SCIENCE EDUCATION AS A DRIVER OF CYBERSPACE TECHNOLOGY DEVELOPMENT [1]

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Abstract

Distributed multimedia learning environments can reshape pre-college science education. This paper provides a perspective on what is required to place these environments into classrooms and details what challenges must be met for their appropriation. The Learning through Collaborative Visualization Project has provided a wide-band high-speed computer network and a desk-top video conferencing network, a means to collaboratively write and structure scientific inquiry, and scientific visualization tools that provide wide-ranging data sets on climate and weather. The development of this environment was guided by a question-centered and collaboration-focused pedagogy that recognizes students and teachers will continue the design process by innovating uses and suggesting revisions to their functionality.

1 Introduction

Educational applications of networking technologies are becoming increasingly prevalent. But "applications" are too often treated as infusions of technology into society, not drivers of new technological or research developments. The premise of the Learning through Collaborative Visualization, or "CoVis" Project, challenges that common belief [23]. Extending media-rich and highly interactive learning and teaching activities beyond single classrooms makes demanding requirements for new applications. We aimed to create "distributed multimedia learning environments" to serve precollege science education needs.

2 The CoVis Project

Our goal has been to create a scaleable solution using the public-switched network to establish distributed multimedia learning environments for high school science. We have designed and now provide wide-area broadband services that integrate desktop videoconferencing and screen sharing, educationally-appropriate scientific visualization tools, newly-developed structured hypermedia collaborative workgroup software, and standard Internet communication tools by hundreds of students and six diverse teachers.

2.1 Serving science education needs with cyberspace technology development

The CoVis Project designed a "network testbed" in which a vision for science educational reform that takes cognitive, social, technological, and scientific breakthroughs into account could be concretely implemented and then empirically studied as a community appropriates and evolves its uses. We have found it essential to attend to learning and teaching needs and technology trends. Our assessment of learning and teaching needs has led us to *project-enhanced science learning* [27] as an embracing approach to pedagogy. Attention to trends in national information infrastructure led us in particular to the public-switched ISDN network, to client-server distributed network architecture, to scientific visualization as a substantive emphasis, and to designs for new collaborative tools for joint work among CoVis community participants.

2.2 Education is a demanding environment

Computer and communications science and industries make a mistake when they assume that advances in technology occur either from technological innovations and engineering alone, or from generalized theories of human-computer interaction. We know from work this past decade on "user-centered system design" for software systems [19] that it is exceptionally important to fit the tool to the task, even as we seek to invent technology paradigms and applications so that new tasks become possible.

Education in particular has suffered as often the last application area for advanced technologies. It has typically taken 15 years for computer tools to make their way into classrooms from their advent in military or industrial settings [29]. Examples include the spreadsheets, graphing tools, simulations, and word processing. But education is far too crucial a function for the future of our increasingly global societies to wait in this long line.

In precollege education, children of different ages participate daily in one of the most demanding challenges of a lifetime. They are supposed to devote some 18,000 hours over about 200 seven-hour days a year for 13 years to learn to engage the different abilities of the mind and body, to become literate in the subject matter, skills, and media of their era, and to contribute to society in work, family, and community. Until recently, students' primary setting for doing so was with one or a few teachers, within a few small rooms, not connected to the world even by a telephone.

Education is not only an "application area," but what we will call a high-priority "invention area." Industry could benefit from working with educational professionals and learning scientists to understand the market opportunities surrounding the provision of better support to the activities of learning and teaching.

While teachers have adapted previous "innovations" such as slide projectors, audiorecorders, radio and TV without making substantive change in their teaching [4], there is strong evidence that teachers are recognizing how computer and communications technologies have vast potential to provide new work tools for transforming their educational practices and the learning experiences and outcomes that are possible in fundamental and exciting ways [18].

The demands and constraints of educational settings can drive the development of very interesting and valuable new technologies and paradigms of computer and telecommunications use in support of human activities. Several years ago, Pea and Gomez made this argument for the creation of Distributed multimedia learning environments [25] integrate computing and communications to provide students with rich resources for learning accessed in the context of geographically separated learners.

