Learning Science through Collaborative Visualization over the Internet[1]

Roy D. Pea
Stanford University (roypea@stanford.edu)
Director, Stanford Center for Innovations in Learning

"...If the network idea should prove to do for education which a few have envisioned . . . and if all minds should prove to be responsive, surely the boon to humankind would be beyond measure." J.C.R. Licklider & Robert Taylor (1968)

Abstract

Ten years ago, we launched the Learning through Collaborative Visualization, or CoVis Project. "Collaborative visualization" refers to development of scientific knowledge that is mediated by scientific visualization tools in a collaborative learning context. Funded by the National Science Foundation as an advanced networking testbed, our partnership of Northwestern University, Bellcore, Ameritech, the Exploratorium Science Museum in San Francisco, and the University of Illinois at Urbana-Champaign's Atmospheric Sciences Department/National Center for Supercomputing Applications (NCSA) sought to design, implement and research the promises and problems of a distributed multimedia science learning environment that used broadband desktop videoconferencing and screen sharing, scientific visualization tools and distributed datasets, virtual field trips, scientist telementoring, and a Collaboratory Notebook for enabling project-based learning of science in the high school using these distributed human and technical resources.   Our project vision was to establish collaborative technology learning environments, or "collaboratories" that would enable project-enhanced science learning among remote project partners using advanced telecommunication networks. For example, our collaboration with NCSA scientists provided learners with access to subject-matter experts, visualization tools and vast databases in the field of atmospheric sciences. Virtual visits using wireless video over the Internet to Exploratorium exhibits helped motivate student questions about central scientific phenomena.

At its peak of use, the CoVis network was in use by thousands of teachers throughout the United States. The project developments were transitioned in 1997 as a set of resources that

continue to be elaborated in the LeTUS Center for Learning Technologies in Urban Schools based at Northwestern and University of Michigan, which is investigating in partnership with the Chicago and Detroit public school systems how to support urban school teachers in using project-based inquiry as their core approach to teaching earth and environmental sciences at the middle and high school level.

In this chapter, after providing a pedagogical background that lays out the rationale for bringing together developments in the sciences of learning with advances in high performance computing and communications in the CoVis Project, I will highlight our design research methodologies for making the powerful features of professional scientific visualization tools usable to students and teachers in WorldWatcher.

Introduction

How will learning take place as we stride into the third millennium? I believe we should emphasize new models for learning that go beyond the antiquated conceptions of education found in most teacher-centered, formally organized classrooms. Reforms seeking to improve education would productively focus on understanding and supporting learning in ways that pay close attention to the skills of social interaction and participation in new activities that currently constitute lifelong learning in working and living communities. In contrast to learning-before-doing— the model of most educational settings—I would urge attention to *learning-in-doing*, a model where learners are increasingly involved in the authentic practices of communities through learning conversations and activities involving expert practitioners, educators and peers. Learning-in-doing requires interactions between groups that traditionally have been separated by the institutional boundaries of such institutions as school, work, university, and home. Scientific and business workgroup practices using Internet and high-bandwidth services recognize that not all partners necessary to an interaction can be co-located— and education needs to exploit the same insight.

A convergence of socio-technical developments has led to early successes and enthusiasm about broad-scale potentials for improving learning, education and schooling in these ways. These developments coalesce in the emergence of "virtual learning environments" or "online learning communities." Virtual learning environments may be constituted within or across classrooms or campuses, within or between businesses (or homes), or involving participants in heterogeneous settings, such as school-home-community, or school-workplace-university. By collapsing spatio-temporal barriers through the construction of virtual learning communities, we may enable greater intimacy and authenticity in the learning process. Such technologies can be used to facilitate the return of learning models that existed with considerable success prior to formal schooling, such as apprenticeship, long-term mentoring, and collaborative groups that learn through work on projects. Expertise that is now geographically dispersed and isolated will become increasingly interconnected to the benefit of lifelong learning. Virtual museums, the emphasis of this workshop, offer yet another context for the consideration of virtual learning environment design and research.

The primary converging trends leading to virtual learning communities have been: (1) the movement toward more socially-situated conceptions of learning, toward viewing intelligence as a distributed achievement rather than as a property of individual minds; (2) the advent and rapid growth of Internet use in support of both informal learning and more formal learning communities; and (3) rethinking appropriate roles for the teacher in effective learning environments. Together, these trends may well have synergistic effects far greater than any of

them could individually for deepening learner understanding and rendering learning more relevant for enabling the learners' participation in cultural practices. Participation in cultural practices is, after all, the kind of "transfer" outcome from one's involvement in learning activities that we ultimately seek. Acquisition of knowledge *per se* is subsidiary to this aim.

