In Proceedings of SPIE '92 (International Society of Photo-Optical Instrumentation Engineers).

The Collaborative Visualization Project: Shared-technology learning environments for science learning

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ABSTRACT

Project-enhanced science learning (PESL) provides students with opportunities for "cognitive apprenticeships" in authentic scientific inquiry using computers for data-collection and analysis. Student teams work on projects with teacher guidance to develop and apply their understanding of science concepts and skills. We are applying advanced computing and communications technologies to augment and transform PESL at-a-distance (beyond the boundaries of the individual school), which is limited today to asynchronous, text-only networking and unsuitable for collaborative science learning involving shared access to multimedia resources such as data, graphs, tables, pictures, and audio-video communication. Our work will create user technology (a Collaborative Science Workbench providing PESL design support and shared synchronous document views, program, and data access; a Science Learning Resource Directory for easy access to resources including two-way video links to collaborators, mentors, museum exhibits, media-rich resources such as scientific visualization graphics), and refine enabling technologies (audiovisual and shared-data telephony, networking) for this PESL niche. We characterize participation scenarios for using these resources and we discuss national networked access to science education expertise.

1. BACKGROUND

In K-12 science classrooms, there are shifts underway from didactic instruction focusing on a textbook-homework-recitation approach to a more project-enhanced curriculum (Blumenfeld et al., 1991; Eylon & Linn, in press; Pea, in press; Ruopp et al., in press; Tinker, 1992). These efforts build on the demonstrated effectiveness of activity-based science education (Bredderman, 1983, Shymansky et al., 1983). In project-enhanced science learning (PESL), to make sense of the world with science, students engage in authentic and motivating tasks that extend over time, that encompass scientific and social issues, that are mediated by various artifacts and expertise, and finally, that require collaboration and communication within the classroom and, most importantly, with resources outside the classroom. The phrase "PESL" was created by the LabNet Project to acknowledge that, for now, projects have to be integrated with more standard curricular approaches (Ruopp et al., in press).

These PESL conditions support a model of teaching and learning described as "cognitive apprenticeship" (Brown et al., 1989; Rogoff, 1990). In cognitive apprenticeship for science learning, problem definition and problem-solving processes are supported and articulated by mentors, and learners gradually take on increasingly complex tasks. Furthermore, learners participate in inquiry, where the answers are unknown and results matter. An inquiry-driven learning process may contribute to a now-uncommon recognition by learners that science is dynamic and purposeful in nature, rather than static and archival (Linn & Songer, in press). This PESL emphasis is also congruent with various commission reports (National Science

Board, 1983; NSTA, 1985) seeking solutions to failings in contemporary American science education (Mullis & Jenkins, 1988).

The NGS-TERC Acid Rain Project and the TERC Global Lab Project are prototypical examples for PESL (Ruopp et al., 1992; Tinker, 1992). Student teams collect data locally, then use computer and telecommunications tools for pooling and interpreting results. However, transitions to such a radically different model of teaching and learning are difficult, because large role changes and demands are placed on teachers and students. Teachers no longer primarily "deliver" information, but serve as managers, critiquers, and modelers; students engage in inquiry and synthesizing activities rather than seeking to accumulate and recite information, often without understanding. The tone of the classroom becomes one of *collaboration*, in that students refine their understanding through social interactions over an extended period of time. Student-teacher negotiations of methodology, time frame, project result, and assessment are central to the success of PESL. PESL teachers face many challenges, including arranging for materials and computers to support students' inquiry activities; tracking students' uses of concepts and contributions to PESL for appropriate guidance of development; and finding appropriate materials and expertise. This last goal often requires help from other teachers, resource librarians, and practicing scientists. The problem, then, is how to facilitate and augment this major transformation of science teaching and learning.

One move toward this transformation will be to make science learning environments more like the collaborative, connected work environments of scientists (Finholt & Sproull, 1990; Lederberg & Uncapher, 1989). Teachers and students will need ways to reduce the complexity of getting access to resources that are inaccessible locally. These resources include expertise in the form of other teachers, scientists and graduate students in business, industry, and research settings, and other learners. They also include tools, instrumentation, hands-on materials and labs, museum exhibits, and computing and telecommunications infrastructures.

