The CoVis Collaboratory: High school science learning supported by a broadband educational network with scientific visualization, videoconferencing, and collaborative computing*

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1.0 Abstract

The next decade brings widespread, networked, multimedia interpersonal collaborative computing. Data collection, exploration, analysis, and collaborative work is being transformed throughout science by new flexible data visualization and communications tools. A question-centered and collaboration-focused pedagogy is supplanting more traditional didactic K-12 instruction. The Learning Through Collaborative Visualization (CoVis) Project has installed a high-bandwidth testbed network using public-switched ISDN services to support synchronous and asynchronous collaboration with rich data sharing (e.g., complex images, large data sets) and desktop videoconferencing among high school students across schools, who also use the network to communicate with university researchers and other scientific experts. We describe students' uses of new CoVis tools for supporting collaborative project-enhanced science learning: a multimedia “collaboratory notebook," and specially-tailored visualization tools for atmospheric science allowing students to record their work and thinking during project-based inquiry using the same data as leading scientists.

2.0 The CoVis Project: Brief background and summary

It is common in newspapers, on television, or on networks to see accounts of how the "information superhighway" will improve aspects of life in the United States. Without careful research conducted in a well-designed HPCC (high performance computing and communications) context, the superhighway will prove to be an empty promise. The Learning Through Collaborative Visualization (CoVis) Project is one of four NSF-funded National Networking Testbeds for Education that is providing an important articulation of the promise of the National Information Infrastructure (Office of Science Technology and Policy, 1993).

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Our central goal in the CoVis Project is to exploit advanced technologies and approaches to pedagogy to help make the teaching and learning of science in classrooms better resemble the practice of science by professionals (Pea, 1993). Today's classroom study of science largely lacks the originality, open-endedness, and community nature that are hallmarks of the practice of science (e.g., Linn, Songer & Eylon, in press; Ruopp et al., 1993). The CoVis Project is developing a broad suite of software, hardware, and networking technologies to support the teaching and learning of science through open-ended inquiry in an extended scientific community. This community extends beyond the boundaries of a classroom and includes, in addition to teachers and students, research scientists, museum-based informal science educators, and science education researchers. The CoVis Project studies and reports on the design and implementation of these network-based and media-rich learning environments for an audience of learning scientists, educators, educational telecommunications policy analysts, and corporations defining "new media" industries and services. CoVis is examining pedagogy and technology questions such as: How should next-generation information networking be implemented to spur science educational reform? What are proper educational support roles for networked multimedia technology, desktop video conferencing, and other next-generation communication and computing technologies? What are the details of a pedagogy which will support diverse communities of practice? How can today's teachers transform their work-roles in new learning environments? What new curriculum materials and tools will be needed to support revitalized science curriculum that keeps pace with developments in the sciences?

3.0 Strategies used for developing the CoVis Project approach and implementing its use in science classrooms

The CoVis Project has sought to design 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. This aim had several specific requirements.

Learning and teaching needs. We have worked to identify science education reform needs in cognitive and social science research; including constructivist pedagogy; small group learning; new roles for teachers as guides rather than as sages; roles of multimedia in tapping multiple learning styles and providing experience with appropriate roles for different representational systems in posing and investigating questions in scientific inquiry; and leading us to project-enhanced science learning as the embracing pedagogy.

Technology future trends. We have continually examined futures trends in national information infrastructure, taking heed of the HPCC initiatives of the federal government in science, and affiliated industry trends in establishing "new media" industries and services. This futures work is necessary to ensure that our software, hardware, and network developments can not only scale and adapt in that emerging environment, but also help attract industrial interest in CoVis as a pioneering enterprise from which they could gain important market information. This led us in particular to the public-switched ISDN network, to client-server distributed network architecture for our software, data, and communications tools, to scientific visualization as a substantive emphasis, and to designs for new collaborative tools for joint work among CoVis community participants that were guided by developments in structured hypermedia systems and "groupware" for collaboration support.

Fertile science curriculum areas for reform and HPCC applications. We identified specific subject matter areas which would simultaneously exemplify leading areas of uses of HPCC in scientific practice, while at the same time offering fertile areas of curricular reform in the classroom which could exploit the datasets and scientific visualization tools which scientists use in those leading areas. This led us to atmospheric sciences primarily with some environmental science emphasis, in particular weather and climate studies. From a curriculum reform perspective, these topics are most broadly represented in high school "earth science" coursework today. While physics, chemistry, and biology offer such opportunities as well, the more rigid curricular frameworks and AP courses in these areas provide considerable obstacles and resistances to the innovations we sought to integrate in the classroom.

