Distributed Multimedia Learning Environments: Why and How?

Roy D. Pea, Louis M. Gomez

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Roy D. Pea

Northwestern University

Louis M. Gomez

Bellcore

Abstract

We outline the societal prospects and business opportunities for much more extensive use of interactive multimedia technologies (IMT) connected through telecommunications to create distributed multimedia learning environments (DMLE). A theoretical framework is provided with a distinctive communications perspective on learning emerging from research in the cognitive and social sciences. A major consequence of this communication emphasis is the special need for rich communication technologies to support highly interactive teaching and learning activities, especially those at a distance but even within a classroom or school. Examples of existing projects using IMT for remote learning communications are among the most dramatic examples of these new possibilities. Based on these foundations, we first depict a vision of IMT for schools that establishes the kinds of DMLE designs that appear from research to offer promising improvements. We then characterize how current educational spending trends and educational technology research and development attitudes could be transformed so that such distributed multimedia learning environments could become a reality more rapidly. Short-term progress in closing the gap from current practices to this vision is possible in specific IMT application areas described.

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Correspondence and requests for reprints should be sent to Roy D. Pea, Northwestern University, Institute for the Learning Sciences, 1890 Maple Avenue, Evanston, IL 60201 (pea@ils.nwu.edu).

INTRODUCTION

This paper examines the prospects for learning and education of what we refer to as "interactive multimedia technology," or IMT. Our emphasis will be on telecommunication-centered, not individual-user IMT, for the creation of distributed multimedia learning environments (DMLE). Distributed multimedia learning environments extend the teaching, learning, and material resources beyond individual classrooms. The information network is an integral part of our definition of the basic IMT structure for education because of: the emerging communication-centered theoretical perspective on learning we will describe; person-to-person IMT communication needs; and the media storage/access needs of IMT multimedia information. One cannot do even classroom-scale local storage on floppy disks, hard disks, or optical media of the extensive video, audio, graphic, and text materials needed for learning and teaching.

We believe that new developments in theories of learning and collaborative work make robust interactive communications such an integral component of the IMT requirements of the future that telecommunications technologies are central to the achievement of a learning society that can meet the demands of education and training during the next century. These theories have communication at their center, and they are based on interactive models of learner and teacher engagement in inquiry around activities such as design and real problem solving, rather than the dominant didactic model of the teacher as a "delivery" agent of knowledge through curriculum materials. Education and training concerns, we argue, are thus squarely in the telecommunications business. We are going to review a broad variety of technological experiments underway with multimedia computing and telecommunications tools that exemplify current trends. While in the spirit of constructive critique, we will time and again point out the limitations of these prior works; of course, we recognize that without the imaginative contributions that led to their creation, our own imaginations for what could be the IMT of the future would not be possible or as rich.

WHAT IS IMT?

While interactive computing using number and text characters has been common for several decades, the advent of desktop publishing incorporating drawn or scanned graphics into documents is less than a decade old. Even newer is the increasingly common use of real-time data types such as sound, animations, and video, in applications such as computer voice mail, desktop video production, and document preparation. Dynamic documents incorporating live animations, video clips, and sound "annotations" to cells in a spreadsheet or paragraphs in a word-processed document are no longer laboratory demonstrations, but can now be produced with commercial products such as MacroMind Director (MacroMind), and Mediatracks (Farallon).

Today's desktop computers are becoming increasingly connected to hardware peripherals such as videodisc or video cassette players, still image digital cameras, CD-ROM, or CD-Audio decks. Dozens of companies sell special add-on video and audio boards that enable the digital capture and use in multimedia software applications of these traditionally analog data types. Virtually every computer manufacturer is working to make their operating systems better able to handle the technical complexities of real-time demands of interweaving the access and display of new data types of sound, video, and dynamic imagery.

These real-time integrated multimedia requirements emerge directly from user needs for synchronization and multimedia editing due to a growing aesthetic derived from exposure to commercial video and film as communications genre. Network data communication of computer-created documents has moved beyond ASCII text and numbers to include formatted documents with graphics and text, and as we will describe, innovative technical solutions are being sought to allow for the interactive exchange of communications over broadband private and public networks and the standard telephone public-switched network.

These changes in the communication and production environments of documents are evidence of the arrival at the desktop of the coalescing of the industries of publishing, computing, video and entertainment, and telecommunications.[1]

IMT as a Communication Vision

While IMT is prototypically thought of as an interaction between an individual computer user and his or her computer (e.g., Kay & Goldberg, 1977), we claim that IMT is first and foremost a communication vision. IMT is about interactions between people that happen to involve interactions with computers in the loop. The technologies serve to enrich the capabilities of participants in a communication to express what they are thinking about, to capture traces of that thought in new forms of representation, and to jointly work to create new artefacts or to learn. With new thinking about education that highlights highly interactive communication activities among all participants, one place IMT can have the most leverage will be in education both in and out of the classroom.

We must distinguish a transformational from a transmissional perspective on communication. Communication has often been conceived of in education as a transmission of information from the curriculum to the mind of the learner (e.g., Reddy, 1979). We now know that carefully crafted curriculum and lesson design is but one part of effective educational communications. A major reason for this is that communication is not only one-way transmissional but also two-way transformational. Both teachers and learners are transformed by means of communicative activities, as are coworkers using multimedia communication tools (Finholt & Sproull, 1990; Galegher, Kraut, & Egido, 1990; Sproull & Kiesler, 1991). Students are not blank slates, written upon with the lessons of curricula, but active learners who have developed substantial beliefs and ways of thinking before ever coming to school. These existing conceptions and strategies, developed through various cultural practices outside of school, are often best met and negotiated

[1]Nicholas Negroponte of MIT's Media Lab depicted these trends two decades ago, and Stewart Brand (1988) has traced the history of these developments in his book on the Media Lab.

by the teacher in a conversation, not dealt with by attempting to simply overwrite those existing practices with lectures and demonstrations.

Nor are teachers simply broadcasters of the information available in a curriculum. It takes significant effort for a teacher to understand what students are thinking about new topics of learning, and significant effort for students to determine what teachers are attempting to communicate through their teaching activities. These interpretive activities are of necessity highly interactive conversational exchanges requiring conjectures, responses, and repairs for participants to determine what is meant from what is said and done. Media technologies need to be developed to foster and allow for the expansion of these transformational capacities of human communication.

If, as we wish to argue, teaching and learning processes are so fundamentally communications processes, in the sense of "communication" that we describe, then we are led to inquire what advances in communication tools are available that we can exploit, and how well these connect to the new communication-oriented theories of learning that we are developing. In other words, the issue is not one of "adding communication" to IMT. In our reformulation of this foundational concept, we would say that IMT, appropriately construed, equals communication tools. Whether one is considering blackboards, telephones, radio, television, or computers, the issue is: What kinds of interfaces do these technologies afford as interfaces to communication? And what impact on learning and instruction can these tools have given a communication-centered theory of learning? We return to these questions in Part II.

IMT for Learning and Education in Schools

Our primary topic in this paper is the use of IMT for learning and education in schools, and not in training for business and industry, although some obvious extrapolations are possible. And we focus on schools rather than community centers, museums, and libraries, not because non-school learning institutions are unimportant societal resources for education, but because of the stability and magnitude of the social investment in schools as providers of learning opportunities and the explicit training of professionals devoted to supporting learning. It is also significant that the research base in informal learning settings outside schools is highly impoverished by comparison to new theory and empirical work on learning that is school-based (see e.g., Linn, 1986; Pea & Soloway, 1987).

We have chosen the education market segment for IMT analysis—rather than entertainment, business, publishing, or science in the broad pantheon of IMT applications—primarily due to the depth of available research that is transforming traditional views of learning in a way the technology can help push to more successful learning and teaching practices, and because of the social importance and investment of this segment. We have a much better sense from the scientific literature on learning and education for what kinds of learning supports to provide than we do for markets such as entertainment or scientific research.

Why IMT Infrastructure of Learning Systems Is Critical Now

One may ask why we view IMT as particularly worthy of analysis for education now. How is it different from other "magic boxes" for education we have seen in the past, such as radio, filmstrips, television, personal computers?[2]

What is different from the postwar enthusiasm with educational filmstrips, or the 1960s with educational television, or the 1980s with stand-alone educational microcomputers, are the design consequences for uses of the communication media that have emerged from cognitive and

[2]We offer three additional answers for why IMT is specially important for learning and teaching today. We may expect change over the long term of human history—*generations*, not a few years. Prominent examples include the telephone's impacts on human communication and community, or the television, or the computer's influence in creating a global economy. For example, it took from the 1920s to the 1970s for Bell to achieve the single goal in the U.S. of "universal service." The telecommunications industry's new goal is "universal information networking." That will take a long time, too. Secondly, IMT is different—it gives one a general representational medium, and a metamedium for connecting previously disparate media. Thirdly, augmentation tools on IMT could dramatically increase teacher knowledge-worker productivity by improving lesson preparation and use processes. A report from the OTA (Roberts, 1988) documents enthusiasm among teachers for IMT when appropriately supported to learn to use it.

social science views of learning. It is only, we would argue, in a limited sense that filmstrips or television broadcasts are "communicative." These new media benefit greatly from interactional exchanges, not only broadcasts, where interaction is only a hoped-for byproduct of exposure to the media.

In earlier eras of enthusiasm over the potentials of media for instructional purposes, learning participants were left out or given a diminished communicative role in the learning equation. (There were some exceptions, as in art, architecture, craft, writing, and other "studio critique"-like apprenticing activities in which learning was recognized to best take place through doing.) Learning discourse (Mehan, 1979) and formal education even developed exotic conversational forms—question, answer, evaluation—and limited views on the development of knowledge and understanding (multiple response testing) to canonize these restrictions. It is through much richer learning conversations (see Pea, in press-a), which require turn-taking-like exchanges most familiar from face-to-face interaction or telephone communications, that the greatest opportunities arise for learning and the development of understanding and skills. Conversation is meant here in a broad sense to include reciprocal action, whether language is used during these interactions or not. It is with learning conversations in the context of the doing of activities (rather than just talking about the doing of activities) that a great leverage for learning lies.

The expressiveness of the learner and the potential use of diverse media channels for communication was also neglected in earlier technocentric approaches to "solving" educational problems by crafting better and clearer ways to "transmit" well-crafted lessons. Education is not only (and perhaps is even rarely) conveyed solely by means of the expertise of the "presenter" who can deliver lectures that are perceived as well-structured by those who already know the subject matter. The multimedia well-crafted lecture, as the curriculum reform efforts in science and mathematics of the 1960s revealed, did not solve the educational problems. The most successful aspects of those reforms emphasized the active nature of the learner, the role of hands-on inquiry activities, and manipulables (e.g., in learning place value arithmetic with Dienes blocks), and provided occasions for students to talk about what they were learning, found confusing, or believed in as they engaged in such rich interactional opportunities for learning conversations (e.g., Bredderman, 1983; Bruner, 1966; Shymansky, Kyle, & Alport, 1983).

So when we see the current spate of projects around audio-visual telephones at a distance using satellites or fiber optics cable installations to replicate the well-crafted lecture, with minimal question asking or real learner interactivity, or absent joint inquiry across communication sites, we are as concerned about the prospects for learning offered as many critics rightfully were in the times of educational TV. The technology per se is not the central issue. It is specific kinds of activities involving the technology that will be likely to pay off. And they center on communication of the transformational kind.

By contrast, computer tools for learning are often thought of as especially well-suited to providing solitary practice for students in the skills of working with externalized knowledge representations (e.g., geometric proof statements; algebraic equations; physics formulae) that it is the student's task to master. We develop the stance on learning technologies that conceptualizes computer tools as enabling augmentation of learning conversations that can take place either between learners, or between learners and teachers.

This emphasis on learning through conversations is not intended to replace that of learning by other means, such as remembering past experiences when alone and reflecting on the usefulness of one's current knowledge in the face of new problem conditions, or learning by reading and engaging in self-explanations (e.g., Chi et al., 1989). In addition, while we are emphasizing the value of technology when it encourages interaction, we clearly recognize that less intensively interactive forms of instruction like lectures by people who have thoroughly mastered some domain of study (e.g., Richard Feynman in physics) can be exceedingly valuable. In some cases they may be the only effective means for learners today to gain access to certain information.

But here, we focus on conversations as a major source of learning resources that have been unreasonably neglected by the cognitive science community in its studies of learning, and yet that, given the pervasiveness of learning through conversations outside schooling institutions, are bound to be critical to achieving successful learning in school settings.

With this background, we will now proceed to characterize the theoretical orientation to processes of learning and teaching that provides the communication-centered approach to education that makes a telecommunications-defined IMT environment so central.

THEORETICAL ORIENTATION ON LEARNING AND TEACHING PROCESSES

There is due cause for excitement among educators and learners in the IMT trends projections of increases in RAM, MIPS, information pipeline size, multimedia services to become available, and costs of multimedia telecommunications and computing. Planning and prototype projects in laboratories now include terabit switches, gigabit data ports, video walls, and satellite wrist-wear Dick Tracy–like multimedia communication devices integrating the technologies of computer networks and wireless telephones. But all for what?