Information technologies play multiple roles in these socio-technical developments in serving:

(1) As a *meta-representational substrate*—in which authors create media-rich documents using symbol systems such as language, diagrams, video, audio, mathematical notations, and scientific or data visualizations, and make conceptual linkages between documents or document components (as in hypermedia) in ways that were awkward or impossible in non-computational systems like print (34).

(2) As a *communication channel* for establishing highly interactive conversations among individuals distributed across space and time (33). These communications in "media spaces" may transcend in some respects what is possible in face-to-face encounters (sometimes characterized as 'beyond being there'), e.g., when the groupware in support of them allows for joint activities such as computer-assisted design in the production of a common artifact.

(3) As *interface to individual, group, and cultural memories*—archives of information, knowledge, and representations of past activities that can be accessed, drawn upon, and extended as needed when new problems arise, or when reflection leads to new insights.

(4) To establish *spaces and places* in which individuals come together in real-time (synchronously) or at different times (asynchronously) to collectively engage in some activity together (e.g., 1, 20). These social activities are mediated by informational representations of space (e.g., a graphical city comprised of buildings incorporating rooms in which individuals throughout the globe may convene through their computers to have meetings, discuss issues, learn, play, and socialize). The persistence of persons, documents, and rooms for meeting in cyberspace is being exploited in multi-user virtual environments, or "virtual worlds."

(5) As *cognitive tools* for augmenting human performance in complex tasks and for learning[2].

Some theorists of mind view the concept of "distributed intelligence" (DI) as crucial for conceptualizing learning and education (e.g., 7, 32, 36). In this perspective, the main sense of DI emerges from the image of people-in-action, and in their activity, we see the configuring of distributed intelligence. Activity is enabled by intelligence, but that intelligence is distributed across people, environments, and situations, rather than being viewed as a resident possession of the individual embodied mind. Intelligence is accomplished rather than possessed; the accomplishments of human activity routinely engage not only an individual's memories but also the intelligence embodied in the design of artifacts and in the social resources often available in situations. As I noted in my chapter on distributed intelligence and education:

> "There are both social and material dimensions of this distribution. The social distribution of intelligence comes from its construction in activities such as the guided participation in joint action common to parent-child interaction or apprenticeship, or through people's collaborative efforts to achieve shared aims. The material distribution of intelligence originates in the situated invention of uses of aspects of the environment or the exploitation of the affordances of designed artifacts, either of which may contribute to supporting the achievement of an activity's purpose" (Pea, 32, p. 50).

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[2] Early and influential expressions of this perspective were provided by Licklider (24), and by Engelbart (12) in his seminal work at SRI International. These efforts lead eventually to the "personal computer" (21). See Rheingold (38) for a fine history of computers as "tools for thought"; see Pea (28, 29) for socio-historical and developmental considerations.

With the explosive growth of the Internet, now connecting hundreds of millions of people around the globe, the relevance of distributed intelligence to the design of interactive learning environments has become much clearer than it was in 1993. And its implications have become all the more problematic, for those who think of designing learning activities and assessing learning outcomes in education as tool-free, individual cognition. Throughout the world, virtual learning communities are being established and growing in shape to fit the ecological niches found necessary to their members' needs. They may be as small as a few people scattered over the net in chat rooms devoted to discussing a mutual reading or a prospective stock investment. Or they may be as large as thousands of individuals coupled together in a virtual fieldtrip, exploring some part of the globe through teleconferencing video connections or updated datasets and commentaries that together establish a knowledge-building community about a learning topic such as global warming (14). Moreover, they are vast as the 50 million E-Bay buyers, the largest online global marketplace.

In this paper, I will describe the CoVis project that exemplifies the application of distributed intelligence to problems of designing learning environments. I co-directed the Learning through Collaborative Visualization (CoVis) Project, with my colleague Professor Louis Gomez of Northwestern University from 1992-1997, and have been involved in collaboration and consulting capacity after that era with its newer developments, especially with Professor Daniel Edelson on WorldWatcher. CoVis provides a broad range of lessons for how distributed intelligence may be effectively supported through the uses of learner-centered collaboration technologies and scientific visualization tools.

Virtual learning communities

First, I should say more about the concept of "virtual learning community." *Virtual* learning communities (VLCs) are first distinguished by their "virtuality"—face-to-face teaching instructions or informal learning activities are actual, not virtual. What makes the learning communities "virtual" is that they are mediated over computers and using computer networks. The applications involved in the communications among participants in VLCs may be as wide-ranging as electronic mail, newsgroups, chat rooms, listservs, remote screen-sharing collaborative work applications, and multi-user virtual environments.