4.0 CoVis Project Emphases

In the CoVis Project, we are coupling science education reform emphasizing science learning through projects, innovative telecommunications infrastructure development to support such pedagogy, new scientific visualization tools specifically designed for learnability and usability by students and teachers, and new groupware environments to support collaborative learning and work by students and educators. A brief introduction to our work in these different areas and affiliated research and evaluation efforts is provided below.

4.1 Science Learning through Projects

Central to the pedagogical approach behind CoVis, that of "project-enhanced science learning," most recently pioneered by Technical Education Research Center with microcomputer-based laboratories and telecommunications programs (TERC: see Ruopp et al., 1993; Tinker, 1992), is the belief that the most effective science learning occurs in the course of open-ended inquiry.

In its initial phase, CoVis is using technology to bring two school cultures into regular contact with one another around the practice of science through projects. Participants in the CoVis Project include 269 Grade 9-12 students and 6 teachers (2 women, 4 men) in two high schools in suburban Chicago within 15 miles of Northwestern University -- Evanston Township High School (ETHS) and New Trier High School (NTHS). ETHS students represent a very culturally and economically diverse community; NTHS students reflect a narrower community diversity.

To identify ways that technology can support this form of pedagogy, we have worked closely with this group of six teachers of earth and environmental sciences who have been transforming their teaching. These teachers have been working to change their pedagogy from one that centers around lectures and fixed curricula to one that centers on student investigations guided by teachers and remotely located scientists and other research professionals. Throughout this process, they have been supported by educational researchers at Northwestern and TERC through one-on-one and workshop interactions. In addition, they have formed an electronic community in which their face to face discussions of pedagogy have been augmented by electronic mail and other computer-supported communications.

4.2. Network Infrastructure

The practice of science takes place mostly in communities, and increasingly relies integrally on high-performance computing and communications, or "collaboratories" (e.g., Lederberg & Uncapher, 1989; Office of Science Technology and Policy, 1993, 1994). The role for the network in the CoVis Project is to connect classrooms and scientists together in a diverse, collaborative, scientific community. Through our industrial partnerships with Bellcore and Ameritech, we have developed a network architecture that provides high-speed data and desktop video-conferencing service over the public switched network, using ISDN lines (Integrated Services Data Network). Bellcore estimates that ISDN switches will be able to serve 70% of the nation's customers by 1996. The twelve CoVis workstations in the two high schools, and six stations at Northwestern, are outfitted with videoconferencing units donated by Sony that include a camera, monitor, microphone, and speaker. These units are connected to codecs (digital compression and decompression devices) which are capable of variable transmission rates between 64kb/s and 1.5Mb/s. The ISDN lines are also used to bridge the local area ethernets at each of the high schools to the Internet through a connection to the School of Education at Northwestern University. These lines are also used to carry 384 kb/s videoconference calls between the sites on the network.

Video connections are established using an interface called Cruiser developed at Bellcore that allows users to place calls to others by selecting their names from a menu (Fish et al., 1993). These connections are established by a network operating system, also developed at Bellcore, called Touring Machine (Arango et al., 1992; Bellcore Information Networking Research Laboratory, 1993). Touring Machine maintains a database of all the network devices, digital switches, and users’ locations, and is able to dynamically establish and terminate calls involving heterogeneous network equipment. Using a Multipoint Control Unit owned by Ameritech as part of its switching infrastructure, Touring Machine is also able to establish multi-party calls. Because the CoVis network is implemented using the public-switched phone network, any user anywhere in the country with compatible equipment can register with Touring Machine and become a party to video calls. The CoVis Project needs drove the first integration of Touring Machine into an ISDN network by Bellcore. To our knowledge, CoVis is also the first school-based integral application of ISDN desktop video conferencing. In upcoming months, the Weather Room of the Department of Atmospheric Sciences at the University of Illinois at Urbana-Champaign and the Exploratorium Science Museum in San Francisco will join the network.