The Vision: IMT Use in Education Informed by Learning Research

A simple engineering perspective on IMT that merely continues or makes more efficient existing practices for teaching and learning would be limiting, perpetuating many of the societal problems that beset education today. We are not naive enthusiasts of technology as a panacea for solving the complex problems of learning support. But we are critically optimistic that more or less effective designs of learning environments can be defined.

Our aim here is to describe what is new in the learning sciences and suggest what would be productive uses of IMT based on these insights. We need to build on a learning-oriented perspective on IMT futures. The vision we describe here first characterizes research in the cognitive sciences of learning during the past 15–20 years, and then builds on these achievements to characterize an emerging social framework for conceptualizing learning and communication that has come from efforts to integrate perspectives from the social and cognitive sciences.

To anticipate, this vision consists of four basic shifts of perspective:

- *On the nature of learning and the learner.* From an epistemology that treats students as receivers of knowledge-as-facts, to one viewing knowledge as socially constructed through action, communication, and reflection involving learners.
- *On learning as situated in communities of practice.* From a perspective on learning and teaching as a decontextualized classroom activity, to a framework establishing connections between teaching–learning processes and increasing student membership among communities of practitioners outside the traditional classroom.
- *On the materials needed for learning.* From a curriculum-centered to a learner-centered view of educational materials, beginning with tasks that enable instructors to start with what the learner knows and construct new understanding based on it. From decontextualized tasks for learning basic skills, to the appropriately situated learning of skills and concepts in working on authentic tasks.
- *On the role of teaching.* From a view of teaching-as-telling (or "delivering" curricula), to teaching as modelling expert practice, and promoting learning conversations that negotiate meanings to promote change in learner concepts and strategies toward proficient performances.

The concomitant shifts in what are appropriate roles of IMT in education are momentous. We see many of the distance learning projects that exploit some aspects of IMT (see p. 87f) as largely accepting a one-way transmission model of education, aiming to replace the teacher rather than augment his or her communicational reach. The technologies should not serve as educational machines, "delivering" knowledge, but as resources and tools for augmenting human interactions and communications required for learning. Learning benefits from rapid two-way communications so that participants may negotiate meanings during their processes of interaction during a task. IMT tools can augment these communications and effective real-time reshaping of the distribution of resources for learning (including materials, peers, and experts outside the school). These conceptual shifts have not only theoretical but business implications for IMT design and use in educational applications. As we argue later (p. 97f), a business interest in accelerating educationally supportive IMT will be critical to defining the shape of education at the turn of the 21st century.

On the Nature of Learning and the Learner

A new consensus view of the learner, incongruent with most current educational practices, characterizes current research in the learning sciences. Research concludes that the dominant transmission view of knowledge is limited (some historically oriented reviews are provided in Brown et al., 1983; Greeno, 1980; Laboratory of Comparative Human Cognition, 1983). In the transmission perspective, the aim of pedagogy is to provide well-structured presentations of material to be learned, primarily through lecture, demonstration, and recitation (Mehan, 1979). We now see that substantial learning occurs outside schooling, and successful learning is constructed in terms of prior knowledge by an active learner in a social context. It is argued that knowledge is best acquired in functional contexts with similarities to situations for future knowledge transfer (Pea, 1987). Brown et al. (1989) have called such contexts "authentic tasks," which may include activities such as scientific inquiry, mathematical exploration, and writing for real audiences.

The new view of the learner, influenced by the work of Piaget (e.g., Piaget & Inhelder, 1969), Ausubel (1968), Bruner (1966), and others in the 1970s (e.g., Case, 1985; Sternberg, 1984), sees the development of intelligence generally, and of subject-matter understanding in education in particular, as actively constructed by the individual (see, e.g., Resnick, 1984). New knowledge is acquired in relation to previous knowledge, building upon intuitive, informal experiences. Such "experiential knowledge" must be reckoned with in education. Much recent research involves seeking to determine the understandings, preconceptions, and interests that learners bring to formal instruction, so that instruction may bridge experiential and formal, school-based learning. Such bridging is important because severe limits arise in the kinds of problems these informal reasoning methods and preconceptions can pose and solve. Analyses of preconceptions have been particularly revealing for topics in science (e.g., Carey, 1985, 1986; Champagne, Klopfer, & Gunstone, 1982, 1985; Clement, 1982; Driver, Guesne, & Tiberghien, 1985; diSessa, 1982, 1983; Harms & Yager, 1981; Larkin, 1982; McCloskey, Caramazza, & Green, 1980; McDermott, 1984, 1991; Novak & Gowen, 1984; Osborne & Freyberg, 1985; Viennot, 1979; West & Pines, 1985; Wiser & Carey, 1983), mathematics (e.g., Briars & Larkin, 1984; Burton, 1982; Carpenter, 1985; Gelman & Gallistel, 1978; Kintsch & Greeno, 1985; Resnick, 1988; Resnick & Omanson, 1987; Schoenfeld, 1985), and programming (e.g., Bonar & Soloway, 1985; Kurland & Pea, 1985; Pea, Soloway, & Spohrer, 1987; Soloway, 1985, 1986). Research work in the development of reading (e.g., Anderson, Osborn, & Tierney, 1983; Beck & Carpenter, 1986; Nickerson, 1985; Palincsar & Brown, 1984) and writing skills (e.g., Bereiter & Scardamalia, 1986; de Beaugrande, 1984; Frase, 1987) also reveals the importance of helping students build upon a rich set of communicative strategies, techniques, and experiential topics derived from oral language use that makes sense to them.

An understanding of subject matter so that problems can be solved or creatively posed requires a richly interconnected network of concepts, principles, and skills (e.g., Glaser, 1984; Greeno, 1983; Greeno & Simon, 1986; Larkin et al., 1980). The necessity of subject matter knowledge in expertise has been recognized for centuries. What is new is the research-based recognition that it is *not* a knowledge base of facts per se that should be an instructional goal. Instead, students need to acquire facts, principles, or theories as conceptual tools for reasoning and problem solving that make sense because they have consequences in meaningful contexts (e.g., Bransford et al., 1987; Brown et al., 1989; Cognition and Technology Group at Vanderbilt, 1990; Cole & Griffin, 1987; Gelman & Brown, 1986). The knowledge base acquired through education should not be inert, memorized for recall on tests, but active, conditionalized for application to appropriate contexts of use. The new educational awareness of the pedagogical priority of facts-in-use has led to an increasing emphasis on what has been described as "apprenticeship learning" (Collins, Brown, & Newman, 1989; Resnick, 1987) or "learning by doing" (a renewal of Dewey, 1956), and "guided microworlds." Students acquire knowledge-in-use, experiencing and employing new concepts and skills in appropriate contexts of application.

View on Learning as Situated in Communities of Practice

Learning is conceptualized as a lifelong process integral to becoming a member of different "communities of practice," and sustaining such membership. The construction of personal identities largely involves defining participatory roles in different communities of practice (Eckert, 1989). Understanding communication conventions like language and symbol use are critical to successfully joining any new community. Persons always are members of multiple communities of practice, which may emerge, change, or disappear during their lifetimes. Such membership is conceived of as an activity[3] system about which participants share understanding regarding what they are doing and what this means in their lives and for the different communities of practice in which they participate. Lave and Wenger (1991), in generalizing the theory of learning as "cognitive apprenticeship" developed by Brown, Collins, and Duguid (1989; also see Collins et al., 1989; Greeno, 1989; Pea, in press-b), have formulated a situated learning perspective that sees learning as an ongoing and integral part of membership in communities of practice (also see Allen, in press).

On this view, as in cognitive science work on the nature of the learner, the acquisition of expertise from education is still viewed as important. But rather than construing expertise primarily as the acquisition of domain facts, problem-solving procedures, heuristics, and metacognition for formal problem solving, expertise is viewed as particular practices of a community. And learning is viewed not only as a relation to problem-solving activities, but in terms of participation as member in the practice of different social communities. Pea (in press-a) has described how, in science, such a practice consists of ways of talking and acting (which include many shared goals, concepts, procedures), belief systems about what is interesting about problems, shared views of when it is appropriate to use particular tools, and developing kinds of sense-making activities that seek to evolve scientific concepts to fit the world (e.g., modelling, theory building, simulations). A community of practice for science includes at its frontiers diverse claims to knowledge, and disputative means for advancing and resolving such claims, as the success of concepts as resources for resolving new problems is tested (e.g., Lakatos, 1970; Toulmin, 1972). Learning then is not perceived as transmission of information from teacher to learner, but as a process of participating in the activities of a community, by means of collaborative sense-making in which knowledge functions as a tool to resolve emergent dilemmas (Brown, 1989; Lave & Wenger, 1991).

A central focus of this broader social framework for conceptualizing learning is an emphasis on how students learn about the practice of different communities by participating in their activities, through joint action and discussion. This emphasis applies whether one is learning mathematics, history, science, art, law, cooking, or foreign languages. Students and teachers come to understand one another's meanings for external representations (e.g., equations, texts, recipes) and strategies for action through their situated use. Emphasizing the communicative exchanges between learning participants shows how the traditional classroom context often radically undervalues the meaning of technical talk, symbols, action, and their mappings to the physical world, which ideally lead to the establishment of common ground between students and teacher. In the didactic mode typical of instruction, few opportunities emerge that allow either students or teachers to use iterations on the interpreted meaning of their discussions as a learning vehicle.

Creation and interpretation are the reciprocal processes of human conversational action, through which meaning gets established and negotiated (e.g., see Goodwin & Heritage, 1990; Heritage, 1984; Schegloff & Sacks, 1973). Meaning negotiation is a central mechanism for individuals to engage in the social construction of meaning through conversation. Its structure consists of reciprocal acts of interpretation between speakers. In education, these processes of meaning negotiation need to take place more than they now do in the context of authentic activities. For example, in science learning, this means engaging in inquiries that require sense-making conversations using the technical concepts and procedures of science, and tasks such as prediction, observation, and explanation. During such inquiries, the meanings of representations for learners such as words for technical concepts and diagram components are continually remade through their use and commentary on their use, through creation and interpretation.

[3]A focus on learning by doing was central in Dewey's (1956) seminal work on education, and in Bruner's (1960) influential formulations of an activity-centered, inquiry approach to learning. The perspective on situated learning under development by Brown (1989; Brown et al., 1989; Collins, Brown, & Newman, 1989), Greeno (1989), Pea (in-press-a, b) places greater emphasis than those earlier works on both the social theory in terms of which learning-by-doing is framed (Lave & Wenger, 1991) and the fine structure of human interactions through which the collaborative construction of meaning for specific subject matter learning takes place (Roschelle, 1990; Roschelle & Behrend, in press).

Meaning negotiation takes place using diverse interactional procedures such as requests for clarification or elaboration; gestural indications of misapprehension; explicit paraphrasings of what-may-have-been-meant to test for understanding; explicit commentaries, repairs, and other linguistic devices for signalling and fixing troubles in shared understanding (e.g., Schegloff, in press).

Ethnomethodologists such as Garfinkel (1967), Garfinkel and Sacks (1970), Schegloff and Sacks (1973), and Mehan and Wood (1975) have highlighted the importance of indexical support for such meaning negotiation. With indexical support, speakers opportunistically use the resources of the physical world to clarify what they mean, given the ephemeral nature of spoken language. Their words are "indexed" to referents in a situation, such as words or symbols on a whiteboard or computer screen. Such indexing is critical for establishing a shared semantics of representations, referential mappings between situations and formal symbols depicting world entities. Herbert Clark and colleagues (Clark & Shaeffer, 1989; Clark & Wilkes-Gibbs, 1986) have referred to this achievement as establishing a "common ground." While these processes are central to day-to-day communicative action, they are often not supported in the classroom context when it is dominated by didactic method.

These points about language generalize to the use of symbolic forms more generally in teaching–learning communications, including such media representations as diagrams, pictures, mathematical symbols and equations, and simulations. Such teaching–learning discourse often involves the use of complex symbolic representational systems in a discourse "workspace" between participants (e.g., diagrams, graphs on a whiteboard, lines of programming code on a computer screen, aspects of a graphical simulation model). These representations come to serve as resources that enable speakers to engage in conversations about complex conceptual entities, such as slopes on a graph, or rays of light. They can point to these entities, have discussions about them to clarify what is meant, and describe how they are connected to other things. IMT could allow such key learning activities to take place over a distance, as remote collaborative activity including diverse media including video and drawing spaces is made possible. Currently, such applications are largely limited to laboratory prototypes, such as CAVECAT (Mantei et al., 1991), Cruiser (Fish, 1989; Root, 1988), IIIF (Buxton & Moran, 1990), TeamWorkStation (Ishii & Miyake, 1991), VideoDraw (Tang & Minneman, 1990), and VideoWhiteBoard (Tang & Minneman, 1991). However, without a fundamental recognition that perhaps the most important role of media in learning is to support and enhance communication, we run the risk of designing instances of IMT that hinder learning or are simply irrelevant to it.