2.3 Science education as driver of CoVis technology developments

We now provide five examples, in a common framework, for how the demanding needs of science education have led to new cyberspace technology developments in the CoVis Project. A preliminary overview of the CoVis network environment and "testbed" suite of applications will be useful. We began working with six earth and environmental science teachers at two Chicago-area high schools in summer 1992. In fall 1993, these teachers and nearly 300 students began the school year with scientific visualization tools for atmospheric sciences and an asynchronous collaboration environment called the Collaboratory Notebook, both developed by the CoVis project, as well as desktop video teleconferencing, and a full suite of Internet tools including e-mail, Usenet news, and Gopher. Students in each classroom use these applications running on a group of six Macintosh Quadra workstations connected to a high-speed video and data network. These applications collectively provide a "collaboratory" environment [16] that couples tools to support communication and collaboration with open-ended scientific inquiry tools.

2.4 A scaleable network desktop video and media-rich communications

Context of problem. K-12 schools have not generally benefited from Internet-connected IP networking, although many schools are beginning to achieve basic use of low-bandwidth networked applications like text-only email. One major goal of the CoVis project is to combine prototype and off-the-shelf applications to create a reliable, networked environment that showcases HPCC technologies for K-12 learning communities.

Educational needs of learners and teachers. As in related industrial work at Bellcore and Xerox PARC, we wished to create rich "media spaces" in which distributed project teams could do collaborative work [10], but in this case, in support of collaborative work and learning among adolescent students. Research in the learning sciences had indicated that learners and teachers need highly interactive conversational environments around media-rich artifacts to provide common grounds for fostering learning communications [24, 25].

What did we develop? The network design and implementation was the result of a collaboration between Northwestern, Ameritech, and Bellcore. We selected public-switched Primary Rate Integrated Services Data Network (PRI-ISDN) as the transport layer for the CoVis network. ISDN is the switched network service with the short-term best combination of high bandwidth and ubiquity, and Bellcore predicts access in 1996 to over 70% of the nation's population. ISDN bandwidth can be broken up into call channels, and dedicated to different functions, so we were able to create a hybrid, two-function "overlay" network that gives student workstations access to both ethernet-based *packet*-switched data services and *circuit*-switched desktop audio/video conferencing. Each CoVis classroom in the first year of the project contained six networked Macintosh workstations with an accompanying desktop video teleconferencing unit.

At each school, the local ethernet is bridged through an ethernet-ISDN bridge and passed through an inverse multiplexer across the ISDN lines to Northwestern's campus-wide network, using a group of six 64 kb/s ISDN channels to create a 384 kb/s "virtual ethernet" connection (compression performance yields ~1 Mb/s).

Because we sought to avoid blocking of video calls, each school required enough line capacity to maintain six 384 kb/s video calls at once (thus 36 b-channels for video). Since a single PRI line contains 23 b-channels, each school required two PRI-ISDN lines. The network layout for the first two CoVis schools is shown in Figure 1.

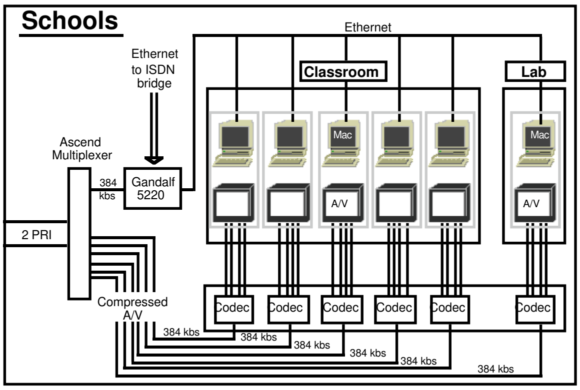

Figure 1. The network configuration for the two Year One CoVis schools, showing both data and video networking.