2. THE COLLABORATIVE VISUALIZATION PROJECT

PESL offers learning partners opportunities to engage in authentic scientific inquiry through apprenticeship that is often enabled by dynamic interactions among learning partners in physical proximity. Yet scientific and business practice using Internet and broadband services recognizes that not all partners necessary to an interaction can be co-located. Our vision in the Collaborative Visualization Project[1] (CoVis) is to use new technologies to extend the collaborative "reach" of PESL to facilitate new types of collaboration and communication among remote learners, teachers, and scientists.

Applications of advanced technologies can provide educators with critical leverage for promoting cognitive apprenticeships in science learning. They can provide the backbone for the transitioning process from didactic science teaching to apprenticeships. Scientific work groups now use advanced computing and communications for remote collaborations, yet a classroom teacher does not typically have the resources or the time that professional project managers have to seek out, connect with, and integrate outside expertise. Moreover,

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[1]The work described here anticipates funding from the National Science Foundation, Applications of Advanced Technologies. While we are exploring the value high performance computing and communications technologies to K-12 instruction, the work itself will not be funded from the HPCC NREN funding initiative.

classrooms do not support the shared construction and communication of various artifacts, whereas cutting-edge laboratories and corporations have moved beyond the chalkboard and paper notebook to support collaboration (Galegher et al., 1990). National high-performance computing and communications centers and tools are in operation (NSF, 1991a), and Congress has funded the National Research and Education Network (NREN) to extend NSF Net. Scientists also now utilize software for *scientific visualization* (based on numerical models to simulate complex phenomena, such as climate, storms, fluid dynamics) and *distributed computing*, e.g., connecting workstations to supercomputers through high-speed networks for computationally demanding functions, or rendering animations of complex visual data displays (Office of Science and Technology Policy, 1991). Students need to learn and do science in context of real problems and with such sophisticated tools.We are extending collaborative media beyond asynchronous text-only e-mail to shared workspaces and two-way audio/video connections that allow for *collaborative visualization* of science phenomena, data, and models. Tools for local- and wide-area networked learning environments will enable highly interactive, media-rich communications among learning partners. We call these "shared-technology" learning environments in that they are participated in, or experienced in common across remote sites.

While the advanced communications and computing technologies we are developing require sophisticated computing power, and, more specifically, higher bandwidth communications atypical of today's schools, these tools will become accessible to many schools within 5-10 years. The emerging generation of audio-video information technologies promises high functionality at acceptable costs: significant computing power is coming to be integrated with consumer-level communications technologies. However, applications and findings in industry or scientific sectors may not automatically translate to a K-12 context (Roberts, 1988). Research is required to craft these next-generation technologies to fit the specific goals and needs of precollege education. Yet policy arguments for improving science education through telecommunications abound (Carlitz, 1991; Lesgold & Melmed, 1992; NSF, 1991b; OTA, 1989, 1991). Our goal is to circumvent the typical 15-year trickle-down from advanced technologies to educational applications, by directly working in educational settings to develop new learning environments with next-generation enabling technologies. By giving learning communities next-generation technology early in the technology deployment cycle, we hope to use our experiences in the K-12 context to shape nation-wide communications services and applications.

An equally important goal of the CoVis project is to establish measures of the impact of these advanced communications and computing technologies on learning and instruction. We will do extensive case-study evaluations of the style of person-to-person interaction encouraged by these new communication media and try to understand the circumstances where they have a measurable impact on learning situations. Exact measures of instructional impact are not clear and cannot be clearly identifed until we have had some experience with people using the next-generation technologies in learning situations. However, it is clear that the products or artifacts of interactions (e.g research diaries, drawings, records of conversational interactions) will be of critical formative and summative importance. It is also clear that our specific designs of technologies will be determined through detailed interactions and iterations with students, teachers, and others who will participate in our new learning communites.