View of Materials Needed for Learning

Massive curriculum reforms in precollege mathematics and science were funded by the federal government in the 1960s and early 1970s, including those of the Physical Science Study Committee, the Biological Science Study Committee, Chemical Bond Approach, Project Physics, and the School Mathematics Study Group (March, 1987). Although these projects were designed to produce materials so that students could acquire subject "understanding," these materials made their major breakthroughs by providing deep, structural analyses of the subject matter, which were then reflected in the curricular structures that were developed. For the past several decades, education has been correspondingly curriculum-centered. The major change wrought through recent research in the learning sciences is a learner-centered view. Even though educational topics, examples, and subject matter structure and sequence still need analysis and careful design, there is a broad consensus that they should begin with the knowledge states of the learner, and build from there.

Substantial evidence indicates that most present curricula as used poorly promote subject matter understanding (e.g., Crosswhite et al., 1985; Driver et al., 1985; Harms & Yaeger, 1981; Holdzom & Lutz, 1984; McDermott, 1984; NAEP, 1990a, b; Ravitch & Finn, 1987; Resnick, 1988). We also know that the lack of specified relationships between traditionally distinct curricula leads for most students to isolated knowledge structures that correspond but too well to the curriculum boundaries (e.g., Pea, 1987). Concepts and skills involved in various disciplines are needed in an integrated manner for reasoning and communicating in order to solve real-world problems. Concerns also emerge in the common lack of transfer of school learning to experiential situations outside school in society and work, and in the non-use of experiential knowledge (such as invented algorithms for addition and subtraction) in school settings (e.g., Carraher & Schliemann, 1985; Lave, 1987; Resnick, 1987).

Present learning materials have several other major problems besides lack of integration. They are often comprised primarily of referentially isolated activities, decontextualized from their meaningful relation to real tasks (Brown et al., 1989; Miller & Gildea, 1987; Resnick, 1987). Prominent examples include syntactic drills in arithmetic and algebra, memorization of vocabulary definitions, rote enactment of cookbook lab experiments, and part-of-speech sentence diagramming. Calls for reform highlight the "inert" nature of much knowledge acquired through formal education, whose "anchorings" to the world are left unspecified (Cognition and Technology Group at Vanderbilt, 1990).

In consequence of these decontextualized activities, it is not surprising that many studies of classroom instruction have shown how little actual instruction takes place of whole activities such as reading to learn, writing for audience, mathematical modelling of situations, or scientific inquiry (e.g., Anderson et al., 1983; Bereiter & Scardamalia, 1986; Schoenfeld, 1985; Stake & Easley, 1978). In designs of new learning environments, what have typically been characterized as "basic skills" are not taught as ends in themselves, but as component tasks whose fluency is required for success in real activities (e.g., Brown & Campione, in press; Cole & Griffin, 1987; Collins, 1985; Sticht & Mikulecky, 1984). Real applications of knowledge to be acquired are at the core of instruction, and students are "scaffolded" as they become increasingly more proficient in taking on parts of the whole, meaningful task, with instructional support "fading" as competencies are achieved (Brown & Palincsar, 1989; Collins et al., 1989) in the "construction zone" for learning (Newman, Griffin, & Cole, 1989). The aim of autonomous or collaborative real-task performance is explicit from the start, not promised at the end of isolated drill activities with unspecified conditions of applicability. Instructional studies utilizing such methods for reading comprehension (Brown & Palincsar, 1989), composition instruction (Bereiter & Scardamalia, 1986), and mathematical problem solving (Lampert, 1990; Schoenfeld, 1985) have been highly successful in improving student capabilities with this approach.

Microworlds have also demonstrated potential as important components of new learning environments. Microworlds (Papert, 1980) are uses of the computer for providing dynamic models of systems that students can explore and study, either without instructor support, with instructional guidance built into the program ("guided microworlds": White & Horwitz, 1987), or to support new kinds of learning conversations among peers and their teacher (Pea, in press-a; Roschelle, 1990). Prominent examples include microworlds for learning introductory physics of motion (diSessa, 1982; Roschelle, 1990; White & Horwitz, 1987), electrical circuit behavior (Brown, Burton, & deKleer, 1982; White & Frederiksen, 1987), steam plant physical systems (Stevens & Roberts, 1983), and geometrical optics (Glaser, in press; Pea, Sipusic, & Allen, in press).

Microworlds are seminal tools for promoting student learning because they highlight learning objectives central to "understanding," that is, how things work. Students can learn by doing, by acting on microworlds rather than merely observing demonstrations of phenomena. They may acquire understanding of the properties of systems and relationships among changes in their properties through their actions upon the systems. Some microworld systems let students build or program their own worlds, and they can then explore how they work, examining the consequences of changes in their properties. An example is the microeconomic simulation Smithtown (Glaser, in press), in which students can vary price and population and observe effects on demand, and use tools such as electronic spreadsheets and graphing programs to support lab investigations. Microworlds can be constructed for close resemblance to real-world activities, so that transfer of learning from working with the microworld and the world of concrete action are closely coupled. New actions that are possible with these microworlds—due to the ability to make changes of scale in space, time, size, and relationships—allow for other powerful teaching and learning opportunities (Lesgold, 1986). Imaginary microworlds can also be constructed—non-Newtonian universes and the like—that offer new capabilities to bring to life and render apparent for students things that they could never see or imagine without the technologies (Lawler & Yazdani, 1987).

Other research recommending the use of multiple media in teaching–learning discourse comes from studies of individual differences in experience with and relative capacity to learn from different modalities, such as text, pictures and diagrams, graphs, and equations (Hegarty & Just, 1989; Snow, 1986; Snow et al., 1980). A principle distinction between text-based and graphically based modes of learning finds some research support (Fleming, 1979; Mandl & Levin, 1989; Paivio, 1971), and suggests the importance of creating and testing new IMT technologies that offer opportunities for enhancing visual learning environments. Most paradigms for educational technologies are print-based, perhaps because print characterizes information environments in schools. For most instructional activities, minimal use is made of recorded voice, music, and other sounds, or visuals such as pictures and diagrams in books, and filmstrips, slides, or uses of video in cassette, videotape, or videodisc formats—even though these media may be highly effective for learning. The "text-reading eye" has been the primary sensory channel for most education, and yet this is a radical impoverishment, given the senses available from which learning takes place in the world outside the classroom.

Beyond considerations of individual differences, a core insight of cognitive science has been the utility of multiple representations of knowledge for supporting learning, reasoning, and problem-solving activities. Each representational system—natural language, symbolic equations, logical formalisms, pictures, functional diagrams (e.g., of circuits, or flow processes), graphs, etc.—has specific strengths and weaknesses in the features it provides to support or guide problem-posing and problem-solution processes (e.g., Bobrow, 1975; Larkin & Simon, 1987). Expert reasoners in a subject area tend to be highly flexible in the representations they choose to exploit for posing and solving problems (Greeno & Simon, 1986), so a desirable goal of curricular design should be to facilitate fluency in the various representations of knowledge that a student will need to use.

View on the Role of Teaching

With new conceptualizations of the learner, and of appropriate learning materials, comes a new understanding of the role of teachers in promoting effective learning and understanding (Carnegie Forum, 1986). Many of these insights are implicit in what we have said, and many of the techniques are used by expert teachers. But there is a new specificity to why such techniques work that supersedes previous understanding. Much more attention to learners' preconceptions is needed for formal knowledge to be acquired through teaching and learning activities. This requires forms of evaluation that are more labor-intensive and teaching-relevant than traditional classroom assessment measures (Frederiksen, N., 1984; Frederiksen, J. & Collins, 1990; Glaser, 1987; Nitko, 1989; Resnick & Resnick, in press). But it also requires far more attention to the discourse among students and teacher that provides such critical materials for learning.

As we have noted, learning is fundamentally built up through highly interactive conversations, involving the creation of communications and efforts to interpret communications. Communication is not viewed in terms of one-way transmission and reception of meanings, but as two-way transformational, enabling the progressive construction of meaning through successive turns of action and talk. And conversations are the means by which people collaboratively construct the common ground of beliefs, meanings, and understandings that they share, and also articulate their differences. These conversations also provide the publicly available resources and thus the opportunities for speakers to determine how they were understood, often occasioning meaning negotiation and cognitive change. The teacher's role is to model inquiry, provoke inquiry oriented to students' conceptual change from pre-existing alternative conceptions of the subject domain, negotiate meanings in discourse with students, and serve to represent a community of scientific practice.[4]

One current problem is that education tacitly espouses counterproductive belief systems of authority-centered epistemology and a passive role for the learner in the knowledge acquisition process (Brown, 1989; Cole & Griffin, 1987; Mehan, 1979; Schoenfeld, 1985). Individuals create, revise, and contribute not only to their own knowledge but to that of the culture. To facilitate this awareness of the purposive and constructed nature of knowing—rare among students but common in the disciplines—the teacher needs to create a community, in which thinking and problem solving of the kinds required for the discipline(s) under study is contributed by all members of the group (Allen, in press; Brophy & Good, 1986; Collins et al., 1989; Hawkins & Pea, 1987;

[4]While teachers can rarely literally reproduce all the details of authentic science activity in their classrooms, they can model authentic practice by engagement and reflection on real exploration of topics occasioned by inquiry activities. Lampert (1990) and Schoenfeld (1985) have experienced success with such practice in mathematics education.

Lampert, 1990; Resnick, 1987). Several kinds of activities appear to contribute to the establishment of such a community: (a) the teacher works on real problems, thinking aloud where feasible, including problems that are novel and for which answers are not immediately apparent, describing reasons for making certain strategic decisions and not others, working through reasoning steps; (b) the teacher solicits contributions to this process from classroom members so that they come to collaborate in the problem-solving process, even when they would be unable to carry out the whole task alone; (c) students come to take on "roles" or subtasks in complex collaborative problem solving, and rotate in these roles; and (d) group discussions take place on such processes, reflecting on and consolidating what has been learned.

Implications of Learning Theory for IMT Design

We have briefly reviewed how research in the learning sciences has led to important shifts in how the theoretical foundations and practical activities of education are conceived. We now wish to use this work to develop a framework on the needed technology for supporting communicative processes.

Our most basic case for defining this framework is what happens when people engage in face-to-face joint activity. They engage in rapid turns at talk involving shared access to objects, external representations, processes. They see each other and other representations that they may share, they can establish joint reference to objects, processes, and data about which they are talking, and they can contribute to a single piece of joint work in real time by interweaving their activities.

We may thus ask a central set of questions about IMT for learning and teaching that build on these findings from the learning sciences:

- *How rich are the media of expression for multimedia communication and/or computing?* One will often need expressive capabilities for both students and teachers that go beyond text to include graphics, video, or other media (Ambron & Hooper, 1987). Understanding complex dynamic content may often be dramatically easier with video (Lippman, 1981).
- *How rich are the communication possibilities of the communication network?* If workstations for learners are connected together within a classroom or school or across remote sites, one needs to ask how they may support the kinds of learning conversations and meaning negotiation we describe as central to learning communications. A set of basic distinctions here is between synchronous communications such as a telephone that do not allow sharing of data, activity, or visual referents, and between asynchronous communications that may allow such sharing, but not in real-time, such as electronic mail, voice mail, video mail, or file transfer. And then one could have various degrees of simulated co-presence, allowing for synchronous sharing of different media types and visual referents if interactive video were part of the IMT system.
- *How integrated are the multimedia computing and communication capabilities of the system?* It may be the case that standalone workstations for learners or teachers are capable of using video, audio, and other media types, but that only text (or text and graphics) can be communicated to remote participants in a learning environment. At the other extreme, one may be able to share through communications with other participants computational artefacts as complex as those one is able to create with one's own multimedia computing resources, such as science visualization animations with voice annotations.
- *How "advanced" are the applications of computing?* One can scale up the complexities of computing applications and make correspondingly greater demands on the communicative and collaborative activities possible at a distance with IMT. Even today, using remote screen sharing programs such as Timbuktu (Farallon), multiple individuals can collaboratively construct a text or graphic document in real-time. But such activities become harder to achieve as the work tasks become computationally demanding, as in the case of complex scientific simulations, due to data transfer rates attainable.

In the next section of the paper, we begin to describe an educationally rich IMT that builds on prior learning research and attends to these questions. The well-known Dynabook design for IMT provides a place to begin these considerations.

IMPROVING THE DYNABOOK: TOWARD EDUCATIONALLY RICH IMT

If the classroom is a major resource of education, and, as we argue, it is fundamentally a social interaction unit that fosters the transformation of knowledge through communication and interaction, how then should IMT technologies become a part of today's and tomorrow's classrooms? Classrooms need to be intelligently re-engineered so that interactions between students and teachers are encouraged and not discouraged by IMT technology. In addition, IMT's entry should break down classroom "walls" such that the classroom community is broadened through tele-presence to include domain experts, other students, and members of communities far beyond the classroom's physical walls. To become a part of the classroom, IMT's realization in specific technologies must improve the educational context and processes while building on the prior media knowledge and expertise of teachers and students. Specific technological realizations of IMT must also accomplish the dual goal of allowing for incremental migration from today's technology while at the same time demonstrating a clear pedagogical value-added.