Videoconferencing adds a synchronous medium to a telecommunications tool suite described below which allows students and teachers to collaborate with each other across schools in their investigations, to work with researchers at Northwestern, and eventually mentors at the University of Illinois and the Exploratorium. This use of videoconferencing to support collaboration and informal mentoring contrasts with the more commonly-touted role for videoconferencing in education: to replicate the lecturer/listener relationships of traditional science education in a "distance learning" context.

4.3 Scientific Visualization Environments

The field of scientific visualization received its definition from a landmark NSF report (McCormick, DeFanti, & Brown, 1987) that defined the field of scientific visualization by linking disparate elements from the disciplines of science, computer science, and the visual arts. Scientific visualization now plays a critical role in the practices of atmospheric scientists and other specialized technical communities (Borroughs, 1991; Brodie et al., 1992; Kaufmann & Smarr, 1993; Wolff & Yaeger, 1993). Scientific visualization uses graphical images, color and motion (i.e., animation, typically used to convey the dimension of time) to present large quantities of data in a manner that allows the user to observe patterns in a large data set in the form of visual patterns in an image. For example, in a typical scientific visualization of weather data, different temperatures are displayed as different colors. As a tool for scientific understanding, scientific visualization relies more on the human visual processing system than on formalisms or quantitative reasoning. Since it offers a different route to scientific understanding from other techniques, it holds great promise as an educational tool and in reaching students that have not been well-served by traditional science teaching tools and techniques (Gordin & Pea, 1994). It also offers the possibility of opening up new domains for study that have been considered too complex for high school students because of their heavy reliance on formulae and abstract representations. Finally, we note that images and animations produced through the techniques of scientific visualization are becoming increasingly common in both the print media and on television. Whether or not students go on to careers in the sciences, an understanding of the nature and source of the visualizations they see in the media will help them to be informed citizens and decision-makers in modern society.

In developing the scientific visualization environments for the CoVis project, which we have called *visualizers*, we have taken tools used by atmospheric scientists and modified them to be usable by high school students. This process requires making them easier to learn and use by providing additional support and information through the user-interface. The first generation of visualizers we have developed include:

The Weather Visualizer and Weather Graphics Tool. The Weather Visualizer is a tool for examining current weather conditions throughout the United States (Fishman & D'Amico, 1994). Using the Weather Visualizer, students are able to view a range of images displaying weather conditions for the most recent hour:

- Satellite images of the U.S. in the visible and infrared spectrums.
- Customized weather maps displaying clouds, temperature, pressure, wind direction, wind speed, dew point, weather symbols, visibility, radar, severe weather watches, fronts, isobars, isotherms, isodrosotherms, and names of reporting stations, as well as wind speed at five different altitudes (850, 700, 500, 300, and 200 mb). Students can choose any subset of these features for display on their weather maps and can selectively view any region or city in the U.S. at any zoom factor.
- Six-panel visualizations displaying temperature, pressure, wind speed, wind direction, dew point, and moisture convergence for the entire U.S., each in a separate image.
- Textual reports providing local conditions and local and state forecasts for all reporting stations.

In addition, the Weather Visualizer is supplemented with the Weather Graphics tool. This tool allows students to draw their own weather maps with traditional weather symbols (thus their own visualizations) to make predictions and explain their understanding of weather to others.

The Weather Visualizer supports investigations of weather nowcasting and forecasting. Student inquiries can be phenomena-centered (e.g., severe storms, front movement, flooding as in the Mississippi Valley this summer) and explore conditions leading to and emerging from these phenomena. Students use a variety of weather representations simultaneously in order to build an understanding of atmospheric processes (McGee & Pea, 1994).

The data for the Weather Visualizer currently comes from the University of Illinois Weather Machine, which is a server for current weather images and information (Ramamurthy & Kemp, 1993; Ramamurty et al., 1994). The weather maps and 6-panel image are constructed from the DD+ data provided by the NSF-funded Unidata Program. The satellite images are received directly at UIUC from the GOES-7 satellites. The Weather Visualizer provides a front end to wxmap, a UNIX program developed at the

University of Illinois. The Weather Graphics tool is implemented as a plug-in tool to SuperPaint 3.5 from Aldus Software.