Desktop video teleconferencing is a critical component of the CoVis testbed. Students use Bellcore's Cruiser™ application [8], allowing them to place point-to-point video teleconferencing calls to other CoVis addressees by selecting an individual's name from a directory. Cruiser is a client application of Touring Machine, the distributed network software developed by Bellcore for managing the heterogeneous resources (e.g. cameras, microphones, monitors, switch ports, directory services). It is significant that CoVis Project needs and Ameritech interests drove the first integration by Bellcore of Touring Machine into an ISDN network. Bellcore's Touring Machine and Cruiser development teams devoted over two person-years to the CoVis Project to develop network infrastructure. To our knowledge, CoVis is the first school-based application of ISDN desktop video conferencing.

In addition to video conferencing and Internet applications, the CoVis communications includes screen sharing. CoVis participants may collaborate synchronously through screen sharing, using Timbuktu (Farallon), which enables one user to see exactly what appears on the screen of another user, regardless of distance, and users at either end of a screen-sharing session may control the remote computer with their own keyboard and mouse.

How did it work in use? Our key result is that the network is running and in daily use by approximately 300 people, mainly high school students. The challenge of this effort has been to take a collection of technologies, many only demonstrated or tested in small-scale lab situations, and place them into daily service in demanding conditions. Our progress culminated in a stage-by-stage installation in Fall 1993 of the CoVis network testbed using public-switched ISDN services. It has been in use since. During the first year, we encountered a range of difficulties stemming from the experimental nature of some of the software, inexperience with novel products and services both within the project and at the commercial service providers, and product and network unreliability. Within three months of its initial deployment, the data and video network were stable and reliable. How specific applications were used within this networking environment is described below.

What does this tell us about design both generally and specifically? For the foreseeable future most school's access to high speed and flexible networked communication will require some degree of customized network design. In the case of the CoVis network, we used special purpose network hardware (e.g., bridges and multiplexers) to create an ISDN-based 386 kb service which was fast enough to meet both circuit and packet data needs of the CoVis schools while remaining reasonably affordable. In the two years since the initial design of the network, high-speed Internet commercial services of the sort that the CoVis project has been providing for schools have become widely available. However, the hybrid of data and video communications service we created does not exist as product.

The particular details of our networking solution may or may not be applicable to a wider audience of schools. Other schools may get high speed network access through a cable TV infrastructure and still others via different telephone-company-based services (e.g. switched-56). The next group of CoVis schools as we scale to 50 schools over the next year will be employing a variety of different options, depending on their local constraints and opportunities. To date, there is no common network access vehicle for schools. All options require some form of special network hardware/software expertise not typically found in schools.

What challenges remain? Given our low level of understanding of the appropriate range of network services to provide high speed school access, the current diversity is valuable. As diverse network infrastructures are implemented in schools we will learn what configuration best meets schools' needs. The challenge is to find ways to document how schools use networking to develop well-founded ways to recommend services that will scale significantly.

2.5 Adapting scientific visualization tools for learners

Context of problem. When starting our work on scientific visualization for precollege education in early 1992, we were impressed with the utility of general-purpose visualization environments for the scientific research community. Data sets were routinely exchanged over the Internet, and a variety of data formats and visualization techniques were available to support their primary goals of seeking pattern in complex data using the distinctive strengths of the human visual system [3, 30]. Science teachers and students might similarly benefit if given the support necessary to appropriate and "redesign" visualization for their needs [14].

Many of students' troubles in science stem from difficulty in understanding the abstractions, formalisms, and quantitative terms of equation-based data representations. By taking advantage of powerful human visual perceptual capabilities, scientific visualization offers a new route to scientific understanding, and the possibility of reaching students traditionally ill-served. Scientific visualization also offers the possibility of opening up new domains for study that have been considered too complex for students because of their heavy reliance on formulae and abstract representations. Similarly, scientific visualizations can give students the ability to conduct direct investigations in areas to which they have only had indirect access before (e.g., global climate data; planetary biomass distribution; ocean temperature).

We had spent considerable time in science classrooms, and knew from previous work on science educational software that a vast gap existed between what students understood and what they would need to know to use such tools effectively in support of science learning.

