in a setting and distributed across a community, rather than isolated within individuals. Contrary to conventional K-12 instruction where knowledge is decontextualized and explicit, in MUVEs and AR the learning is situated and tacit: Problem finding is central to problem solving. This parallels the nature of 21st century work, as well as the “neomillennial” learning styles and strengths of today’s digital-age students (Dede, 2005).

MUVE and AR immersive interfaces for collaborative simulation foster situated learning and can aid students in learning collective problem resolution via mediated interaction as a key cluster of skills in the global, knowledge-based economy. But will students have access to the types of ICT infrastructure – in and out of school – that can support this type of transformative educational model?

The Growing Availability of "Cyberinfrastructure"

In recent years, the National Science Foundation has championed a vision of the future of research that centers on "cyberinfrastructure": the integration of computing, data and networks, digitally-enabled sensors, observatories and experimental facilities, and an interoperable suite of software and middleware services and tools (National Science Foundation Cyberinfrastructure Council, 2006). Gains in computational speed, high-bandwidth networking, software development, databases, visualization tools, and collaboration platforms are reshaping the practices of scholarship and beginning to transform teaching (Dede, in press-b). Sophisticated simulation software and distributed, wireless observation-networks are enabling the exploration of phenomena that cannot be studied through conventional experimental methods. Research in the sciences relies more and more on computational models to understand topics such as genetic decoding, weather prediction, and information security.

Cyberinfrastructures developed for research purposes also create intriguing opportunities to transform education. Scientific and educational resources can now pervade a wide variety of settings, rather than being accessible only in limited, specialized locations. Real-time data collection can enable assessing students' educational gains on a formative basis, providing insights into the microgenetics of learning knowledge and skills. Students can customize and personalize learning environments to a degree never before possible. Extensive "online" learning can complement conventional face-to-face education, and ubiquitous, pervasive computing can infuse smart-sensors and computational access throughout the physical and social environment.

Accomplishing these shifts requires more than the creation and maintenance of the cyberinfrastructure itself:

> To employ the tools and capabilities of cyberinfrastructure-enabled learning environments effectively, teachers and faculty must also have continued professional development opportunities. For example, teachers and faculty must learn to use new assessment techniques and practices enabled by cyberinfrastructure, including the tailoring of feedback to the individual, and the creation of personalized portfolios of student learning that capture a record of conceptual learning gains over time. These conditions permit new learning organizations to form, raising in turn new research questions about the creation, operation, and persistence of communities of practice and learning. In such cyberlearning networks people will connect to learn with each other, even as they learn to connect with each other, to exploit increasingly shared knowledge and engage in participatory inquiry (NSF, 2006, pp. 32-33).

Just as the invention of the microscope enabled the creation of whole new fields in biology, New disciplines may result from these emerging methods of education, fields as important as the relatively new areas of computer science, mathematical biology, genomics, environmental science, and astrophysics are today.

During 2004-05, with NSF funding, four workshops attended by experts in education were convened by the Computing Research Association (CRA). The CRA report from these workshops (2005) described the probable effects of cyberinfrastructure on the evolution of learning and teaching:

> As STEM [science, technology, engineering, mathematics] research becomes increasingly collaborative, distributed, and dependent upon access to large amounts of computational power and data, students as well as teachers and educational decision makers at all levels will need to learn how to think with data—using diverse forms of data, information resources, tools, and services in many different fields of study to support making a broad range of decisions. They will need to become proficient in navigating a rich universe of data resources; in engaging with statistics, probability and evidence-based argumentation; and in discerning the authenticity, quality and reputation of these data sources. Emerging tools and frameworks for interactive and dynamic visualizations of patterns in data will be integral to these new literacies for thinking and decision making (CRA, 2005, pp. 5-6).

However, the report cautions that networked systems can create unexpected side-effects, citing usage of data and usage privacy and accessibility, as well as the potential intertwining of formal schooling and assessment with ubiquitous informal learning.

In addition, the CRA report presents a vignette of a "serious game":

> Learners cooperate in designing and conducting a mission to Mars, in the context of a game-based simulation. In the course of the project they carry out a variety of STEM-related learning activities, spanning physics, chemistry, biology, engineering and mathematics. These become springboards for seeking other learning resources outside the game, and collaborating with other learners in online working groups. Learners access online science and engineering data sets and models in order to compare their predictions against results from space scientists. They receive guidance in inquiry skills, metacognitive learning skills, and collaboration skills. The

> game itself is constructed and adapted through the collaborative efforts of the participating learners. In his earth sciences course, John, for example, studies terrain data from Mars Rover missions and creates a model of the Martian terrain to be explored by others. Manuela, in her high-school engineering class, designs an autonomous rover vehicle to collect geologic samples and constructs a simulation of her rover design for use in the mission. She can then compare her model's performance in the simulation against records of actual Mars Rover missions. Sherry, the teacher, is assisted by virtual assistant teachers (intelligent tutors) embedded in the game that help her monitor learner progress and offer guidance and challenges. One of Sherry's virtual assistants reports that Manuela is having difficulty getting the controller of her virtual robot to work, and is not availing herself of online resources, so Sherry suggests that she discuss her design with an online community of robot enthusiasts. Data collected from learner performance within and surrounding the game provide the teacher with documentation and evidence of learning progress relating to curriculum standards and goals. In some contexts this may replace the need for standardized tests, but in others the teacher already has sufficient evidence to predict that the learners will meet the required standards (page 7).

While not articulating the role innovative interfaces for situated learning might play, this vision resonates with teaching 21st century skills, such as collective problem resolution via mediated interaction, in and out of school settings. Cyberinfrastructure can provide the tools, applications, and media needed to instantiate transformative models of K-12 education.

Conclusion

This chapter sketches a vision, not a prediction, of how emerging ICT might shape the evolution of teaching, learning, and schooling. A prediction portrays the future as like a train track leading us to a predestined outcome for which we must prepare. In contrast, a forecast depicts the future as like a tree: one trunk (the past and present), with many branches (alternative futures). In this model of the future, individuals and institutions are like ants crawling up the trunk toward the branches, moving through the present to the future. Decisions made in the present strengthen and weaken various branches (fortify and undermine possibilities) because the choices not made are constrained as alternatives; by the time our present becomes our future, only one branch is left (the new trunk).

How difficult in 2007 is developing forecasts about the effects on civilization of ICT in 2022 and beyond, at period during which today's students are assuming roles of responsibility in society? The equivalent in recent history would be describing in 1992 the impact of computers and telecommunications in 2007. In the early 1990s – before the WorldwideWeb, universal email, digital telephony, massively multi-user virtual worlds, and similar civilization-wide advances – scholars did accurately articulate many of the shifts in society we see today (Dede, 1992). However, very few people predicted some important changes, such as sociosemantic networking, and many "futurist" forecasts (e.g., widespread, sophisticated artificial intelligence) were unrealized.

At this point in history, the primary barriers to altering curricular, pedagogical, and assessment practices towards the transformative vision of ICT in education this chapter advocates are not conceptual, technical or economic, but instead psychological, political, and cultural. We now have all the means necessary to implement alternative models of education that truly prepare all students for a future very different from the immediate past. Whether we have the professional commitment and societal will to actualize such a vision remains to be seen.

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