We may contrast the capabilities of the Weather Visualizer with other weather information services that are increasingly becoming available on the Internet. For the most part, those services provide access to precompiled weather images (Samson et al., 1994). The Weather Visualizer enables students to create their own weather maps by specifying a region, the height in the atmosphere, which stations to include, and particular variables of interest. This capability to generate their own images is characteristic of the practice of scientific visualization by professional researchers, and gives students the ability to tailor their investigations in order to pursue questions of particular interest.

The Climate Visualizer. The Climate Visualizer provides a learning environment for students to explore important climatic variables (Gordin, Polman & Pea, in press). For example, the Climate Visualizer allows students to easily produce scientific visualizations of temperature over most of the northern hemisphere for any day or month in a twenty-five year period from the early 1960's through the late 1980's. In addition to temperature, wind speed and direction, and altitude of constant atmospheric pressure can be displayed.

In the Climate Visualizer, temperature is encoded as a color image, altitude as contours, and wind as arrows (or vectors). The user can choose from prespecified palettes of colors for drawing the images. Individual points on the images can be selected and their value displayed on a "display palette." This palette shows the range of colors used in constructing the image, the minimum and maximum values for the data set, and the value that has been selected. When a student clicks on any point in the display, its latitude, longitude and the variable values for that location are shown. These values appear as highlighted numbers superimposed above the color palette, thereby reinforcing the relationships between the colors and the numbers. Additional support is provided by accompanying all values with their appropriate scientific units and the minimum and maximum values that appear in the data set. An optional overlay showing the continental boundaries provides geographic context. The user can also create new data sets by performing operations on existing data sets. For example, seasonal difference can be seen by subtracting January temperature from July. Such a visualization highlights the differing properties of land and water in absorbing heat.

The Climate Visualizer uses data from the National Meteorological Center's Grid Point Data Set (File ds195.5 Version 1.4)[1]. An NMC data set can be selected by choosing the date and time the data was collected and by specifying a single independent variable along with one or more dependent variables. The NMC data sets include several decades of data collected twice a day covering temperature, altitude, and wind at five different pressure levels. This data is present for the region from twenty to ninety degrees north at a resolution of two degrees latitude by four degrees longitude. Students are able to investigate basic atmospheric processes using this data, including major climactic cycles and weather events, such as cyclogenesis.

One other visualization resource we are examining is the use of multimedia databases over distributed client-server network architectures such as that provided in the CoVis

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[1] Currently, the data sets for the Climate Visualizer are retrieved from a CD-ROM attached to a Sun Sparc10 UNIX workstation. The appropriate scientific visualizations are then generated by an application called Transform from Spyglass, Inc. This application is controlled through the use of Apple Events by the Climate Visualizer. The visualizations are then imported to the Climate Visualizer which presents them to the user. These underlying processes are concealed from the user who is only aware of the Climate Visualizer interface.

Project. As students create and attempt to make sense of scientific visualizations, they necessarily encounter many complex concepts. Some of these concepts are basic to science, such as units, and others are specific to the scientific domain. An optimal time for students to extend their understanding of such concepts is when such lack of understanding impedes their progress in their present task. However, teachers are often unable to provide the necessary help on this timetable. We have established the goal of integrating multimedia databases with the visualization environments we create to allow "just-in-time" conceptual learning support. In the current phase of the CoVis Project, we have worked with two collaborating institutions to produce a prototype multimedia database that links explanatory graphic images produced at the University of Illinois at Urbana-Champaign with concept-indexed video footage of exhibits, demonstrations, and natural phenomena produced at the Exploratorium Science Museum in San Francisco, California.

4.4 Collaboration Environments

Collaboration is a central element of science practice (e.g., Finholt & Sproull, 1990; Sproull & Kiesler, 1991). The collaborative software in the CoVis project is designed to support students as they conduct scientific inquiries as members of a community. This software is designed to allow students to work together with other students or with scientists across the boundaries of space and time.

As part of the standard software environment on a CoVis workstation, students have access to a wide range of standard Internet tools including electronic mail, Usenet newsgroups, gopher, mosaic, and ftp. Students use the network to communicate with university researchers and other scientific experts in teleapprenticing relations (inspired by earlier work, e.g., Levin et al., 1987; Riel, 1992). In addition to these tools, we have developed a collaborative application called the *CoVis Collaboratory Notebook* (Edelson & O'Neill, 1994). The Collaboratory Notebook is a groupware application for scientific inquiry. It provides a place for students to record their activities, observations, and hypotheses as they perform scientific inquiry. It allows students and teachers to plan and track the progress of a project, and it provides a means for collaborators to share and comment upon each other's work. The Collaboratory Notebook has been designed to support authoring and browsing equally well, as well as allowing teachers to monitor and guide student inquiry.