Educational needs of learners and teachers. The needs for kids to make scientific visualization technologies usable were great [14]. Typically, scientific visualization software, such as Spyglass's *Transform*, provides a powerful general purpose programming language for transforming such data as spatially gridded temperature and moisture data into a colored image in which temperature values are mapped to colors. The data sets for scientific inquiries like these are commonly so well-known by the scientists who use them that they do not even bother to label the variables represented in the data tables. The operations in the general purpose programming language which are sensible ones are typically so familiar that the scientist does not even notice all the possible programming commands which could be issued which would yield nonsensical transformations (and hence visualizations) of the data, such as dividing temperature values by moisture values. Scientists demonstrate shared tacit knowledge about the data sets that students lack. For example, units are frequently not specified and highly distorted spatial projections and perspectives are used.

What did we develop? Work to adapt scientific visualization for the classroom involved creating "knowledge engineering" techniques and new visualization tools for learners. For the techniques, our team worked closely with atmospheric scientists to adapt their research tools for use in high school science by creating "front-ends," or supports for novices to work with complexity. We defined a four-step methodology for adapting scientific tools for learning [7]:

1. <u>Investigate science practice</u>. Scientists are observed using visualization tools and data sets for a specific domain, with the goal of eliciting the sorts of questions the visualization tools and data sets can be used to investigate for their area, and how the tools are employed during inquiry.
2. <u>Identify tacit knowledge used in science practice</u>. We seek to articulate the tacit knowledge scientists employ when using visualization tools, e.g., scientific principles, understanding of the limitations of data collection processes and models used to enhance the data, and how-to knowledge for tools.
3. <u>Scaffold the science practice for students by making the tacit explicit</u>. We adapt these visualization tools to make explicit in the software interface and affiliated pedagogical activities the tacit knowledge so as to assist students in pursuing meaningful questions.
4. <u>Refine the visualization tools in response to formative evaluations.</u> Through a combination of observation and direct user feedback, we evaluate the patterns of use that emerge and iteratively redesign the software as needed.

We developed three visualization environments using this four-step process for building "front-ends" to scientific visualization tools and data sets. These visualization environments cover three aspects of atmospheric science and are called: (1) the Climate Visualizer [13, 14], (2) Weather Visualizer [9], and (3) the Greenhouse Effect Visualizer [12]. Each of these is built on top of a scientific visualization tool used by researchers (e.g., *Transform* from Spyglass, Inc. for (1) and (3), and *wxmap*, at the University of Illinois, Urbana-Champaign, for real-time weather data [26].

How did it work in use? During 1993-94 and 1994-95, students in the classrooms of the CoVis testbed have used the different visualizers in their science projects. Yet while they found the tools comprehensible and the visualizations to offer new insights into the phenomena of the domain we underestimated the need to provide activities for teachers and students that would provide them with an understanding of appropriate contexts for use. As a result, teachers perceived relatively narrow curriculum scopes in which these specific scientific visualization programs fit, and students often lacked the ability to develop meaningful uses of these investigation tools on their own.

What does this tell us about design both generally and specifically? The successes in being able to evolve a high-end scientific workbench into a precollege-age appropriate learning tool by this process we called "front-ending" were important achievements. Our industry partner Spyglass became particularly enthusiastic about these results as they related to the market for their software. Previously, they had conceived of their market as scientists, who would use visualization technologies in their research. Now they conceive of their software, if joined with age and knowledge-adaptive front-ends, to have a much vaster audience, including children with little background in science, an entirely unexpected result from their perspective.

What challenges remain? A major challenge is the issue of curriculum scope. We believed that "weather" and "climate" and "greenhouse effect" were each not topics for only a set number of weeks in the earth sciences curriculum, but topics involving such interesting, diverse, and complex phenomena that they could be investigated in projects throughout the school year. But to do so required too large a change in teaching philosophy and curriculum theory for the CoVis teachers. On the other hand, it would not have been practical for the CoVis team to conduct the ethnographic observations and interviews which were integral to the design of our knowledge-scaffolding front-ends to the visualization software and data sets for each and every one of the other cognate fields -- astronomy, geology, oceanography - which the teachers sought to "cover" in their teaching of earth science. A second challenge is the development of appropriate activities and materials for teachers to rely on in their initial appropriation of these tools. We now plan to develop tasks and activities that contextualize our tools with reference to fundamental scientific questions and principles and choreograph their integration with existing classrooms practices.