3. OUR ENABLING TECHNOLOGIES

Near-term technology allows for very flexible asynchronous (time-shifted) sharing and development of multi-media applications. The Collaborative Visualization Project anticipates that the next important technology window will open a new class of applications we call MUMMS, for Multi-User Multi-Media Synchronous applications. Significant research efforts have been underway at Bellcore and other labs to create infrastructure and sample applications for MUMMS. Bellcore has developed a fundamental software ensemble to enable this new communication medium: (1) Rendezvous™[2] (Hill, 1992; Patterson et al., 1990), A Lisp-based language for building shared-data multi-user applications for domains like instruction and design; (2) Cruiser™[2] (Root, 1988), a suite of communications services for informal real-time personal point-to-point and point-to-multi-point audio-video telephony; and (3) Touring Machine™[2] (Arango et al., 1992; Gopal, Herman & Vecchi. 1992), network operating system level software providing programmers with high-level communications abstractions to build, deliver, and manage MUMMS applications without worrying about low-level network details like transport and connection management.

Parts of this prototype ensemble are currently in daily use by over 100 people, will soon be used by over 125 people across 50 miles. The ensemble is flexible and robust enough for the CoVis project to build new prototypes that will uncover communication protocols and customized application needs of PESL. Current efforts have established the reality of MUMMS applications as an emerging communications medium. The CoVis Project will explore their communications utility for pre-college science learning and teaching.

The primary focus of this work is the application of network technolgy that will be available on a broad basis in the near and medium term. For purposes of cost and efficency, we would like to understand some of the variables that create need for bandwidth in learning applications. The Integrated Digital Services Network (ISDN) for example, enables the style of communication we are exploring. Since ISDN has bandwidth options ranging from 64 Kb/s to 1.5 Mb/s, we would like to understand how learning communities use both Basic Rate ISDN (128 kb/s) higher bandwidth (i.e. 384kb/s and higher). In addition, existing PESL projects have used standard telephone service and our work will use it as well. Our project, therefore, will include both today's and tommorow's network technologies.

4. SOFTWARE TOOLS, PARTICIPANTS, AND SCENARIOS

Using our multimedia software platforms and tools, we are creating new applications for supporting collaborative, inquiry-oriented project-enhanced science learning and teaching. We are developing a network-based Collaborative Science Workbench ("Workbench") which includes a Science Learning Resource Directory ("Directory") for accessing science education expertise.

The software will initially run on personal computers (68030/80386 - 68040/80486 machines) at two high schools in the Chicago metropolitan area, where a UNIX server in each of these schools will manage call connections, files, and application's management for the Workbench's multi-user synchronous access to data and individual user interfaces. We will also be augmenting existing classroom computer setups with specialized switching and CODEC hardware. Each school site minimally includes a networked cluster of six computers. The configuration allows for classroom-realistic group assignments, such as half of a classroom engaged in on-line CoVis work, with half engaged in hands-on and other off-line work (e. g., five student teams of three using the CoVis facility, one workstation for the teacher).

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[2] Rendezvous, Cruiser, and Touring Machine are trademarks of Bellcore

In this section, we describe the software while also characterizing "participation scenarios" for its use, that is, organizational arrangements for learning and teaching using our CoVis tools in the school context. These environments are substantially different than the single-worker office environments in which these technologies have explored to date.

For effective designs of educationally-appropriate and useful materials, activities, and software tools, we consider extensive science teacher involvement to be essential. Teachers understand the context of work practice in which their tools must function, recognize the time flow of learning and teaching in the classroom, and provide insights into whether specific tool designs are too difficult to learn or use in the realities of classrooms. We are working closely with teachers and learners to collaboratively envision tool designs, to refine systems in response to experience, and to fit the tools to science education tasks in our participants' work practices. The two Chicago-area high schools we are working with as "high-bandwidth schools" have a high level of maturity with educational technology integration, and computing facilities and staff. Each site primarily involves two or three teachers, within a larger science department, who will work with these technologies for several class periods each. Three teachers based throughout the U.S. who are involved in the TERC LabNet Project, are also participants. They are highly experienced in high-school PESL, and will be connected with each other and the high-band sites using low-bandwidth telecommunications.