Problems of Classroom Media Today

Today's classrooms are media-rich places. They also contain all sorts of media-display devices, such as blackboards, overhead projectors, film projectors, VCRs, and computers. Each device gives teachers and students particular expressive qualities. Today each device is a separate communication palette, not electronically connected to the others. In essence, there is no underlying theory or well-understood set of experiences that detail the particular expressive value that each device, and the media that may be created or displayed with it, brings to learning or how the media can be combined for particular communications outcomes.

Why, for example, does a teacher at a given moment in an instructional conversation choose a blackboard as the means to support teaching–learning communication, and choose an overhead projector at another time? Or, what defines those occasions where a still image works best as conversational support in comparison to motion video? We currently lack the principles or the appropriate lenses on the decades of experience with communication media to answer these questions. Yet answers to these questions become very pressing in an IMT future where communication bandwidth, software, and hardware will combine to give teachers and students orders of magnitude, more raw media access, and expressive potential than that available today, and where choices along with these dimensions have service and pricing implications, as Schramm (1977) years ago argued for noncomputer media in education.

The expressive potential of media, however, will be diminished unless we understand how to engineer classrooms, other learning environments, and the tools they contain so people can use them. In today's classrooms, for example, teachers use tools whose design and expressive potential are not well suited to the tasks to which they are put. Films and videos are a perfect case in point. Teachers often acquire and show a 30- to 60-minute video when only a 2- to 5-minute segment buried in the middle contains the material that is crucial to the educational matter at hand, and even this segment needs special elaboration and annotation. This is in essence an example where the medium is useful (film and video) but its representation as a sequence of analog images is ill-suited to the two-way communication intensity of the classroom. In situations like this, teachers are often forced to retrospectively point out to students the salient aspects of the just-presented film or video. In a similar vein, it is easy to find examples from classroom observations where a teacher or a student wants a specific graphic or picture but it is not readily available from any classroom book (Cruz, Gomez, & Wilner, 1991). If time is taken to attempt to get the needed example from elsewhere, the instructional immediacy of the moment for the creation of a learning conversation is lost.

In addition to resolving the mismatch between expressive potential and expressive need in classrooms and other learning environments, IMT can make the technology and the data available in the classroom available at home. Children spend a significant amount of time using media for both entertainment and instruction. For the most part, media used for these purposes are separate from any school-based or other learning activity. For example, video games that kids use at home are wholly separate from the computers and other data they use in the classroom. It is also the case that people who work together in classrooms (e.g., with computers) cannot continue to easily re-establish those collaborations and their computational context outside the classroom. Properly networked IMT could encourage a merging of entertainment and educational technologies and make it possible for all students to continue in-class collaborations outside classroom boundaries.

It is clear that IMT, as it makes its way into the educational infrastructure, has to have a well-articulated vision and theory of the classroom interactions in need of technological support. Neither a theory nor well-articulated vision exists now.

IMT technology and its precursors, however, continue to develop. As we will illustrate later in this section, there are several ongoing technology experiments that perhaps signal the coming of an IMT future. Given this reality, we cannot wait for a well-articulated theory of IMT construction and use in learning situations just because today many people have essentially no access to educational resources (people and information) in significant quantity. The immediate instructional need and the ongoing explosion of critical information may make it impossible to have such a well worked-out vision without drawing on the valuable experience of several well-run sample IMT-like experiments and the current use of technology to meet educational needs. We may be at a fortunate moment in history to develop a new vision because information networking, multimedia software technology, and hardware technologies are all maturing at a time when national attention is being focused on education, with such initiatives as President Bush's America 2000 plan, and the related New American Schools Development Corporation's $250 million competition for 5 years of support to various groups to design the "break the mold" school systems of the future.

Dynabook Plus

If a new vision were created and realized, and classrooms had educationally rich IMT, what would it be like? The classroom IMT would almost certainly bear some resemblance to Kay and Goldberg's (1977) Dynabook and John Sculley's 1989 interactive computing vision of the Knowledge Navigator. Dynabook and Knowledge Navigator envision most people computing with small notebook-sized computers that handle in a straightforward way all of a user's information-related needs. Information needs in this context include all remote person-to-person and person-to-information interactions. These visions are intriguing because the computing portrayed in them gives users transparent access to vast stores of multimedia information. They envision information represented so flexibly that it is easily reconfigured on demand by its users on-the-fly. What is perhaps most startling about these visions of computing are their immediacy—how they close the gap between thought, action, and realization. The Dynabook and the Knowledge Navigator, if they really existed (neither has been built), would have such flexible input and display characteristics that the computer as an explicit device apart from the particular problem-solving and communication context would simply "disappear."

However, what was fundamentally lacking from the Dynabook vision (that motivated personal computing) and also from the first Macintosh that Apple created, was fundamental communication capabilities in the computer itself. The first Macintosh was a closed machine, and person-to-person communication was not described at all in the first Dynabook vision. How striking that personal computing was not thought to be personal computing and communications! By the time of Knowledge Navigator, this had changed, as had the world of computing, which had realized the basic need for network communications to support collaborative work and the communication activities required by day-to-day business. So the Knowledge Navigator video simulation of the future includes a depiction of a science lecturer engaged in an audio-visual phone call with a colleague who sends data to him, thereby enabling a better lecture.

What Will the IMT Interpersonal Machine Look Like?

We do not know. But, we may fruitfully ask, what functionality does the communication IMT machine need to have in order to support learning–teaching activities such as those we describe? Basically, wherever and whenever you want to use it you can, with comfort. Inevitably, there will be different niche markets defined for specific machine designs where users trade off cost and performance for such criteria as relative portability. We also would like to see interpersonal IMT designed so that it has appropriate fit to its use situation. What we describe below are some defining parameters of interpersonal IMT. For IMT to be integrated in the full range of teaching and learning activities, it must be supported by technologies that allow virtually ubiquitous access to information and people.

- *Rich information networking.* The first and perhaps most important characteristic of an educational IMT environment is that it be supported by a seamless high-bandwidth universal information network that allows people of almost any age to plug into it on demand. Such a network should provide "information [including access to other people] anytime, anywhere, in any volume, in any form" (Handler, 1990). No existing network today meets this demand. In terms of universality, perhaps the closest approximation is the public-switched telephone network. The telephone customer can pick up a phone and call virtually anywhere in the world in a matter of seconds. As facsimile technology has made its way into the marketplace, the same network is used to deliver paper documents in addition to voice communications.

  The sort of network that will support the IMT vision will allow people to initiate "telephone calls" (which start as voice transmissions) and grow to include multi-way video of other people or interactions with stored data and program sources. Network visions like this imply rethinking the fundamental infrastructure of public network communication (White, 1990; see Weinstein & Shumate, 1989, or Handler, 1990, for a discussion of the information networking visions and challenges). It is not clear that current network architectures, layered communications protocols, and signaling protocols can service as the infrastructure for IMT (Hardt-Kornacki, Gomez, & Patterson, 1990), which is why, as Handler (1990) points out, the process of defining future networks must focus on human needs. We suggest that educationally rich IMT *is* a centrally important need.

- *Lifelong access and utility.* Another characteristic of IMT is that it should have lifelong utility to people. IMT infrastructure and instances of hardware/software interfaces should support a high school student doing a multimedia term paper as facilely as a preschooler engaged in exploratory learning. This need points out many unsolved problems, not the least of which is the design and development of hardware and interfaces that serve people at all stages of physical and intellectual development. Today's hardware and software market places the bulk of its design and development effort on those who work at desks, type, and have good eyesight. Yet it is easy to see how new styles of interfaces, like those developed by Nintendo for home video games, can open interactive computing to new audiences. It is equally easy to see from the revolution in cellular communication that people need and want communications access while not physically tethered to the communication infrastructure. If IMT technology is going to be useful to people in the ways they learn and work, it will have to expand interaction opportunities, be usable while tether-less, and become much more compact in the style of notebook computers with gesture-based interfaces (Carr, 1991). Recently these trends have come to be broadly characterized as "nomadic" computing.

  We are not arguing that the IMT interpersonal machine will be a notebook computer or some other know-now design but simply that for educational IMT to dawn, computing and communications technology must evolve to accommodate the wide range of physical environments in which people learn. We believe this variety in effective physical conditions for learning is a constant fact of learning. Schools and classrooms as physical environments have remained relatively unchanged over decades of technological onslaught. Computers, for example, have come into classrooms and found their way into corners, covered with dust covers rather than human hands. We believe that traditional learning environments have often resisted technology because the technologies have failed to be designed (in terms of both hardware and software structure) with the needs of effective education in mind. On this last point then, educational IMT technology must provide sufficient flexibility to allow a child to explore biology in the park and lie down on a dining room floor to do his or her homework.

- *Standards.* Thus far we have mentioned the need for ubiquitous information networking and an expanded array of human interface technologies. To these requirements, we must add the need for interoperability standards for both multimedia data and systems. In many ways, today's access to communication media via interactive computing or otherwise is best described as an assortment of information islands rather than as an integrated body.

- *Situationally appropriate interaction technology.* Display and interaction technologies that support rather than hamper human interaction are key to IMT success. For example, when computers are put into classrooms they are likely to be more successful if they are unobtrusive, perhaps installed into desks to avoid blocking eye contact. Classrooms may also require collaborative input devices to allow teachers and students to work together within computational media. Future IMT technology should also seamlessly integrate personal and group media display (e.g., integrated LCD and video projection) so that teachers and others who are the focus of attention can interact with IMT between workstations. While technical roadblocks exist, it is clear that current progress in flat panel, portable head-mounted and front screen display technology (Baran, 1991; Nelson & Wullert, 1991) are starting to make design of display technology appropriate to the variety of IMT use situations possible.
- *Expanded message creation.* IMT technology has to accommodate an ever-growing list of media creation tools that allow people to create messages. It is already the case that a growing number of enterprising students are starting to replace paper artefacts with video artefacts as methods to exhibit their knowledge. For example, some colleges report that some applicants submit videotapes rather than submitting typewritten entrance essays. Voice mail and voice annotations to text documents are becoming increasingly commonplace in the workplace (Francik, Rudman, Cooper, & Levine, 1991). And some political candidates and office holders now mail constituents videotapes rather than newsletters. Examples like these suggest that future IMT technology will have to allow message creation with technologies like scanners, digital still and video cameras, and microphones.

In sum, we are envisioning an IMT future that is supported by a rich information networking infrastructure that will enable expanded interpersonal communication. In order to create new learning environments and support the preexisting variety in physical environments people use to learn, IMT must have true shared access to data, interactive messaging, and audio-visual communication that is not only broadcast but point-to-point and point-to-multi-point. Educationally rich IMT will not, obviously, come all at once. It will be the product of several years of development. Technologies that will make IMT possible are currently deployed to some extent, albeit limited. Next we survey the several technology experiments and discuss the extent to which they are consistent with the IMT vision.

ON THE ROAD TO THE DYNABOOK-PLUS?

Thus far we have been characterizing visions, not actualities. There are, however, several areas of active research and technology development that may give us a picture of where we are on the road to realizing IMT. We will discuss each of these areas of technology in turn. Our goal here is to identify the activities that are consistent with our emerging vision of educationally rich IMT as Dynabook-plus and to point out where the vision is not being supported by current efforts in research and technology. There are several candidates deserving mention. But before we begin our review (which is sometimes critical of existing applications and experimental applications of technology), it is worth recalling that in spite of their limitations, we see current services and applications of technology to education as having two valuable functions: First, experience with them will help to shape IMT for distributed multimedia learning environments (DMLE). Second, current applications are an important response to information and instructional needs that exist now and often are unmet.

Distance Learning Experiments and Services

One aspect of the IMT vision is the expansion of educational communities of interest beyond the physical boundaries of classrooms and school buildings with the aid of technology. In many ways, modern audio-visual distance learning applications capture this aspect of the vision. Modern distance learning uses satellite or high-bandwidth terrestrial communications to bring teachers and students together. Below we briefly describe some major examples of interactive video classroom experiments that have begun, using high-bandwidth transmission media to connect classroom sites.