2.6 A groupware application for systematic science inquiry

Context of problem. Early approaches to the use of technology in education were based on a transmission model of instruction, in which technology (e.g., film and broadcast media) was used to transmit instruction in a more engaging fashion and to larger numbers of students. Distance education inherits this tradition when it uses phone lines, satellite links, and microwave to transmit static knowledge to wider audiences, with minimal opportunities for highly interactive conversations with instructors or learners [25].

With the advent of the personal computer, technology took on new roles for learning, including supporting students to interact with responsive environments that support compelling active learning. However, in workplace and other environments, computers have shown great value in supporting communication and collaboration, as in e-mail and in groupware tools such as Lotus Notes. Increasingly technology has assisted in broadening the form that collaboration takes to include not just discussion but the sharing of artifacts and cooperative work across time and distance. Technologies with similar emphases can play a revolutionary role in supporting new forms of learning conversations in educational settings [7].

It has been a commonplace from cognitively-guided research in science education to document how lecture and demonstration centered pedagogy is not effective at securing student subject matter understanding [17]. Learning which builds from students' questions, which engage the knowledge that they have, is characterized as a "constructivist approach" to learning [15, 28]. Projects in the sciences can build from students' questions, and when well-guided by mentors, provide motivating and effective contexts for the acquisitions of research skills and scientific understanding [27]. We thus aimed to create a groupware application for fostering student learning and systematic science inquiry through project-oriented learning.

Educational needs of learners and teachers. When teachers seek to integrate open-ended science projects into classroom life, they find many challenges to their goals of keeping records of inquiries and monitoring student progress in their investigations. We expected technology could provide significant support to these goals.

What did we develop? We created a wide-area network-based hypermedia Collaboratory Notebook, on top of an Oracle database server [5]. The link types of the Collaboratory Notebook "scaffold" processes of scientific inquiry, and enable distributed work groups to define and conduct science projects. Throughout their work, students are able to record text as well as tables, graphics, sound, video, and animation within their notebooks. These groups may be students within schools, across schools, and often involve adults as mentors, including teachers, scientists, science graduate students, and science education researchers. Project workgroups negotiate project topics with one another and teachers, log observations from scientific visualization and hands-on investigations, and communications from Internet document and data identification useful for their project. It is also designed to provide teachers and other mentors with a window into the students' thinking processes and activities.

In a typical use of the Collaboratory Notebook, a group of students might develop an idea for an inquiry, negotiate its details with their teacher, and begin by recording questions and hypotheses. These could be followed by a plan for how to pursue their inquiry. A teacher or other mentors might read the students' questions, hypotheses and plans and add comments to help them focus their efforts or to alert them to useful resources. Students may go on to engage in separate research activities that they could individually record for the others to view. In doing so, they store both data and analyses within the Notebook. Without needing to meet in person, students can exchange questions and comments on their findings. Once they have conducted their investigations, they can get further guidance from an instructor or a scientist mentor, and use their recorded information to draw conclusions or initiate further research.

How did it work in use? Throughout 1993-94, teachers and students used the Notebook in a variety of ways to support their open-ended activities. In one case, a teacher conducted a weather prediction activity using the Collaboratory Notebook, in which groups of students would all record their predictions and the evidence for them for the same day. After recording their own prediction, students then had the opportunity to view and comment on the predictions of other groups within the Notebook software. Other activities involved recording questions and progress during more traditional open-ended classroom research projects.

The Collaboratory Notebook was designed for an environment where access to computing resources would not be a limiting factor. In fact, given access generally to only six workstations in each classroom for about 25 students, resource limitations became a real issue. As a result, many projects were developed with only minimal use of the Notebook [6], and some teachers chose not to use the software at all. As far as the nature of the activities that were conducted with the software, some uses of the Notebook for projects used few resources beyond textbooks and reference materials. Many Notebook projects could have benefited from mutual influence, but students were unaware of one another's efforts [21], thus failing to produce cross-school collaborations. One collaboration at a distance occurred when scientific mentors from the Atmospheric Sciences Department at the University of Illinois and Exploratorium Museum in San Francisco advised students investigations.