The Collaboratory Notebook is implemented as a structured hypermedia database. A particular notebook can be private or shared among a group of collaborators. The table of contents of a notebook is displayed in a hierarchical fashion indicating which pages are related to each other. When the user displays a page from a notebook, it appears in a window with buttons that represent links to other notebook entries. There are several types of links that can be used to indicate different relationships between notebook entries. For example, a question can be linked to a conjecture that answers the question, which in turn, can be linked to evidence for or against that conjecture. These link types provide a structure that helps students to organize their open-ended scientific inquiry.

The Collaboratory Notebook is tightly integrated with the visualization software that has been developed under the CoVis Project. For example, when a student uses one of the CoVis visualization packages, that visualizer maintains an activity log for that visualization session. The student can take the contents of this automatically-generated activity log and copy it into the Collaboratory Notebook. Once there, the student can annotate this log with comments that elaborate on the process that was just completed. This activity log can serve as a trigger for reflection on the inquiry process. In addition, users can store the images produced in the course of a visualization in the Notebook.

In addition to these asynchronous collaboration tools, a CoVis workstation is equipped with videoconferencing software that allows a student to initiate a videoconference with any student or researcher who is currently available. This videoconference software is accompanied by Timbuktu screensharing software from Farallon Computing that allows a remote user to view and control the screen of another. Through the combination of videoconferencing and screensharing, two individuals are able to work as if they were in the same room in front of the same computer, in spite of the physical distance that may separate them.

5.0 Framework for assessing project results

An important element of any educational innovation should be an assessment of its impact and effectiveness on learning and teaching. From Summer 1992 through Fall 1993, we planned, developed and implemented the software, hardware, network, and initial classroom uses of the CoVis Project. We designed and implemented inquiry-centered tools for students and teachers, created new scientific visualization software and materials that are useful in school contexts while being grounded in real scientific datasets, and established the CoVis high bandwidth ISDN-based network. Since Fall 1993, we have also been engaged in a research program comprised of six interdependent studies on student and teacher uses of aspects of this testbed. Our strategy for assessing project results emerged from first year planning activities to provide useful design-information to all the CoVis technology, pedagogy, and policy stakeholders.

The research operations plan is divided into six studies for clarity of focus, although some studies, such as student profile, will be used in a number of different subsequent analyses, comparisons, and reports. Brief and preliminary highlights are described below.

Study One: CoVis Student Profile Study. This study is an ongoing assessment of student background and attitudes toward school, science, and technology. Through surveys administered three times during the year, this study provides a detailed picture of each student's demographics and longitudinal data on attitudes toward science and technology. We have completed only the first survey at this time, and can report broad initial variability in the science backgrounds, science attitudes, and student demographics. In this study, attitude improvements would provide evidence for the proportion of students, and the profiles of students, who are becoming more enthusiastic about learning science and working with HPCC technologies for learning. Technology and education researchers can use our survey instrument and research design to study the broad-based attitudinal impact of new pedagogy and technological infusion. The data will be of direct value to people interested in the specific impact of CoVis-like applications on student attitudes regarding science and technologies like e-mail, network socialization (e.g., newsgroups), network information retrieval technologies (e.g., gopher) and synchronous audio/video conferencing. The data will also inform people about the contributions of a project-enhanced science pedagogy to student attitudes toward school and learning. The policy community can potentially use the data to talk concretely about the preconditions for technology infusion and adoption. Differences between student groups will help policy makers to understand some of the background characteristics associated with successful/unsuccessful uses of new pedagogy and technology in science education reform.