Our CoVis work augmenting PESL builds on knowledge of how to effectively use text-only, asynchronous "tele-learning". Riel and Levin (1990; also see Hawkins, 1991) describe several properties discriminating successful from problematic educational telecommunications projects. Successes require purposeful collaboration and communication, activities structured around real problems, activities that invite collaboration through software design support or the properties of materials used, and the presence of a coordinator to manage and help out in guiding the activities. PESL fulfills these properties using the Workbench and Directory tools that we will develop. Levin and colleagues have also developed different participation models for collaborative "tele-science". They include "tele-apprenticeships", and "tele-taskforces" (Levin et al., 1987; Waugh & Levin, 1989). Our definition of participation scenarios in terms of the learning inquiry model below aims to make this specification more precise.

4.1. Collaborative Science Workbench

From the user's perspective, the Workbench will allow teams to work together within and between classrooms, jointly constructing and sharing PESL artifacts (such as data, notes, graphics, models) relevant to their inquiries, which they can talk about and see in real-time. As described later, projects in atmospheric sciences on phenomena such as thunderstorms, winter storms, ozone depletion, and the lake effect's contribution to rain/snow severity, are a likely focus of the work. The Workbench will also function as a "telephone" for establishing and managing the needed audio-video and shared data connections. The Workbench will provide design support for PESL collaborative work by students across distinctive phases of a commonly-used "inquiry model" in science education. We expect that these PESL phases will have distinctive media and bandwidth support needs, to be determined in our classroom studies of the "inquiry model".

For purposes of Workbench design, we consider the phases to be:

• *Motivating Inquiry*: In this phase, learners observe phenomena, often arranged to lead to puzzlement and surprise vis-a-vis expectation, or to interesting things not easy to account for. Using the Directory, one might experience 3 minutes of remote shared team video experience with a severe thunderstorm or remotely share a view of an animation of real-time weather data visualizations depicting changing weather conditions before an impending storm.

• *Project Definition*: To define a project, learners raise, log, classify, and prioritize scientific questions, and finally come to negotiate a manageable scope and method for a project.

• *Project Investigations*: During the course of a project, roles and tasks for different persons/teams in a project collaboration are defined; questions are asked of experts; a plan is developed, monitored, and refined given time and other resource constraints; teams use empirical strategies to address questions; data-recording tools, and analytic tools appropriate to questions are used. Collaborative visualization needs may include joint view of data windows, and provision of audio and/or video channel for collaborative analysis and interpretations. It may also include provision of real-time weather data viewed with scientific visualization tools, including color maps of clouds, temperature, moisture, and barometric pressure.

• *Project Reporting*: Presentation of scientific results; remote critique and annotation of reports by peers and mentors. This may need to involve video and high-quality graphics.

The teacher perspective on the Workbench is a superset of the student functions described above. In addition to being able to view and manage ongoing inquiries by individual students and teams, teachers will be able to craft designs of "participation scenarios" for collaborations. These scenarios may serve as plans for future use by the teacher, and for sharing with other teachers. Participation scenarios are plans noting project goals, activities, people, resources, and technology configurations. The teacher may add documentation to the Directory to share these experiences with other teachers or for the teacher's own future use. The Workbench will extend the model provided by the Conversation Board, a multi-user electronic white board for conversational communication, (Brinck & Gomez, 1992) to a synchronous, multi-user software environment that provides students and teachers with the functions of collective note-taking and writing, media capture, and access control, organized in terms of the PESL inquiry model above.

There are key differences between our strategy for supporting collaboration, and current LAN-based "integrated learning systems (ILSs)." In each, multiple students use a file-server to access software to do computer-supported work. But there are major pedagogical and technical differences. The ILS paradigm is a computer-extension of the textbook-problem-recitation approach to instructional computing. The Workbench instead views the learner as an active contributor to an inquiring team where problems are not predefined and answers may be unknown. The Workbench also recognizes that different team members often need to see the same data in different ways. Therefore, our applications will support multiple versions of artifacts (such as notes, or sketches) created through collaborative work by separating the data from the view onto it, thereby enabling different views for various learner teams, and teachers.