What does this tell us about design generally and specifically? On functionality, the scaffolding supports of the link types in the Notebook provided important guidance for students in their project work, and for teachers in their goals of monitoring and shaping student progress. Heeding the structure of the work tasks in science projects, rather than using a general hypermedia notebook with untyped links, was an important aspect of this success. On the other hand, attention to resource limitations and their effects has proven to be a critical issue.

What challenges remain? We would like to see much more integral use of the Collaboratory Notebook in the science classroom. Such use would require several major changes, however. One is the growth of a classroom culture of presentation, commentary and revision of notebook-supported projects. Too many projects which have relevance to one another are underway in the CoVis testbed, and yet due to teacher practices do not find their way into discussion, on-line or otherwise, with respect to one another. A second major change would be availability of a computer and network connection to every student and the teacher, during school and, ideally but especially for the teacher (who often reviews student work at night), at home. Another alternative in this vein is to discover designs for applications like the Notebook that encourage use without each person having personal on-demand access to the application. A third and crucial major change will be in establishing the critical mass of classrooms throughout the country in the next phase of the CoVis Project that can contribute students wishing to work together, and sufficient experiences among teacher practices in establishing agreed-upon standards for assessing the quality of learning and research in students' collaborative projects.

2.7 Desktop video for classroom use

Context of problem. Considerable enthusiasm has been developing in the industrial community, and in the "new media" marketplace for video-to-the-desktop. The industry focus has been on supporting formal videoconferencing participation by groups who do not need to go to a special facility, or on supporting the informal communications, much like running into a colleague in a coffee area, that tend to enhance the chances that such colleagues with engage in collaborative work [8]. There have been complex technological and social design issues. Technologies for desktop videoconferencing have been expensive primarily because of codec costs, and sustaining acceptable frame-rate performance for person-person communication needs over either LANs or WANs has provided a demanding environment for engineering. On the social side, the crafting of software and communication protocols for launching and managing desktop videoconference calls to support human communicative needs at work has taken considerable effort. Videoconferencing to the desktop in the classroom was virtually non-existent, although many examples existed of "distance learning" uses of classroom-based videoconferencing [25].

Educational needs of learners and teachers. Our expectation was that there were a range of likely needs of the activities that go on in a project-enhanced science classroom which desktop videoconferencing could fulfill. First, we conjectured that a teacher's use of initial resource materials to motivate student interest in a science topic from which projects could be developed, such as videotapes, would carry over to a use of remote visits to interesting video sources, such as exhibits at the Exploratorium Science Museum (a CoVis partner). Second, we conjectured that students would wish to conduct some of their collaborative work across schools with the additional media channel of desktop video, to enhance the communicative feedback possible as they worked to further their project activities. And third, we conjectured that being able to create a distributed audience for the presentation and discussion of project results would be an appealing use of the desktop video medium.

What did we develop? We made it possible, with extensive engineering and redesign work from Bellcore and Ameritech, for students to use the

Cruiser™ application to place calls to other CoVis addressees, including other classrooms and Northwestern researchers. Late in the 1993-94 school year, Cruiser installations at the Exploratorium Science Museum in San Francisco and at the Department of Atmospheric Sciences at University of Illinois, Urbana-Champaign made possible virtual field trips and interactive weather briefings.

How did it work in use? Cruiser was technically available in CoVis classrooms beginning in January 1994. Surprisingly, it was used primarily for troubleshooting pedagogy and software use between teachers and Northwestern research staff, not between classrooms in cross-school collaborative projects as anticipated. Since teachers were worried that adolescents would use it as a medium for socializing and ignore their project work, they were leery to incorporate videoconferencing into project activities or requirements. This limitation in access to the students meant that it was not used in their investigative work.