- *WETC and Contel of Minnesota* (Nelson & King, 1988; Price, 1988). The goal of this project was to share costs of faculty and resources for advanced instruction with other school districts, colleges, and universities. The resource pool of teachers accessible to students was thus enlarged. In the 1987–1988 school year, 85 participating seniors from three school sites in the Wasioja Education Technology Cooperative (WETC) studied math, physics, Spanish, and psychology-sociology. WETC is made up of 10 independent school districts that were slated to become part of the project. WETC covers 2,396 square miles in southern Minnesota, with sites 25 miles apart. Contel installed a six-fiber cable between its central offices (two exclusively used for the analog streams of video for the school project, four for Contel's future customer service). The school decided against microwave transmission because of hilly terrain that would make interference and transmission delays likely. Fiber was required between schools and their central telco offices (which schools leased), and between the central telco offices (which Contel provided as part of their cable upgrade plan).
- *Stromberg-Carlson Corporation and Northwestern Bell Des Moines Iowa FOCIS Project* (Gramkow, 1988; Nelson & King, 1988). Stromberg-Carlson and Northwestern Bell teamed up to create FOCIS (Fiber Optic Communications and Instructional System) for broader access to academic and enrichment courses such as advanced placement, foreign language, and other courses in science and social studies not available at home high schools. The Des Moines school district serves 30,000 students in 41 elementary schools, 10 middle schools, and 5 high schools, 1 of which (Central Campus) is a magnet resource center for the district. Classrooms were each equipped with a video camera, a television monitor, and a video codec. An IBM-compatible computer controlled the FOCIS from the teacher school site. The system was primarily for multi-point broadcast—from a single teacher to multiple classrooms. The teacher could "see" into the other classrooms because of a scanning mode that stepped through video connections from each of the remote classrooms in sequence (i.e., every 2, 5, 10, 20, or 30 seconds). The teacher could then select a remote school to allow for "talk-back" from students in that site. Any high school site could originate a multi-point broadcast, and any two sites also had the capability to do point-to-point video conferencing.
- *The Grass Valley Group's (GVC) MASTER (Multiple Access System for Televised Educational Resources) Interactive Learning System* (Morsfield & Lehner, 1990). GVC, owned by Tektronix Co., first installed this system in northwest North Dakota in early 1990, connecting a "studio" classroom in each of five rural high schools using digital fiber optic transmission. As in the FOCIS project, an instructor could see participating classrooms on a scanning basis, but MASTER could also support continuous viewing of all classrooms by the others (with much higher costs in transmission equipment, optical fiber, and monitors). Their network controller was a workstation that could support as many as 128 classrooms, with as many as 9 classrooms that could connect together for the same teaching session, and multiple sessions could be conducted at once. In scanning mode, MASTER used an interesting video configuration, in which four monitors were placed in every lesson-originating classroom on the network. Two were for the teacher—one scanning through the different classrooms to which his or her lesson was broadcast, and one letting the teacher see what was being broadcast to the remote classrooms. The other two monitors were for the students—one was of the teacher, the second displayed any other selected classroom or printed images, video, or computer images, all under the teacher's control. When a student had a question, he or she signaled the teacher, who could then display that student's classroom for all connected classrooms to view.
- *A-Plus Network* (Advanced Photonics for Linking Unified Schools) with Southwestern Bell in Kansas. Announced in March 1990, this project's goal was to install 181 miles of fiber optic cable to create Southwestern Bell's first interactive video network. The A-Plus network provided full-

motion analog video with multichannel capacities. Students in nine remote Kansas schools across eight unified school districts could use the network to share teachers and participate in class discussions, up to four classrooms at a time. As in most interactive video experiments, course offerings in fall 1990 were in advanced courses—science, mathematics, and foreign languages. In these interactive classrooms, continuous monitoring took place between the teacher's classroom and the three other classrooms with a four-monitor system. A-Plus could also take programs from any of these classrooms and send it out to all community households receiving cable service.

Commentary. Unfortunately, none of these experiments, in our view, is adequately accompanied by studies of learning, or teaching–learning processes and how they may be transformed by the communications technology. They all appear to be demonstration projects allowing for remote "chaining" of classrooms accomplishing distributed traditional lecture instruction. The teacher is remote from some or all the students. The teacher's lecture is broadcast to one or more remote classrooms. In most situations video communication is one-way. Students ask questions and otherwise interact with instructors via audio callback channels. In a few cases teachers have two-way audio and video. In these cases it is the teacher who has sole and relinquishable control over who (i.e., which remote class/classes) is seen and heard. The current crop of distance learning systems and prototypes have no facilities for small-group interaction. It is truly a remote lecture. Teachers, for example, cannot interact with a small group of students to the exclusion of others. Similarly, students who use these systems cannot establish small remote "in-class" collaborative teams to work on some aspect of the problems at hand. In addition, the image remote participants see is a TV-sized image that, needless to say, is orders of magnitude smaller than the real thing. These small images may fail to convey the subtleties in instruction apparent in physical classrooms.

For the most part, modern distance learning does not integrate data into the educational experience. Students in remote locations see examples projected on monitors. But, unlike a "real" classroom, students cannot go to the board and interact with the teacher's example. The sole exception to this is that a teacher can ask multiple choice questions and students can respond with a yes/no with a TV-like wired remote control device. Techniques like these give teachers a gross estimate of a student's current level of understanding. This clearly falls short of the multiplicity of ways teachers have to access students' understanding in physical learning environments. Even the most modern desktop audio-visual communications systems like Bellcore's Cruiser (Kraut, Fish, Root, & Chalfonte, 1990; Root, 1988) or Xerox EuroPARC's Polyscope/Vrooms (Borning & Travers, 1991) have not accomplished the sort of full integration of media needed by classroom IMT. These systems provide very flexible personal two-way video communication. But they too have not solved the problem of truly integrating data communications with audio-video telephony.

In short, it is safe to say that today's distance learning technology and even modern desktop teleconferencing fail to create with tele-presence a great many of the important aspects of the physical classroom environment.

Electronic Mail and Conferencing

In quite a different class of systems, we see another aspect of the Dynabook-plus vision being accomplished. There have been several K–12 instructional initiatives that have sought to expand educational communities of interest with the aid of e-mail and asynchronous conferencing systems. The most well-known of these projects are the AT&T Long Distance Learning Network (Riel & Levin, 1990), EarthLab (Newman, Goldman, Brienne, Jackson, & Magzamen, 1989), the Inter-Cultural Learning Network (Levin, Riel, Miyake, & Cohen, 1987), National Geographic Society (NGS) Kids Network (Julyan, 1991; Tinker, 1987, 1989), the Quill Project (Bruce & Rubin, in press), the TERC Star School Project (TERC, 1990; Tinker, 1992), and the 5th Dimension Activity System (Cole, 1990). Hawkins (1991) has succinctly reviewed the issues in the development of these distance learning projects. Research on college level "virtual classrooms" and online education initiatives have been described by Hiltz (1986) and Harasim (1990).

These K–12 projects vary quite a bit in instructional goals. For example, EarthLab was designed to allow elementary school students to form collaborations, and discuss scientific data collection. The Intercultural Learning Network, by contrast, was used by older students to explore cultural differences and similarities through communication. The Kids Network supported collaborative science research in several thousand elementary schools across the United States. The TERC Star Schools project engaged collaborative scientific inquiry among middle-school students with micro-based laboratories. These projects also varied in the amount of distance that separated the collaborators, from within the same building to halfway around the world. Each project used some form of e-mail or asynchronous conferencing to establish pedagogically based collaborations.

Commentary. The systems that support these projects have no facility for integrated interactive computing and synchronous communication. Thus participants primarily share text messages deferred in time and do not interact with common data. NGS Kids Network participants do seek to interpret common, aggregated data that are graphically displayed; for example, in one study they observed regional differences in acid rain concentration and hypothesized causes for these differences.

Multimedia Interactive Computing

One of the aspects of physical classrooms that today's distance learning applications fail to capture is the ability of participants to interact directly with computer-based data used for instruction. For some time, this ability has been provided for by systems like Plato where students use networked multimedia self-paced courseware. While not originally designed primarily for learning, systems like Intermedia (a hypertext document browser: Yankelovich, Meyrowitz, & van Dam, 1985), or the Andrew Message System (a multimedia messaging system: Borenstein, 1990) can provide interactive computational access to educational materials.

The most researched example of networked multimedia interactive computing for children of elementary school age and beyond to date is CSILE (Computer-Supported Intentional Learning Environments: Scardamalia et al., 1989; Scardamalia & Bereiter, 1991). CSILE was designed to be an example of a multimedia system that explicitly allows students to collaboratively contribute to one another's learning through the social construction of communal knowledge. It combined a communal database built up by students of text and static graphics with messaging capability that allowed students to create "notes" as annotations to other documents they have browsed or searched for. These notes are the focus of multimedia asynchronous dialogue between students. They were also the main source of growth in the communal database, which achieved thousands of notes in a school year even among sixth graders.

Of course there are many innovative educational applications of stand-alone use of computers with videodisc without network access. An exemplary research-informed system is the Jasper problem-solving series of videodiscs and interactive learning activities designed and researched by the Cognition and Technology Group at Vanderbilt (1990). Used now in nine different states, their multimedia environments have been designed to enhance the mathematical problem-solving skills of fifth and sixth graders and to provide rich "macrocontexts" for investigating issues in mathematics, science, social studies, literature, and other topics.

Commentary. Applications like these achieve part of the Dynabook-plus vision in that they allow people interactive access to significant amounts of multimedia material. Since systems such as CSILE, Andrew, and Plato are networked, the information contained can be frequently updated to adapt to frequently changing education needs. While these systems provide direct interactive multimedia computing, they are not yet designed to support concurrent person-to-person synchronous networked communication. And video is still a rare medium in the multimedia mix for these networked systems.

Remote Video Technology to the Classroom

In addition to uses of video for connecting teachers and students in remote classrooms, educational uses of e-mail-like applications, and single-user multimedia computing in the classroom, broader and more flexible access to video databases is a growing trend in education that IMT can build upon. We now describe several important national projects that are demonstrating the capabilities of daily uses of video by teachers and students. These efforts range from what might be called classroom video-on-demand to traditional TV with a classroom focus.

- *Linkway to the Future Project* in Fairfax County, VA (Johnson, 1989). This project was a joint venture of IBM, Fairfax County schools, Pioneer, and CEL Communications, Inc. Its goal was to create a demonstration network cable system that teachers and students could use to access and use video resources for "video term papers" or customized video-enhanced lessons. It was described as a "prototype for future library and information design" (Butler et al., 1989). Fairfax County serves 135,000 students in the tenth largest school system in the country, covering 400 square miles. The heart of the materials was a video jukebox, which provided PC access to the 38 videodiscs (80 hours), containing 2,217 units of primary source material ranging from 1 to 9 minutes in length, of the Video Encyclopedia of the 20th Century. In 1989–1990, development of the system took place in the Chapel Square Media Center serving the district's 5,500 teachers. In mid-1991, a new electronically networked Centerville High School began use of this system, with the video jukebox located in its library media center, and video accessible through the school's internal cable television system.

- *Project Glass*, and *Projects Superman 1 and 2*: Sasktel and Cable Regina provided elementary school access to a video jukebox. These experimental projects used analog fiber optics for video-on-demand. In Project Glass, teachers in 22 classrooms selected from 192 pre-loaded VCRs videos for elementary school students by dialing a touch-tone phone in the classroom, and receiving that video over a classroom monitor in less than a minute (Bradley, 1988, 1989). Because teachers wanted full VCR functionality, not just select and play, the Superman-1 Project began, which provided 16 VCRs in the school library that offered full VCR functionality through the telephone touchtone pad (Bradley, 1990). But then frequent renewal of videos was needed. So in Superman-2, videotape delivery to the school library took place over late-night satellite or batched fiber optics. A teletext directorly of 100 titles was broadcast to four school sites, and bandwidth for overnight video database updating was determined by telephone-toned voting from the school-site teachers.

- *The Education Utility*. Jack Taub, who created the Source (a collection of computer databases now largely owned by Reader's Digest), has begun a National Information and Education Utility to make it cheaper for computer and video programs to flow into the schools for customization of educational opportunities. The New York City–based National Information and Education Utilities Corp. (NIEU) equipped schools with a lease for $21,000 a year with a 2.4 Ku-band satellite dish and reception equipment, a VCR and switcher, an interactive laserdisc player, a three-disc CD-ROM server, a laser printer, a main "resource computer" (with NIEU's proprietary software), two computer workstations, and basic software (including calendar, electronic mail, word processor, spreadsheet, administrator, teacher, student and curriculum management systems). Their computer-switched router based in Memphis allowed software, courseware, databases, video programs, and interactive videos comprising over 10,000 titles from over 700 educational publishers (including Apple, MS-DOS) and video producers to be ordered for use from the Utility.

Any program could then be distributed either live or overnight by satellite, phone lines, VHF and/or UHF television channels, or fiber optics networks to all or any number of networked workstations in the school through the local mass storage capabilities of the school's central computer. Different programs could then be used on any of the school's computers at the same time. Program usage was metered by the server computer and charged on a pay-per-use scheme, and the Utility paid royalties to software suppliers. Participating schools purchased few materials.

The 1990 estimates were that usage fees would be approximately $28,500 a year for a school with 20 classrooms with a 25/1 student/teacher ratio, and six computers per classroom (or about $57 a student). Students, parents, businesses, and community organizations equipped with a modem and computer could also call up programs after school (including homework for students) for $1.50 an hour, with one third of revenues to the software supplier, one third to the Utility, and one third to the school, which helps pay for their system (Perry, 1990). Besides Arizona, Long Island, and other states and regions to be announced, the Association of California School Administrators (ACSA) voted to begin partnership with the NIEU in 1991. Based in Sacramento, the ACSA planned to support and market the Utility in California. They also planned to use this infrastructure for professional development programs for educators.