We also distinguish three models of video use that learners and teachers will try out in participation scenarios. The broadcast television and distance learning paradigm defines the "information transmission model," in which lecture, demonstration or video source material is sent one-way. The second is an "experience port model," which opens a minimally-interactive videoport (e.g., two-way audio, one-way video) to experiences or demonstrations that are difficult or impossible to replicate locally for the school -- a virtual fieldtrip. The third is the "conversational model," in which highly-interactive communications are facilitated. Participants at both ends of the video link see common visual referents and discuss them, as they would face to face. This provides plenty of opportunity for cycles of negotiation of important but subtle shades of meaning, and refinements of skills. While the third model is the most demanding in terms of bandwidth and computing power, we believe it is vital as an instructional tool. Pea and Gomez (1992) review studies on conceptual change in science in face-to-face settings that indicate the need to support highly-interactive conversational interchanges with shared visual field and data in new communication infrastructures for remote teaching and learning.

4.2. Science Learning Resource Directory

A broad range of sites will serve as nodes of distributed science education expertise for learners and teachers. A major rationale is to provide help during project activities from a broader community than the isolated classroom. Our challenge is to provide software tools that minimize the effort of teachers and students in establishing these connections, while enhancing PESL. From the user perspective, the Directory helps teachers and learners identify relevant non-local resources, negotiate connections, and manage the telecommunications issues underlying the "conversation." From the software perspective, the Directory will provide a live port, with specific categories of resources, which can be "dialed up" by selection, including live Cruiser video links to some participating project sites. During our work, we will refine the following taxonomy of types of resources in our Directory[3]. These types will include our collaborating partners in the CoVis Project, whose contributions are shortly described.

• *PERSONS AND PLACES*: Access to Internet (and other gateway-supported) connections to PESL- experienced teachers and researchers; virtual travel to guided-tour Exploratorium science-museum exhibits; the expert help of practicing scientists and graduate students as mentors for PESL (such as National Center for Supercomputer Applications, Exploratorium); other students in connected sites.

• *SOFTWARE TOOLS* such as NCSA science visualization software for viewing weather data in terms of color maps and other representations.

• *MATERIALS*: Media-rich databases for use with software tools, including image databases from NCSA, the Exploratorium, and TERC materials; product information on science kit materials (Science Kit, Inc.); and student project reports.

• *PROJECTS*: Both "live" ones in development by student teams, and archival PESL activity ideas, indexed according to curriculum areas involved, and in terms of "participation scenarios" as the project builds them up with teacher experiences.

Our project collaborators below represent a different type of distributed science expertise for the Directory (i.e., Exploratorium is a science education museum; NCSA is a HPCC scientific research center; UIUC/NCSA are a university scientific research context; TERC LabNet teachers and researcher are PESL-experienced teachers; Science Kit, Inc. is science education materials supplier). The available resources will support computer-based simulations, remotely-accessed physical demonstrations, and on-line expert support to scientific inquiries and will be complemented with in-classroom, physicalinteraction with scientific apparatus.

The *Exploratorium* will participate as a remote node on the proposed network, providing access for remote learners to activities within the Exploratorium's three divisions: the Center for Public Exhibition, Center for Teaching and Learning, and the Center for Media and

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[3]While we are aware of Internet Resource Directories and many efforts underway (e.g., WAIS, the DARPA PSI White Pages X.500 Project, and Z.39.50) to make these databases readily searchable for educational and other uses, in this phase of our project we are not planning to integrate these predominantly text-based resources.

Communications. Project schools in Illinois will connect to the Exploratorium Museum regularly. Broadband links could provide students with remote live access to exhibits on the museum floor, Exploratorium science education staff and local natural phenomena; students and teachers will also have access to new materials to be developed for the CoVis Project, including an image database of weather-related phenomena for real-time video viewing, and file transfer activities from various museum exhibit and educational databases developed by science teaching staff, including a topic-based interface allowing search among descriptions and affiliated materials for over 700 exhibits representing 400 natural phenomena.

UIUC/NCSA (Univ. of Illinois, Urbana-Champaign; National Center for Supercomputer Applications). Besides bringing a software base that enables scientific visualization, collaboration, and distributed computing, NCSA and UIUC-affiliated science faculty and graduate students will contribute to developing precollege materials and activities in computational atmospheric sciences using these tools. They have developed a computerized weather laboratory and introductory freshman course permitting interactive access to real-time weather data (image data from remote sensing; and ground observations), and to output from numerical weather prediction models. Networked computer workstations such as MacIIs permit the use of public domain, general visualization tools that NCSA has developed for interactive exploration of these data for exploratory and simulation activities that can be connected to experimental information, and used to exemplify "abstract" physical concepts. The UIUC/NCSA group will also make their domain experts available for periodic synchronous and asynchronous interaction with our participating schools, so they may experience scientific professional activities involving uses of visualization and high-speed networking technologies.