Study Two: CoVis Student Project Analysis Study. This study is a quantitative and qualitative analysis of student projects as learning artifacts. In this study we are looking to demonstrate the extent to which the CoVis students, teachers and professional scientists, as a community of practice, develop a common set of quality criteria for "good projects". Our initial results indicate that scientists and teachers largely share a definition of projects as involving original inquiry involving data collection and original or derivative data analyses, while our high-school students have a much more inclusive perspective of science in the project context that includes more routine, "pre-cooked" work with data, tools, and theories. And over 120 student projects are completed or underway in the first semester of their uses of the CoVis testbed. These include students' investigative projects using the Climate Visualizer on such topics as: (1) the impact of the eruption of Mt. St. Helens on local weather; (2) the impact of oceans on coastline temperatures; (3) characterizing the climate of areas with a high number of thunderstorms and lightning strikes; and (4) the effect of El Nino on northern hemisphere weather. Student projects using the Weather Visualizer and related tools have included: (1) analysis of the weather leading to the massive firestorms around Los Angeles, CA; (2) analysis of the progression of recent major hurricanes, such as Hurricane Emily, Hugo, and Andrew, through animations of their movements in visible and infra-red satellite maps and tracing their progress and changes on weather maps; and (3) investigations of the effects of Lake Michigan on local weather.

Study Three: CoVis Communication Study. Students and teachers in the CoVis classrooms are using a diverse suite of communication technologies, involving different media (text, graphics, animation, video). In this study we are attempting to understand, through a series of surveys administered throughout the year, how these are used, and we are assessing the value of the asynchronous (e-mail, newsgroups, networked information retrieval software) and synchronous communications (components: screen-sharing, audio, and video links) from the perspectives of students, teachers, and other participants. From our first completed survey, we have documented the previous minimal experience of our participants with electronic telecommunications, and a complex set of results on their anticipated utility of these diverse communication technologies for different aspects of science project collaborations, learning, and teaching. We have also seen an explosive increase of use in both CoVis science-oriented tools and the more general telecommunications suite and travel on the Internet, with most students routinely using these tools in their day-to-day classroom work.

Study Four: CoVis Scientific Visualization Study. Through both formal and formative observations of software use, we are seeking to identify the strengths and weaknesses in students' and teachers' patterns of use of the new scientific visualization tools. We are investigating patterns of differences in uses of scientific visualization tools and datasets across schools, teachers, and class sections of the CoVis testbed and relating them to background parameters of students, to the context of CoVis communication tool use, and to learning and attitudinal outcomes. Particular teachers favor the visualizers, and within high-visualizer use classrooms, particular students take the lead in visualizer use in inquiries. We are tracking these differences longitudinally, and are now engaged in statistical comparisons of patterns of these student differences.

Study Five: CoVis Communication Bandwidth Study. In this Spring 1994 study we will carry out experimental and observational analysis of bandwidth needed for effective and satisfactory communication within a learning community. How much bandwidth does a learning community need for satisfactory desktop audio/video communication? Given a choice with quasi-economic implications, how will a learning community spend its communication resources "budget"?

Study Six: Teacher Support Study. Teachers are usually the primary instructional agents in the classroom, and project-enhanced science learning brings new challenges to the instructional tasks involved in supporting student learning. Given the new computer and communications tools, and the distributed character of the learning environment CoVis makes possible, we are attempting to determine through periodic, detailed interviews what the teachers' perspectives are on the changes brought about or initiated by these innovations. We hope to inform those concerned about teacher adoption of project and/or technology-intensive learning and teaching technologies, whether in-service or pre-service teacher development programs; teachers; the research community concerned with educational technologies and teacher education and enhancement; and educational administrators.

6.0 Significance and implications

The emerging National Information Infrastructure has the promise to leverage science educational reform in this country in radical ways. While documenting early successes in receptivity and use patterns for its approach to distributed multimedia learning environments for science educational reform, the CoVis Project has also identified a broad range of challenges to these opportunities in the design issues affiliated with scaling up the range and diversity of networked participants. The challenges include the need for adequate school technological infrastructures; the diverse nature of regional communications infrastructure in urban, suburban, and rural sites; the present high tariff rates for ISDN communications transport aimed at business rather than education marketplaces; teacher education efforts in science education content, pedagogical methods, and technology use; administrative support for curricular and technological innovation by teachers; consistency of curricular reforms with state frameworks and emerging national standards; and work in evolving experimental testbeds such as CoVis to larger scales while seeking to sustain its close coupling of developments in new software, networks, curriculum, access to the scientific community and its datasets, and research on learning and teaching outcomes. We also need to broaden the range of visualization environments and data sets provided for students beyond climate and weather, significantly extend the functionality of those environments, and generalize the architecture and development process to allow for the rapid construction of future scientific visualization environments for educational contexts in the future.

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