- *Whittle Communications Educational Network* (*Satellite Week*, 1990). In March 1990, Educational Network (EN) began its satellite-based high school cable video network in over 2,500 schools. By April 1991, this number had increased to over 8,000 schools (*New York Times*, April 5, 1991) with an estimated audience of 4 million students (Whittle, personal communication, December 14, 1990). To offer their network service free to schools, EN provided the core element of its network—Channel One—as 12 minutes of weekday newscasts sponsored by 2 minutes of commercials. This program was broadcast before dawn for recording at the school site, for subsequent school distribution via video cables. The satellite dish, two VCRs, a 19-inch color video monitor per classroom, system installation, and all maintenance was also free to the school. Although banned in California and New York because of its commercials, over 35 other states have schools that participated in the program. Two other channels were offered, an independent noncommerical educational-program service called The Classroom Channel, and a program service dedicated to teacher professional development called The Educators' Channel.
- *Turner Broadcasting and CNN Newsroom.* Unlike EN, Turner's satellite cable video broadcasts to schools contained no commercials. The National Education Association estimated that by mid-fall 1990, over 12,000 of the country's secondary schools had signed up for CNN Newsroom (*Broadcasting*, 1990).
- *Discovery Channel's Assignment Discovery* (*Satellite Week*, 1990). As of February 1990, over 180,000 teachers were using at least part of Assignment Discovery. Like CNN Newsroom, commercials are not a part of Assignment Discovery.

Commentary. Unlike traditional distance learning, each of these efforts attempts to bring produced video material into the classroom with the goal of making it part of traditional instructional interaction. Work of this sort shows that even with only teacher-access to standard TV and VCR control of the signal, teachers can find ways to integrate material available in this fashion to serve classroom goals. Of course systems like these suffer several limitations because of their lack of flexibility. The broadcast services require teachers to be prepared to use the materials when they are sent. Cable video jukebox services have no interactive access to the video itself for students or teachers. Even with their limitations, these systems demonstrate the potential importance of flexible access to large stores of educationally relevant video information. One important aspect of IMT in the future will be flexible daily use access, over networks and phone lines, to the wealth of professionally produced video stored in archives.

In-situ Multimedia Computing Composition and Display

One very important aspect of the IMT vision is the ability of teachers and students to have composition-level access to multimedia information for display in classrooms and other learning environments. Recently the utility of this capability has been explored in two experimental systems and one product. In general, the goals of the following systems are to give teachers and/or students the ability to compose multimedia documents and display them in conversational or extemporaneous learning environments.

- *MultiMedia Works.* The MultiMedia Works computer software developed at the Institute for Research on Learning allows students as young as 10 to research, create, analyze, and synthesize a wide array of multimedia information, including text, graphics, images, full motion video, and sounds in a virtually unlimited number of content areas (Pea, 1991). These presentations may be made interactively using a computer, or recorded on videotape. Using a workstation and videographics boards, and implemented in SuperCard, MultiMedia Works consisted of a MediaSpace, a multimedia database and research tool, MultiMedia Works Composer, the multimedia composition and presentation environment, and Video Light Table, a direct manipulation video clip editor.

  Thirty 7th- and 8th-grade students from an economically disadvantaged urban community have participated in a research and development project using MultiMedia Works as part of an afterschool club (Allen, in press). Expanding the communication bandwidth available for students to express their ideas and expertise beyond text appeared to be a powerful learning strategy. While students worked, researchers examined how students collaborated in producing and learning from multimedia documents, and documented the cognitive, social, and technological support issues for future educational environments using such tools.

Students developed "multimedia compositions" on their topic of specialization and presented them to other teams of students in order to explain, tell a story, or be persuasive about that topic. Through this approach, students creating the compositions learned both about the subject matter and about how to effectively communicate using written text integrated with other media such as graphics and video. While these tools were useful for any content area, students' initial work examined issues in environmental science (e.g., global warming, toxic wastes, and species depletion), social science (e.g., urban development, First Amendment issues, drugs, and crime), and popular culture (e.g., music groups). Small groups of students researched and collected various media including newspaper articles, magazine illustrations, television documentaries, and their own slides and videotape of field trips to local museums and local communities. With guidance, the students learned to employ critical thinking skills to analyze the media they collected, focus on a topic, and then select and logically organize the media to communicate their ideas. MultiMedia Works was then used to assist in composing texts, graphics, video, and sounds into presentations for critical discussions and revisions. Students could then take a videotape of their compositions home.

- *Mozart and the HyTime Player.* Two tools were developed at Bellcore in conjunction with research into classroom use of MultiMedia. One was a multi-window lesson planning tool called Mozart, and the other was a program, called HyTime Player, that allows one to present multimedia compositions using a VCR-like remote control. Both were written in C using CGI and SunView. Before lesson planning with Mozart began, lab equipment was used to digitize images, slidefilms, and audio clips. The resulting files were held on a network server. Film conversion and video editing equipment was used to break conventional AV materials into brief clips that were copied onto laserdisks. The digitizations and laserdisc segments were typed, labelled, organized, and annotated using a single archival representation that conformed to HyTime, a recently proposed ISO standard for time-based documents and hypermedia. Because of a common representation, the software treated all media uniformly, which gave teachers equal flexibility in handling each medium in planning and presentation.

  Mozart displayed stored materials as a multimedia pool from which lessons were composed. Mozart tried to simplify the process of composition by providing templates whose structure mirrored that of units, lessons, activities, quizzes, demonstrations, vocabulary drill, reviews, and so on. A teacher began by selecting a template, populated it with elements from the pool, and added it to the pool as a modified composition. Elements were located visually by scanning reduced images, or computationally by entering text strings that were matched against labels and annotations. During the process, individual and composite elements were previewed in a portion of the screen.

  Two grade school teachers spent 2 months in the lab working on several lessons. They suggested numerous improvements, such as "cue cards" that are displayed only on the teacher's screen, on which they place reminders about items to mention. The teachers constructed multimedia lessons on the "water cycle," and on the art and architecture of the Renaissance.

  The HyTime Player was set up to display five items: a pool, a lesson, an individual item, a cue card, and a control panel. The lesson held a primary set of materials to be displayed and discussed. However, any item in a lesson or a pool could be shown at any time. In the classroom, the workstation fed any individual item (which may be a video sequence) to a video projector, which put it up in a large, bright image. Teachers operated it from the keyboard, or using a mouse, or from anywhere in the room with an infrared remote control.

- *Visual Almanac.* The Visual Almanac was created by Apple's Multimedia Lab and made commercially available by Optical

Data Corporation. It provided an interactive almanac, mainly with materials from science and history, including hundreds of video clips and still images, and numerous activities on the solar system, mathematical reasoning, everyday physics, animal life, music and sound effects, world cultures, and the history of everyday life. Most centrally relevant to our concerns was a note-taker and documentary-making tool that allowed the student to browse these multimedia archives and create a linear sequence of sounds, text windows, and video clips or still images to tell a multimedia story.

Commentary. These three applications are important because they give the participants in learning activities some compositional control over multimedia. This is a critical step because teachers and students need to be able to play prepublished artefacts like videos, but they must also have the capability to compose their own special purpose multimedia presentations and documents. This objective is congruent with the communications perspective we have outlined, since it provides expressive capabilities for the base materials of learning conversations. In addition, all participants in the learning activity should have collaborative access to the stored libraries of information. It is here that the aforementioned tools fall short because they do not have significant network support for composition and collaboration in the cases of Visual Almanac and MultiMedia Works. Mozart has minimal local area network support for networked composition of materials (i.e., the media used in Mozart are delivered via a local area network). But Mozart has no support for synchronous collaboration during the preparation or presentation of materials.

Do These Applications Represent the IMT That Is Needed?

In no sense can we argue that any of these technology experiments represent a realization of educational IMT as we have envisioned it. They are not supported by an extensive and integrated information network. By and large, high-bandwidth media such as video, audio, or animation are delivered via broadcast, not interactively. The exceptions either do not use a network, or use local area networks or special-purpose (i.e., not broadly integrated) terrestrial transmission faculties. For the most part, interaction technology is limited to standard keyboards or remote control devices. For all their shortcomings, these experiments do capture the classes of applications that researchers and entrepreneurs now believe to be important for IMT. Next we explore likely IMT use-models suggested by the technology experiments reviewed here.

HOW WILL IMT TECHNOLOGY BE USED?

The array of current educational technology experiments is impressive. They point to the groundswell of interest on the part of the computing, communications, business, and educational communities in providing new educational directions with the aid of interactive media. These experiments show general trends toward making more dynamic media a part of education, augmenting the capabilities of people separated by time or space to communicate, and placing the tools for what is now sophisticated media creation in the hands of the teachers and students in the day-to-day life of education in classrooms. Next we explore the educational niches that IMT may fill and create.

Next-Generation Textbooks

We see two separate trends in consumer electronics providing the market base for educational materials—miniature network-accessible TV/movies, and electronic books. These may coalesce during the 1990s in portable integrated multimedia "books," incorporating text, sounds, graphics, animation, and video as needed for the purposes at hand.

First, with the wide market penetration of flexible information networks, the traditional text and reference books may be replaced, at least partially, by easy access to large bodies of stored pre-produced video material. In this scenario, both in-class reference materials and personal textbook-like material are available via the information network and used with personal and group workstations. We interpret projects like Linkway, Project Glass, and Project Superman as harbingers of this possible future. In each of these cases, teachers and students have on-demand or near on-demand access to the sort of instructional materials that today exist on reference shelves in classrooms and libraries. As for future portability, we see the miniaturization of video display technologies utilizing 8-mm tape and CD format, as already evident in Japanese products such as the Sony Watchman.

Current participations of information venders like Turner Broadcasting (CNN Newsroom), Discovery Channel (Assignment Discovery), and Whittle Communications (Educational Network) illustrate a willingness and desire to make their vast stores of pre-produced video material available for educational purposes via remote transmission. While it is not a remote transmission example, ABC News Interactive is also worth noting. ABC News is making its information warehouse available for education in the form of pre-produced videodiscs. They have, for example, produced interactive videodiscs on AIDS, Martin Luther King, and the Holy War in the Middle East, which are designed as reference and educational materials. These products are important as further evidence of the willingness of owners of information to participate in education.

Second, the electronic book is now appearing (Markoff, 1991). This trend is evident in the rapid growth market in Japan, and the U.S. release in November 1991 of the Sony Data Discman (at $425), a palm-size viewer that allows for compact disc storage of vast volumes of text, numeric, and graphical media (but not video as yet). This technology suggests the prospect of electronic textbooks with animated illustrations to convey difficult dynamic concepts and processes. Markoff reviews product plans for several companies, including one called Booklink, that will show a prototype early in 1992 of a technology called Bookmark. Bookmark is a thin large flat screen with three buttons for turning pages, but most significantly, it will encode books on a Smartcard—a credit card–sized storage medium. The Smartcard will enable users to purchase new books by inserting their cards into vending machines. We imagine that the use of Smartcard-like technologies and compression techniques may ultimately allow paperback movie storage. In a third approach, the Voyager Company utilizes the notebook-sized Macintosh computers, with a much larger screen than the Discman, and is introducing a line of books in January 1992 including sound effects, hypertext links, and animated drawings. The Sony, Smartcard, and Macintosh formats are currently not compatible, although in 1992 Adobe Inc. will introduce Carousel, their effort to create a standard format allowing Macintosh, IBM-compatible, and Bookmark-like platform approaches.

Traditional Distance Learning

New technology is almost always shaped and designed to solve old problems. Thus we expect that as the IMT infrastructure grows, one of its most active applications will be improvements to current standard distributed lecture forms of distance learning. For example, rather than current cumbersome forms of interaction between instructor and students, IMT infrastructure will in all likelihood provide integrated channels of communication. Teachers will then not only be able to see students, but will be able to interact with their work as well. We can also see Open University–like specialized lecture series available on a next-generation textbook format as described above.

Enhanced Message Interchange

Teachers have long recognized the need to give students first-hand experience with people, places, professions, and cultures remote from their normal experience. Activities as diverse as developing distant pen pals to school "career days" can be viewed as examples of this felt need. Projects like NGS Kids Network, and the Inter-Cultural Learning Network are electronically mediated efforts to meet this need. Today, however, educational message services are primarily text-only electronic mail applications. We expect that a rich infrastructure for IMT will broaden this niche to include multimedia messages that are not only asynchronous but synchronous. NGS Kids Network today lets students collaborate with distant scientists with text messages, and static graphic displays. One can imagine young learners and scientists exchanging video that shows climatological phenomena, actual executable programs that allow collaborators to study the same software models together, or distributed control and collaborative interpretation of readings from remote scientific instrumentation. It is intriguing to imagine, as Landauer (1988) suggests, students simply "calling" the Smithsonian for a virtual museum visit. Museums and other holders of intellectually enriching information will be able to make them available without physical display space.

Learners and Teachers as Multimedia Composers

The last media composition technology to have universal penetration in the classroom was pencil and paper. The multimedia computer, widespread portable video cameras and scanners, the coming of relatively inexpensive video/audio editing equipment, and the development of large-scale warehouses of multimedia information should make it possible for each teacher and student to flexibly communicate and express ideas in media other than text. MultiMedia Works and Mozart can be seen as anticipating this class of application. The need for more channels of expression has been an ongoing need in education. Teachers are constantly looking for just-the-right set of examples depicted in just-the-right media to make a point. We conjecture that educational IMT with fingertip access to a multimedia library and tools to manipulate it (search and edit functionality) will certainly grow to meet this need.