Furthermore, few cross-school projects developed, since it turned out that teachers did not have a strong enough motivation in favor of cross-school collaboration by students to overcome the challenges that such collaboration presented. For example, the teachers had never before needed to negotiate standards for assessing student work on projects across schools. Without common grounds for assessment, they were not going to encourage cross-school student collaborations. Reflecting this difficulty, video conferencing was not used within cross-school collaborations. The same limitation prevented the expected use of Cruiser to extend the audience for student projects.

What does this tell us about design both generally and specifically? In short, the "office worker" paradigm of informal videoconferencing to the desktop does not transfer "whole cloth" to the classroom. New design must acknowledge the different goals and social arrangements present in classroom environments than in the workplace. The social conditions for collaboration assumed to be supported by videoconferencing must be in place before the tool will be seen as serving useful functions. Further, the user interfaces to video conferencing applications for classroom must specially designed. Just as the Cruiser application we used was crafted with the realities of the white collar office in mind, we have to articulate the design constraints from the classroom that should shape informal video conferencing for teaching and learning.

What challenges remain? We are finding a strong potential in uses of CoVis testbed videoconferencing in support of scheduled events that can be drawn on by teachers as dynamic classroom resources. These events allow students and teachers to interact remotely with scientific experts in informal and formal activities. We are able to provide CoVis workstations with live daily weather briefings from atmospheric researchers (faculty and students) at the UIUC Weather Room. Such briefings can illustrate, through interpretation and analysis of weather charts, satellite and radar animations, and forecast products, key concepts that will enable a student to conceptualize the structure and dynamics of the atmosphere. CoVis students may participate in real-time discussions of weather processes, collaboratively interact with scientists around shared data involving atmospheric, kinematic, and dynamic processes depicted on weather charts. In a similar vein, students are able to take virtual field trips to San Francisco's Exploratorium Museum. Students set up a video call and Exploratorium staff wheel a remote video production cart to the exhibit floor and provide interactive discussions around exhibits on particular subjects (e.g., investigating the weather section or exhibits on erosion).

How to effectively scale network-accessible video events is an obvious challenge. Here, too, designs must be evolved for how teachers and children will make use of these events for classroom purposes. Since there are no preexisting models of applications like these, a certain amount of experience-informed iteration will be necessary.

We are investigating means to supply video and audio communication over IP connections on Internet data networks as our current model of circuit-switched video connections has proved costly to schools. The challenge is to identify more off-the-shelf solutions to providing wide scale integration of desktop videoconferencing into classrooms.

3 An educationally appropriate world-wide web resource

Context of problem. Exponential growth in uses of the World Wide Web (WWW) recently has also benefited education, as many K-12 schools are now regularly seeking information and resources for learning and teaching there. But web servers do not automatically make for educationally-useful resources. What will be required to establish education-oriented WWW servers which are guided by the needs of learners and teachers [11]?

Educational needs of learners and teachers. Educational web servers will have teaching and learning centered design, including special purpose "front-ends" to web resources, and supporting structures which help educational users match resources to teaching-learning needs.

Among the resources that learners and teachers will need are to: (1) publish to audiences which will motivate better documents, (2) solicit commentaries that may help advance learning, (3) engage communities of practice in the world beyond school to make school knowledge-production shareable to school and non-school users beyond a single school's boundaries, and (4) seek connection with members of professions in relevant areas of specialization for professional development purposes.

An education-focused web server will also include suggested or tried-and-true activity structures, and assessment rubrics. The resource will recommend how to set up teaching-learning activities in the classroom which use specific WWW resources. We also believe that web-based forms are needed so that users of educational WWW servers can provide commentaries on the found utility (or not) of specific web resources or activity structures for their use. In this way, web servers would cybernetically adapt as their value is determined through uses in practice.

What did we develop? We are working on the Geosciences World Wide Web server. The aim is to provide a new paradigm for environmental science and earth sciences education. It will include an on-line weather and climate laboratory for schools, with such resources as climate data sets, locally-collected data sets which student groups around the world have entered, editorially-reviewed student projects, and an indexing scheme for all the resources and services that are provided by it.