How about the concept of "learning"? For a socio-technical arrangement to constitute a "virtual learning community," its membership should explicitly express "learning" as an objective of activity participation over the net. Otherwise, *any* telecommunications-involving activity would be a VLC, since many of us would argue that most any activity in which one engages may correlate with learning of some kind, even if only tacitly.

Finally—and most problematically—is the notion of "community." What makes one? Certainly each of us belongs to many communities, is peripheral to others, and does not belong to yet many others. Yet, we cannot be too thrilled that the concept is difficult for sociologists, anthropologists, and other social scientists concerned with social phenomena. The core sense of a community, for our purposes, is a collective of participants with significant persistence whose members align around some common activities. Communities *do* things, of virtually infinite variety—they may learn, advance knowledge, collect things, provide help to one another, read books, do crossword puzzles, design jets, watch sporting events together. In addition, typically, such communities are comprised of participants who tend to have access to encounters with one another. Information technologies change the ways in which such

communities can be formed and sustained in their activities (1, 43). Let us now consider the design of CoVis as virtual learning community.

The CoVis Project: Learning through Collaborative Visualization

How can the perspective of distributed intelligence be used to guide the design of virtual learning communities for science? How can we use the different affordances of information technologies to support the material and social distribution of intelligence that will better enable the accomplishments of science learning?

In 1992, with NSF funding[1] and support from industry partners, my colleague Louis Gomez and I created the Learning through Collaborative Visualization (CoVis) Project (31). We had a vision for science educational reform through *distributed science learning* —taking cognitive, social, technological, and scientific breakthroughs into account—which we sought to implement and then empirically study as a community appropriates and evolves its uses. Our development of the CoVis learning environment and its components was guided by a student-question-centered, collaboration-focused pedagogy, and our commitment that classroom science learning should more closely resemble the open-ended, inquiry-based approach of science practice. As we put it in our January 1992 NSF proposal:

> "We believe that science learning environments should look and act more like the collaborative, connected work environments of scientists. To this end, teachers and students need ways to *reduce the complexity of getting access to resources* that are inaccessible locally. These resources include human expertise in the form of other teachers, scientists and graduate students in business, industry, research settings, and other learners. They also include tools, instrumentation, hands-on materials and labs, museum exhibits, and computing and telecommunications infrastructures...

> [We] aim: To examine how geographically dispersed teachers, students, and collaborators can *integrally and readily use* advanced information technologies to facilitate the types of collaboration and communication demanded by project-enhanced science learning.

> We argue that applications of advanced technologies provide American educators with critical levers for promoting cognitive apprenticeships in science learning. We aim to build the next generation of infrastructure for new forms of science learning and teaching, and create a national model for the kinds of distributed multimedia science learning environments supportable with the future NREN [National Research and Education Network, later called the NII, or National Information Infrastructure].... We argue that these new [High Performance Computing and Communications] technologies can provide the backbone for the transitioning process from didactic science teaching to cognitive apprenticeships in project-enhanced science learning.... Students need to learn and do science in *context* of real problems and *with* sophisticated tools."

After its first five years of invention, empirical studies of use patterns, and design iterations, CoVis came to provide a testbed "collaboratory" (5, 23) for learning science by doing science over the Internet—that directly worked with over 100 teachers and thousands of students in 54 middle and high schools in 11 states, with thousands of other teachers using CoVis resources. CoVis schools were connected with high-speed Internet access (commonly T-1) that we used as a critical leveraging technology to develop and evolve through use a wide array of new resources for learning. We provided teachers and students with a software suite of learner-centered tools for doing project-based collaborative learning. Student projects often involved pursuing inquiries using scientific visualization of datasets in the atmospheric sciences and geosciences, and use of a full set of Internet communication tools including e-mail, Usenet news, Gopher, Web browsers, and desktop video-conferencing, that enabled new kinds of learning relationships. Participating classrooms typically had six or more desktop computers, and students had individual net accounts. Our ambitious aim was integral use of high performance computing and communications tools for project-enhanced science learning.