In a similar vein, many educators have recently argued that today's students have limited means (e.g., multiple choice tests and essays) to express their expertise. IMT will make available to students the means to show what they have learned through any number of media options and combinations. It will be more straightforward for each student to develop a "portfolio" that may more accurately represent diverse levels of achievement (Resnick & Resnick, in press). If as some theorists believe (Gardner, 1990), some individuals have a propensity for effective expression verbally, others pictorially, and still others through different channels like programming, then IMT may bring to education new, more equitable techniques for assessment.

Finally, there are a diversity of tools for augmenting human intelligence through better exploitation of the power of human visualization processes and the automation of components of problem-solving processes (Pea, 1985; Pea, in press b; Pea & Kurland, 1987). Exemplary tools include visual statistics programs, spreadsheets, scientific visualization workbenches, simulation languages such as Stella, symbolic calculators, decision aides, and writing aides. We see these new dynamic media as fundamental to the new expressiveness made possible for learning by computation.

The New Classroom

We expect that IMT will lead to a restructured classroom, more like a learning studio, with new electronic collaboration possibilities not seen today and only partially envisioned by the current crop of technology experiments. Unfortunately most of today's classrooms don't even have telephones. We believe IMT will bring network access to every classroom and lead to the development of the "smart classroom," which is an extension of now-existing product visions of the "smart building" and the "smart house," which integrate communications and control technologies for work and home life activities. In the "smart classroom," each desk will have a connection to the information-networked world. It follows that all students in each class will have electronic access to each other and to the teacher. In that eventuality, the whole class could work electronically with the teacher when the lesson calls for it, but classroom teachers could break the class up into small collaborative teams without anyone losing access to the electronic learning environment. It would be easy to configure rotating designs with small-group work for some of the class and more traditional instruction for the remainder. Teachers could also engage in remote collaborative activity (Hunter, 1990) and share what works for "effective schools" (Sizer, 1984), as in recent studies of writing teachers (Rubin, 1992), and project-enhanced science teachers (Ruopp et al., 1992). These scenarios raise fascinating and complex educational technology policy issues as traditional boundaries are violated by new interconnections: Information, teacher expertise, and other resources are traditionally geographically isolated, regulated, controlled, and financed locally by regions and states.

It is, of course, impossible for us to serve as precise technology sages for IMT. If the application niches we propose have some glimmer of viability in the marketplace, we suspect that they will be dwarfed by future applications currently now not even in our dreams. This is almost certainly true because IMT is not simply a series of applications—it is really a communications medium in itself. Like any communications medium, it is impossible to forecast its use in its infancy. The computer, telephone, and television are all good examples. For example, in its earliest days, sages of the time thought the world would not need more than five digital computers (Ceruzzi, 1986). Telephone (Pool, 1983) and fax technologies (O'Brien, 1989) had similar sluggish starts. Theory on technology transfer has begun to specify the necessary "critical mass" required for innovations to meet or exceed designers' intentions in adoption (Markus, 1987). Clearly the challenge is not to predict all or many of IMT's uses. The challenge is to understand and anticipate fundamental educational needs, to provide an infrastructure capable of meeting them, and to develop strategies for attaining critical mass for universal access and adoption. If these goals are met, then creativity and market needs may take over to provide the applications. In addition to understanding IMT infrastructure design in light of true human needs as they relate to education, we must understand why IMT, and the significant capital investment it will require, is sound business.

STRATEGIC AND BUSINESS ASPECTS OF DMLE

We have characterized a vision of IMT for distributed multimedia learning environments (DMLE) that is grounded in new theories of learning–teaching processes. There is good reason to believe that, if established with sufficient critical mass, such technologies could make a major difference in improving results from education, provide critical improvements to the human resources needed for an adequately educated and robust workforce, and contribute new markets for technology that could spur economic competitiveness for U.S. industry. But we also have good reason to believe that this vision for IMT, with interpersonal high-bandwidth computing and information services, will not happen universally for K–12 education until 2020 or beyond,[5] given:

1. the current trends in place for K–12 educational spending, and
2. prevalent attitudes about the place of educational technology research and development in industry, the military, and the federal government.

We will address each of these issues in turn, and then recommend a set of initiatives for transforming the current situation so that distributed multimedia learning environments can be a reality on a more rapid time-scale.

Creating IMT for DMLE is a fundamental issue for applied science. It establishes a set of fundamental problems: We do not yet have in hand the appropriate social science, computer science, communication science, or learning science to implement the visions we have described.

[5]This is our estimate for the United States, based on projections of fiber optics installation that include local loops to homes and schools, not only to central offices (e.g., Vanston, Lenz, & Wolff, 1989). We may contrast the state of high-bandwidth service installation in Japan, which has committed $20 billion to building a national fiber data highway (Markoff, 1990), or countries such as Denmark, that have fully installed fiber to all central offices and many homes in the country.

For this reason, educational uses of technology should no longer be a result of the weak trickle-down process from basic advances in technologies from the military, industrial, commercial, and higher education sectors (see Roberts, 1988, for details). Education applications of IMT for DMLE are as technically demanding as applications in these sectors, and should serve as a leader among rather than a trailer of these sectors. If education were allowed to serve as a driver of technological development, IMT for DMLE could spur both educational change and development in several sectors of the economy.

The Business for IMT Is Not There *Now* in K–12 Education

There is a substantial but inadequate sum of money in the budgets of school systems beyond salaries that could go toward creating the necessary infrastructures of IMT for DMLE. Let's review the numbers:

- *Students and teachers* (NCES, 1989). In fall 1988, there were 45.4 million total students in public (40.2 million) and private (5.2 million) schools, 2.6 million teachers, and 2.2 million other professional, administrative, and support staff (NCES, 1989). 32.4 million of these are K–8 students, and 13 million are in grades 9–12. Projections are for 49.1 million students by fall 1995.
- *Schools* (NCES, 1989). In 1987–1988, there were about 111,200 total elementary and secondary schools—83,200 public K–12 schools, and approximately 28,000 private schools.
- *Classrooms*. There are about 2.5 million classrooms in the United States (Michael Kelly, DARPA, personal communication, December 1990).
- *Computers* (Roberts, 1988). The comprehensive Office of Technology Assessment (OTA) survey of technology in U.S. schools reported that between 1981 and 1987, the percentage of schools with one or more computers for instruction escalated from 18% to 95%, with an installed base of over 2 million. In the past few years, this figure has climbed to 2.5 million.
- *Video-cassette recorders* (Roberts, 1988). In 1980, few schools had VCRs; now over 90% do.

- *Videodisc players*. We have been unable to unearth firm statistics here, but the introduction of videodisc-based products for the classroom like ABC News Interactive, and the recent decision by Texas to allow videodisc product selection as a "text" for K–12 instruction, suggests there is a reasonable videodisc market penetration. California is following Texas's lead, and given past trends, other states can be expected to as well.
- *Schools with modems* (Roberts, 1988). Informal observation suggests that most classrooms in the United States still do not have direct telephone service, even if they do use computers.
- *Schools with networked computer systems* (Roberts, 1988). 13% of schools, or 14,500, utilize some form of networked computer facilities.
- *Distance learning programs*. Over 35 states support them, using satellite technology to distribute teaching resources to students geographically isolated. Not all involve two-way video or audio, some using primarily electronic mail services (Roberts, 1988).
- *Expenditures* (NCES, 1989). In the 1987–88 school year, the estimated total expenditures for K–12 education, including public and private schools, was $187.1 billion, or 4.1% of the Gross National Product (GNP). Of this total, $172 billion was for public schools. By comparison, the expenditure of all U.S. colleges and universities was $123.7 billion, or 2.7% of the GNP. Estimated 1988–89 expenditures for public elementary and secondary education was $183.4 billion, and private schools, another $15.7 billion, for $199 billion. If we assume for 1988–89 the percentages of expenditures for public elementary and secondary education devoted to instruction (61.1%), support services (35.4%), and non-instructional expenses (3.5%) found for 1986–87, we see $112.1 billion as public

lion in total expenditures for that year, or only 0.74%. Of that total, $5 per student, or $200 million, was spent on computers for instructional use. We do not know whether library and media services materials budgets are included in these estimates or not. But it is clear that the funds for materials and computer support for instruction are an exceptionally meager proportion of the total educational expenditure per pupil. In fact, these figures are so miniscule they are hard to believe.

Like many other analysts, we can see how education is defined as almost wholly a labor-oriented, not infrastructure or materials-oriented, enterprise. A review of these numbers also shows a willingness and ability on the part of the educational community to acquire media technology that appears to work. For example, educators recognized the flexibility and wealth of material on video-cassettes. Thus we see the VCRs in schools grow from being essentially nonexistent in 1980 to near saturation in less than a decade. A similar pattern is apparent in the growth of computers in schools. It is quite clear that the level of investment necessary to equip schools with PCs or VCRs is very different from that needed to produce DMLEs. We believe, however, if integrated IMT does lead to superior instructional value for the dollar investment, schools will find the funds to contribute to its funding process.

- *Contrast to* Fortune *500 expenditures*. It is instructive by way of comparison to see how much money is spent on technology per employee for computer support and educational materials by the average *Fortune* 500 company. A result of a recent survey in *ComputerWorld* magazine created a rank-ordered list of companies based on the effective use of information systems technology. That survey makes it clear that at least some *Fortune* 500 companies treat computers as a primary business tool. For example, some top-rated companies were the economy. This statistic also stands in sharp contrast to 1987's 0.03 computers per student computer density in U.S. schools (Roberts, 1988). The *Computer-World* survey also points out that top-rated companies also assign a significant amount of their information systems budget to take advantage of computing as a tool in the workplace.

Part of the problem in this comparison is how differently computers are conceived in the two contexts. We consider it a problem that computers for students are thought of as instructional materials, while computers for workers are thought of as work tools, not for education per se. Why shouldn't computers and other IMT hardware and wiring be thought of as tools for students as knowledge workers? as a basic part of the infrastructure of education, like the walls, the desk, the halls, and the computer used for financial accounting in the principal's office?

Attitudes about Roles of Educational Technology Research and Development

There is a tradition and a set of attitudes dating from at least the first world war that technologies developed at the frontiers of new work in the defense, industrial, and commercial sectors shall trickle down for use in higher education, and then finally, for the purposes of K–12 education. In fact, analyses provided in a comprehensive (Roberts, 1988) report on educational technology R&D indicate that this trickle-down lag is typically 15 years in duration! We must change these priorities, for two fundamental reasons. One reason is that the evidence is so overwhelming that K–12 education is in trouble that it can no longer be a place of rest for technologies developed for other purposes, over a decade since their introduction. The second reason is that, as we have indicated, the use of IMT for DMLE is technically demanding, not a simple application of existing knowledge, but a challenge to the fundamental sciences of computation, communication, behavior, and pedagogy. It is not yet known how to develop new IMT for DMLE fulfilling the vision we have described. Indeed, the technical demands of high-bandwidth interpersonal multimedia computing and communication for education activities may exceed the demands of IMT for many sectors of the U.S. workplace, such as financial transactions, where certain media (such as video) seem unessential.

Consider, for example, the software needs of a classroom truly equipped for IMT. It would have, as we have speculated, networked access to each student "desk." Each student would have to have some form of portable display and interaction technology. Further, each student would have the ability to communicate publicly to the entire "class" (local or distant) or privately to others. Given the state-of-the-art in computer science, communication science, social science, and learning science, we conjecture that it is not technically feasible to implement such classrooms on a large (perhaps not even a small) scale today. Only short pause makes it apparent that this claim is not outlandish.

Today's communications networks do not have built-in mechanisms or protocols to talk about the class of applications that we suggest are needed to support DMLE. The goal of traditional communication protocols is to establish a "call." This is just a simple request for connection initiated by one user and confirmed by another (Bussey & Minzer, 1990). The task of developing protocols to support next-generation communications multimedia and multi-user applications of which DMLEs are clearly a part is at the core of much of the current research in communication science (e.g., Bussey & Minzer, 1990; Clark & Tennenhouse, 1990; Griffeth, 1991; Spears, 1987). As this work proceeds, it needs to draw on demanding classes of potential applications that can serve as forcing functions on protocol development. DMLE, unlike many applications, inherently makes large demands on communication bandwidth resources and requires extreme flexibility in information delivery. As we have described them, DMLEs also appear to have very different interaction requirements than other proposed high-bandwidth services like entertainment video and home shopping.

Before the computer hardware can be considered up to the challenge of IMT for DMLE, it has to, at the very least, expand the set of available interaction technologies to encompass more varied techniques for people to interact with information. We are certain that current trends in the amount of computing power that is being made available for desktop use indicates that computing power in and of itself will not be a bottleneck to IMT for DMLE (Roberts, 1988). Current projections for microprocessor chip RAM capacity, chip speed in MIPS (millions of instructions per second), and magnetic storage density all indicate consumer videogame-like devices late in the 1990s that will exploit the capacities of today's supercomputers (Bell, 1991).