How did it work in use? The Geosciences WWW server is still under development. Ultimately, we hope it will be an integrated platform for learner-centered asynchronous collaboration. If we are successful, its design will encourage teachers to consider it as the first resource to consult when planning or implementing an activity from the Geosciences in the classroom. We also want it to become a repository for examples of "best practice." Teachers will be able to add their activities to the server. Students will use the server as a place to share their project results. Our goal for the Geosciences web server is to be the first integrated example for a web application that completely supports classroom science activity.

What challenges remain? Web servers -- like textbooks and other media before them -- must evolve to be useful in teaching and learning contexts. The CoVis Geosciences WWW server will provide an initial step in this sequence. The aim is to provide several examples of web applications focused on learning situations. Applications must be developed that can be appropriated by teachers -- such applications will pay provide advise on the social and activity structures in which the information provided can be utilized.

4 Conclusions

In the past, technologists and marketers have considered education an "application" for their existing products and technologies rather than a driver of new products and services. Our point here has been that it is more productive to think of teaching and learning as a driver of technology development. While this perspective has been rare in the past, the development of cyberspace is an opportunity to design new underlying features and applications motivated by the needs of teaching and learning rather than seeing education as just a reason to re-purpose and re-package existing applications.

We used our experience in the CoVis testbed to illustrate this point. It is clear to us from our experience to date that we have had successes engaging teachers and children when we have understood their needs and created applications that fundamentally reflected teaching and learning contexts. In contrast, we have been least successful when we attempted to transfer, wholesale, an application or application-concept to schools without the necessary rethinking or fundamental re-conceptualization. Our experience with Cruiser videoconferencing is a perfect case in point. We believe that teachers, at least in part, shied away from video conferencing because the form we presented it to them came directly from the world of white collar office work. In that world, for example, people often have private space in which to work. Personal video conferencing makes sense. In the class, private space is minimal. Therefore, informal video conferencing must be re-thought for the classroom.

On the other hand, we were more successful with the Collaboratory Notebook and Visualizers because they were informed by the needs of learning communities from their inception. In the case of the Collaboratory Notebook we started with a general notion -- collaborative hypermedia, and shaped the design of the application in iterations of classroom use and teachers' commentaries. In the case of the Visualizers, the tacit knowledge of the scientists was made explicit and easy access provided through the creation of custom visualization front-ends.

Part of our effort to create applications of cyberspace that reflect the needs of teaching and learning contexts has meant changing our view of what it means for technology to be integrally used in schools. Traditionally, the designers' goal has been to get technology "adopted". The adoption metaphor is a one-way view of the route to integral use. It assumes that a technology comes packaged to a community. Shortcomings are viewed as problems with the adopters, not with the technology. A contrasting view is that technologies and other artifacts are "appropriated" by people rather than adopted [22]. In this view technologies come to be used by individuals and communities based on a two-way process of "reciprocal evolution" [1]. The user and designer each interpret the utility of an artifact. The artifact is then subject to cycles of iteration that reshape it based on the needs of the community of users and the designer's ongoing inventive responses to those needs.

The CoVis design goal is to create a tool suite shaped by a process of appropriation that includes the use of participatory design methods for refining the functionality and interface properties of new cyberspace applications coupled with intensive professional development activities for teachers as co-designers. If we are successful, teachers will innovate educational practices which are learner-centered. They will not see applications as simply being "delivered" to them for a prescribed use, but will invent uses in their local contexts that we cannot foresee.

Over the next three years, we are scaling the CoVis testbed to include over 50 schools and thousands of students, to become a National Collaboratory for Science Education. These schools will be diverse in terms of socioeconomic profile, geography, and in bandwidth connectivity to the Internet (from a base of 56Kb/sec to T-1 rate and beyond). The primary challenge is to develop the Collaboratory such that it is appropriated into teaching and learning practices, not simply "delivered" for use. In addition to the Collaboratory itself we hope to evolve design principles that will assist others in the creation of collaboratories that can be appropriated by other communities of practice.

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