TERC (Technical Education Research Center). In the NGS-KidsNet, Star School, Global Lab, and LabNet Projects, TERC has pioneered the development of computer tools, scientifically-sound materials, and participation models for PESL which use "low-band" telecommunications. TERC's LabNet Project, involving an electronic teacher community of over 400 PESL teachers in 37 states, has developed new understandings of teacher development assistance needed to establish and sustain PESL in the classroom. TERC is providing contributions from an experienced team of three PESL science educators and researchers, who will be accessible over the network.

Science Kit, Inc. is a supplier of science education equipment and materials. The Directory will include on-line access to their 19,000 product database, indexed by science curriculum topics, and cross-referenced to major science textbooks. Hands-on equipment and materials that complement the classes' investigations can be selected for immediate delivery. Science Kit will also cooperate in efforts to disseminate project materials and results to the community of science educators.

4.3 An Example Scenario

It is 1997, and in a high school classroom in Alabama, Olivia Jones is worried about the loss of a cousin's home to a twister. When her physical science teacher asks her to think about possible projects, she considers learning more about tornados, and examining how her community might set up a local early warning system.

• *Motivating the question*: First of all, Olivia wants to see examples of what tornadoes do and what they look like. At her workstation, Olivia is encouraged by her teacher to open the Science Learning Resource Directory, and she begins to explore available resources. She finds that the Exploratorium Science Museum has an experimental whirling air setup, providing a vivid demonstration of tornado wind effects. Science Kit, Inc. has videos illustrating a range of tornadoes. The National Center for Supercomputer Applications in Urbana has stunning graphic simulations of tornado conditions, historical archives of digital imaging data for U.S. weather conditions, and experts in atmospheric sciences who may be contacted as mentors. Moving beyond a "yellow pages" directory service, the Resource Directory makes connections with these resource providers, and establishes the subsequent call exchanges.

• *Students working together*: Engaging and illuminating follow-up activities are needed so that Olivia and her student team (including two students from another school she found to have similar interests) develop a deep understanding of the scientific content and social issues that arise with tornadoes. She and her fellow team members negotiate project scope and methods with their teachers, using asynchronous email and Cruiser-style informal audio-video conference chats as needed. They use the resources described earlier, and also find out from followup discussions with meteorology content specialists at NCSA how early warning systems have been developed. With the Collaboration Science Workbench, Olivia's team works together to create their own multimedia report incorporating video of twisters, digital imaging data of precipitating weather conditions, audioclips of an interview they have conducted with a meteorologist, and a written synthesis detailing specific early warning system properties, for each location identified in their research. The Workbench facilitates intra-class shared data and collaboration, and provides the telecommunications support for inter-school collaboration.

5. A TESTBED FOR NEXT-GENERATION EDUCATION NETWORKING

What are the demands placed on public networks by such collaborative visualization activities? It is not clear. The next-generation public network will be able to provide a wide variety of new communications services to the user. For example, ISDN will create a national integrated digital service with siginificantly increased bandwidth. Switched Multi-megabit Data Service (SMDS) will provide very high-speed lan inter-connection services. Other technologies will make it much easier for new communications services to become available via the network. The CoVis project will provide a testbed to judge the viability and utility of next-generation communications services and applications to education. The project will also provide a rich set of user requirements from students, teachers, and the community at-large working in a real educational setting. One of our key objectives in this research is to understand and articulate the value of various types of technologies the breakthroughs they might provide in educational applications. What are the bandwidth requirements for providing satisfying collaborative learning environments for students and teachers? To address these questions, we expect to conduct comparative studies in the classrooms that focus on the utility of different bandwidth services.