However, the software that supports the construction and use of DMLE applications is quite another matter. DMLE implies the existence of many people using a great many highly interactive multimedia educational applications. Relatively few such things exist today. In part this is because they are very difficult to create. DMLE will not flourish if it depends solely on the classic model of a software industry creating applications for customers. Customers (i.e., teachers, students, and parents) have to have the tools in place to contribute to DMLEs themselves. Today's very best software prototyping tools require too much computer sophistication to allow custom software creation to become a part of every teacher's daily instructional repertoire.

Similarly, the social science of collaboration, for example, is in its infancy. We currently do not have a deep understanding of the factors that enable people to work together effectively when they are physically proximate or remote (Bowers & Benford, 1991; Galegher et al., 1990; Grudin, 1989; Kling, 1991; Olson, 1989). A deep understanding of this sort will probably only come after we acquire much more experience than we have now in building and studying systems designed for collaboration and coordination. The world of learning science has not yet addressed in any serious way the design of artefacts like teaching materials that are meant to support instruction in a highly networked, highly interactive, and media-intense environment. We therefore reiterate our earlier position. IMT for DMLE is a technically demanding class of applications that can serve as the leading edge to spur fundamental developments in the sciences that support computing and communication.

Accelerating the Development and Installation of IMT for DMLE

Several properties strike us as central to the kinds of initiatives that are needed to transform the systems that could give rise to IMT for DMLE fulfilling the vision we have described.

- *Corporate attitudes should shift from perceiving education IMT as "risky investment" to "in the public interest."* A major reason for the lack of corporate interest in developing cutting-edge applications of IMT for education is the low budget expenditures within the educational system for educational materials, which are defined to include computers and other IMT technologies. Education has thus been viewed as a risky investment market for new technologies. But the facts remain that there will be 50 million students and nearly 3 million teachers by the end of the century, that virtually all 80 million homes in the U.S. have telephones and television services, that interactive technologies like Nintendo have an installed base in 30 million American homes (Moozakis, 1990), and that U.S. education needs a fundamental revitalization that could be provided in part by compelling new uses of IMT.

The chicken-and-egg problem that has plagued investment in educational IMT could be overcome if a first phase of technology push from the commercial, industrial, and defense sectors established the viability of DMLE through working examples of IMT in educational settings created in the public interest. A major part of that push is already underway in the recent funding of research activities to create a high-speed national data communications highway (see below). But K–12 activities involving DMLE are not as yet a planned part of these efforts.

If, as we argue, what these industries will learn about creating IMT from these experiences with K–12 education experiments will advance the technologies that define their business, then their expenditures in these R&D efforts will have been spent in good cause. These industries will also be contributing to the establishment of a new future customer base for their products. They also will be perceived by potential customers for these IMT services as contributing to the public good, and thereby attract home consumer attention to the purchase of related goods and services in the markets thus created. State and local education authorities, which now provide most of the funding for education, could also see reason to reallocate their future expenditures to more realistically contribute to the IMT infrastructure for education, more on a par with materials and tool costs for office workers (as described above).

- *Corporate–governmental–academic partnerships.* Academic research on learning environments has too rarely been able to work with and advance fundamental technologies in computer and communication sciences, while defense, industrial, and commercial development of IMT has rarely taken education activities grounded in academic research on learning as one of its leading development areas. For these reasons, we consider these complementary talents to be essential to accelerating the educational attainment of IMT for DMLE.
- *In-situ research and development of educational applications of IMT.* Laboratory experiments miss too many of the situated properties of educational settings, including the demands on teachers and students of using new technologies, so demonstration experiments that evolve the design and properties of IMT in its situations of use are a central priority (Pea & Soloway, 1987).
- *The opportunities for distributed multimedia learning environments with the NREN.* Exciting developments during 1990 led to the real beginnings of the long-awaited gigabit national "data highway," also known as the NREN, or National Research and Education Network. No current wide-area gigabit network exists. Such a very-high-speed information transport system would allow for optical transmission of billions of bits of data per second, rates that would more than support DMLEs as we have described them. One of the major incentives for such a system is that a number of the most frontier scientific problems in the world can only be addressed (Lederberg & Uncapher, 1989) by means of remote interaction with scientific colleagues, data archives (e.g., the global seismic database), and scientific instruments (e.g., the space telescope). Addressing the team science approach that characterizes much of modern scientific inquiry, Lederberg and Uncapher describe the objectives of the National Collaboratory that such a high-speed national network would enable in these dramatic terms:

  > *The goal is to build no less than a distributed intelligence, fully and seamlessly networked, with fully supported computational assistance designed to accelerate the pace and quality of discourse, and a broadening of the awareness of discovery: in a word, a Collaboratory. (p. 3)*

Rapid progress in inquiries across multiple scientific institutions on complex programs of research such as those designed to understand global change, or to map and sequence the human genome, will require these supports.

As these scientists describe a National Collaboratory:

> *It is the combination of technology, tools and infrastructure that allow scientists to work with remote facilities (co-laboratory) and each other (collaborat-ory) as if they were co-located and effectively interfaced. (Lederberg & Uncapher, 1989, p. 6)*

In June 1990, the NSF awarded Dr. Kahn's Corporation for National Research Initiatives (CNRI) a $15.8 million grant to coordinate the establishment of five networks involving experiments with new software and hardware technologies (CNRI, 1990). The information infrastructure developments will include not only those in computing and communications, but advances in distributed database storage and retrieval using multiple supercomputers and workstations. They will contribute to the research required for the proposed NREN, which is intended to link government, industry, and research-oriented university communities.

Private funding estimates of corporate commitments to the NSF project to date, including those of GTE, IBM, Cray Research, the seven regional Bell operating companies, AT&T, and MCI are placed at more than $300 million (Markoff, 1990). Collaborating laboratories include AT&T Bell Laboratories, Bell Communications Research, IBM, the Jet Propulsion Laboratory, Lawrence Berkeley Laboratory, the Los Alamos National Laboratory, the Microelectronics Center of North Carolina (MCNC), the National Center for Supercomputing Applications, the Pittsburgh Supercomputing Center, and the San Diego Supercomputer Center. The universities included are California Institute of Technology, Carnegie-Mellon University, Massachusetts Institute of Technology, University of California-Berkeley, University of Illinois-Urbana-Champaign, University of North Carolina-Chapel Hill, University of Pennsylvania, and University of Wisconsin-Madison.

As Markoff put it:

> *Dr. Kahn has successfully orchestrated a remarkable coalition that brings together major*

corporate competitors, Government agencies, and educational institutions. All have agreed to take part in the research necessary to create a fully integrated, high-speed national network of computers, possibly early in the next century, that will unleash a tremendous burst of scientific, educational and economic activity. (1990, p. 1)

The applications to be studied in the CNRI collaboration include multiple remote visualization and control of simulations, radio astronomy imaging, multimedia digital library, medical imaging, and distributed supercomputing over wide-area high-speed networks to provide new levels of computational resources for frontier scientific problems in chemical reaction dynamics, climate modeling combining ocean and atmospheric data, and geophysics problems of earthquake prediction. It should be obvious that this initiative will provide an exceptionally critical foundation for the kinds of distributed multimedia learning environments we have described using IMT.

Senator Albert Gore of Tennessee has proposed a 3-year $1.75 billion Congressional bill that would provide initial financing of the data network between supercomputer centers and major U.S. universities. A version of this bill passed late in 1991. Estimates of the cost of building this network so it will reach all American homes and schools are $200 billion. While this may seem a large sum, as Markoff notes:

Many economists, scientists and others, when asked about the cost, say the economic and, ultimately, the social benefits will exceed the costs by a large margin . . . the potential for hundreds of new businesses will be created and old ones will be energized by the emergence of a vast coast-to-coast electronic marketplace. (1990)

What these observations suggest to us is that the economics of education expenditures could dramatically change given this foundational structure. With a broad distribution of costs and new business incentives, the educational system itself may have to bear little of the cost of the actual "plumbing" of the national data highway. Instead, it will need to worry about the IMT boxes, as we have called them, that enable students and teachers to connect to these resources, and the costs of uses of the information services available, however these come to be established (e.g., on a per-use scheme).

One problem to date is that the education activities proposed for the NREN are all targeted at the college level, not K–12 education. As we have argued, the technical demands of DMLE for K–12 will be as challenging in many respects as those of university education, and important to include as testbeds for evolving and using these interactive multimedia technologies. Several of the rationales for the CNRI work apply to K–12 as well. As CNRI note, they need:

to understand the utility of the gigabit networks to the end user. That is, why will access to such networks be of importance to the research community and ultimately to the rest of society? Both of these goals will be addressed by hands-on experimentation with actual facilities. (1990, p. 2)

We need exactly this kind of hands-on experimentation with DMLE to understand the ways in which IMT will make major contributions to K–12 education and to society more broadly (e.g., in connecting up education efforts within school walls and within communities). The needs of K–12 education could serve as a forcing function on the development of network technology in ways that the current crop of NREN's envisioned customer, higher education and scientist, may not. One of NREN's goals is to serve as a technology transfer vehicle for next-generation network technology. It may be much easier to accomplish this if the technology is designed from the outset to serve more than just the narrow market niche of scientist and technologist. It is easily within the realm of imagination that future broadband information network traffic and use patterns generated by young children and adolescents will be very different from that of adults in the academic and scientific community. It is clearly the case that children use other media (e.g., film, television, and telephone) very differently from adults (e.g., "channel surfing" with TV remote controls). We also suggest that if the NREN is to be the nation's beginning investment in the next-generation information infrastructure, the nation's next generation should be exposed to it and made comfortable with it as soon as possible.

It is clear to us that the business justification for widespread DMLEs will not come from the redistribution of current nonsalary monies now spent on education. So new money is needed. It is equally clear from developments like NREN that the importance of infrastructure to support DMLE-like applications is broadly recognized both for the advantages it provides as an application and for the markets it is likely to create. It seems then that the fundamental hurdle that must be surmounted is coming to the realization that K–12 education itself and the technical insights it can bring are worthy of far more than technology trickle-down.

CONCLUSIONS

Just as the '80s was the decade of personalization of computers, the '90s will come to be seen as the decade of collaborization of computers—and as we have argued, synchronous distributed work opens up dramatically new opportunities for education oriented to learning as participation in communities of practice.

If we are correct in this conclusion, then the telecommunications, computing, and public policy communities must, in short order, come together to establish key priorities (a blueprint for paths to solution) and incremental concrete steps to reach this vision.

What are the early problems to be solved? Today's classrooms and schools are islands of instruction, not electronically part of greater intellectual communities. Therefore, first and foremost, classrooms need telephones and simple network terminations for integrating communication and computation. Then plans should be put in place to give schools, at all levels, access to high-speed national networks, such as NSFNet. Each school need not be a termination point on a gigabit network, but architectural provisions should be made to give the nation's primary and secondary schools on-demand access to the world's information resources as very-high-speed networks come online. This could mean, for example, providing each school with full-time access to megabit metropolitan area networks and on-demand access to higher-speed infrastructures.

At the same time, the communications industry should be encouraged to investigate and deploy technologies that could, in relatively short order, extend greater communications bandwidth to the home (Shumate & Snelling, 1991; Waring, Lechleider, & Hsing, 1991), so that parents and neighborhoods can join educational communities of practice.

Steps like these could have a profound impact. One implication is that the computer industry will recognize a vast new market for hardware and software to support education. This recognition may lead to the introduction of the first affordable and practical IMT boxes for the home and school with a sustained market for them, driven in part by consumer spending.

A burgeoning market for interactive media educational computing supported by rich information networks may not only bring down costs, but provide part of the impetus needed to put in place standards for the representation and production of multimedia materials for supporting learning conversations.

In addition, as we have argued, these technological developments must be shaped by sound learning theory and educational practice. Fundamentally, learning scientists need to establish why multimedia use will make a pedagogical difference, and at what cost, for what instructional benefit. It will be through injecting these sorts of considerations of cost/benefit reasoning into learning/technology research that a prima facie case for DMLE investment will be made. However, DMLE's value should not be accessed in isolation. Its direct impact should be studied in light of new services and applications made easier, like new methods to assess student and teacher achievement (e.g., video portfolios).

DMLE's value should also be assessed in light of its potential for indirect impact on instructional costs like those associated with student dropout rate, absenteeism, alienation, and the competitiveness of the labor force. If DMLE can create novel learning environments, it may keep at-risk students in school and engaged intellectually. If true, then IMT's indirect economic benefits will go well beyond direct measures of educational achievement. Research programs designed to study and evaluate DMLE should, therefore, look to assess its value from a number of perspectives.

We have presented a case that IMT represents a special, timely opportunity to change education practice. Combined with telecommunication technology, it will be possible to create new DMLEs. We have seen that through recent developments in theory, the learning sciences are ready to shape DMLEs. We have also seen a groundswell of interest in IMT projects from many sources, including the business and academic communities. From our perspective, the set of preconditions are right to start down the road to a new educational future.

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