With the CoVis testbed in place, we will be able to examine the utility of different candidate designs for communication services for PESL. We can vary communication-service details such as bandwidth-transmission rates, synchronous/ asynchronous needs, symmetry, and packet/circuit switching telecommunications infrastructures. We will examine computing and communications infrastructure needs for the PESL participation scenarios that teachers and learners find important, concerning the amount and type of collaboration allowed by the Workbench and Directory tools, and how flexible the call models are that allow that collaboration. For example, can PESL communications between classrooms be done with less than full DS1 transmission rates (1.5Mb/s), such as Basic Rate ISDN or swift DS-1 (allowing fractional DS-1 rates such as 384 kb/s)?

We can develop interactive demonstrations for students, teachers, and PESL activity developers in our team that use different bandwidths, that range from two-way video with shared data (high demand) to only shared data (low demand). These demonstrations will be used to elicit their intelligent guesses as to which PESL activities need which kinds of bandwidth support. After defining a set of options we will then examine several questions in the flow of PESL classroom work over the school year: First, do students and teachers notice the difference between the steps in this progression as they are engaged in collaborative inquiry? Second, we expect to develop experiments in tradeoffs of utility vs cost by providing communication bandwidth as a limited resource, which teachers and students can choose to use in the ways they find most helpful for achieving the different activities of PESL. They will have the opportunity to refine through their experiences which bandwidth configurations work best for which purposes. For example, consider two bandwidths A and B. If bandwidth A is twice that of bandwidth B, they might only get half the use time of bandwidth A as compared with bandwidth B. This design has the advantages of: (1) having some market realism, since broader-bandwidth services are likely to be more costly; (2) leaving the design of their communication environments up to them, so they discover what is useful in their classroom experiences with specific PESL scenarios; (3) overcoming the problem that, in an unlimited resource situation, more bandwidth is very easy to prefer; and (4) providing powerful data on what the primary users of these technologies find most useful about differing bandwidths in providing CoVis functionality. Through this work we will be able to provide the first empirical results of user-selected variable-rate telecommunications services to support distributed science learning.

6. CONCLUSIONS: TOWARD A NATIONAL MODEL

In the CoVis Project, we are creating an experimental testbed for new forms of science learning and teaching supported by telecommunications technologies, and hope to define a national model for distributed multimedia science learning environments.

Experience with Internet has shown that ubiquity of access exposes the true value of a new communications medium. We are going far beyond known uses of Internet and such technologies as videophone for remote communications. These tools will allow us to create software applications for student and teacher use that provide audio/video and shared data connections, potentially using both the local exchange, and the inter exchange (long distance) public switched networks. Our vision leads to use of the public switched network for highly interactive multimedia conversations among groups of collaborating students and teachers. We will use a deeper understanding of PESL and its implementation in learning situations with real collaborating students and teachers to inform the development of new communication services. We will also inform changes in classrooms and other learning spaces about how to form useful distributed collaborating learning teams.

How will MUMMS applications focused on PESL become available to all students in the United States? Only the public-switched telecommunication infrastructure can easily evolve to meet the basic technical needs of next-generation MUMMS applications because it provides national point-to-point and point-to-multi-point connectivity. The open question for the CoVis Project is not whether high-bandwidth (>1.5Mb/sec) and multi-functional digital services can be provided, but how such services should be structured to meet classroom needs. Since our design work is situated in classrooms, not laboratories, we will learn what teachers and learners find useful, in ways that could significantly influence the telecommunications services and technologies that will serve education in the future. We foresee a future of the provision of research-guided, and educationally-sensible uses of the public switched network for highly interactive multimedia communications for science learning/teaching, and collaborative inquiry. When appropriate telecomunications services can be defined for science education, the scaleup will come first through , the commercial availability of such services, and second, through their regular use by public educational institutions.

7. ACKNOWLEDGMENTS

This research is being supported by the National Science Foundation, Applications of Advanced Technologies. We would also like to thank our partners and colleagues, including Gene Dunne, Robert Fish, Shahaf Gal, Douglas Gordin, Arnie Lund, Marie Macaisa, Douglas Macfarlane, Rick Omanson, Mohan Ramamurthy, Nora Sabelli, Rob Semper, Elliot Soloway, William Spitzer, and Robert Wilhelmson, for their contributions to conceptualizing the project.

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