Our assessment of learning and teaching needs led us to project-enhanced science (39) as a fundamental pedagogy for achieving deeper learner understanding and distributed intelligence among the science learning community. This approach to science education was based upon several contemporary research strands in the cognitive sciences of learning (2). Chief among these is the idea that, long before and outside of formal education, people have learned through participation in "communities of practice" (e.g., 22, 41). In contrast to the common "course delivery" models of instruction and distance learning, the advantage of such communities is that learning is situated with respect to community-based goals and activities in which knowledge is developed and used (4, 30, 40). In the classroom, this benefit may take the form of "cognitive apprenticeship" (8), with students guided, both by their teachers and by remote mentors, to think about science in many of the fundamental ways that scientists do. In designing CoVis learning environments, we acknowledged the large gaps between students and scientists in motivation, purposes, knowledge, and physical distance. The point of science education is not to take the "little scientist" that Piaget said was in every child and create an actual scientist. Heeding these gaps, we sought to design settings in which students could engage as "legitimate peripheral participants" in "communities of practice" for science.

In the community of science practice, the computational tools used—such as scientific visualization and modeling environments—as well as the data collected for investigations are critical to the scientists' abilities to formulate, think about, and work on their problems. In designing the CoVis testbed, we sought to take advantage of this reliance by providing students with learning-appropriate ways to access the same real-time weather data and globally gridded archival earth sciences and environmental data that the scientists study, using tools that we modeled on those used by scientists (10, 15, 18, 19). Scaffolding access to these tools and the scientists and other professionals that use them is a central design technique we used to "seed" a sense of legitimate peripheral participation for students in the CoVis learning testbed. There are other recent efforts to bridge the science education-scientific practice "gap," including the GLOBE Project, Global Lab, GREEN, Earthwatch, Kids as Global Scientists, Hands-On Universe, and BioKids, which have developed related models, of what have been called "student-scientist" partnerships (6, 40).

A crucial resource that made broad scale CoVis participation in our testbed work out was the ongoing nature of professional development for teachers, supported in the mid-90's by our CoVis Geosciences Web Server (http://www.covis.nwu.edu/), one of the first educational web projects, with a focus on ironing out the details of effective engagement for learners in project-oriented pedagogy. This focus made clear how important "fingertip effects" are for teachers' appropriation of innovations such as CoVis, and as I will describe, we created "model" learning activities for interschool project collaborations in which students' learning can be guided. I will highlight some of the technical features and social affordances of designs that made more fingertip-accessible such new classroom activities as collaborative knowledge inquiry, telementoring, and expressive and interpretive uses of scientific visualizations as a representational vehicle for sense making in science.

CoVis has taken a design-intensive and iterative re-design approach to developing the learning and teaching software, curriculum activities, and participating groups (schools, education researchers, content experts and telementors, science educators and science education institutions) that became part of the "CoVis testbed" (10,13,35). It is challenging to briefly describe this process of mutual influence among researchers, technology specialists, and educators in our work, but overall, we shifted from building new tools and resources with

participatory design advice from educators, to learning more about their situations of technology use so that we could co-evolve activity structures in which sustained use of telecommunications in support of project-based science learning would become commonplace.

Because much of the effort in establishing a distributed science learning "collaboratory" has required technology development and integration, it is not surprising that much emphasis has been on the "material" aspects of distributed intelligence, as embodied in the affordances of the properties of learner-centered scientific visualization software (e.g., 10,17,18), and groupware (9,11), datasets, and other media designed for learner and teacher use. The following table provides a few illustrations for how design of material aspects of the CoVis distributed intelligence (DI) systems in which learners and others now participate has fostered, and in many cases, enabled, the kinds of activities central to our vision of distributed science learning.

Material aspects of DI used in design	Social aspects of DI that are enabled
(1) Time-shifting communications (e.g., email, listservs, newsgroups, web site annotations).	Facilitates broad access to distributed group inquiry; Enables collaboration across global time zones.
(2) Space-collapsing communications.	Facilitates broad access to distributed group inquiry; Enables virtual field trips to remote places.
(3) "Semantically typed" hypermedia links in our CoVis Collaboratory Notebook (e.g., Question, Conjecture, Evidence For, Evidence Against).	More readily-achieved structured scientific inquiry; Simplifies tracking learners' questioning and project inquiry processes that are central to constructivist pedagogy, and navigating the information products of a group's knowledge-building project.
(4) Archival memory for communication records.	Creates 'living' database of knowledge building community; Builds persistent and re-usable database of scientists and other mentors for distributed learning communities.
(5) "Scaffolding" front-ends to scientific visualization tools (e.g. geographic context map overlay, semantic units, and semantic constraints on operators for manipulating visualizations).	By starting with qualitative inquiries, enables broad learner access to complex science topics and systems; By making scientists' tacit knowledge explicit in the tool interface, makes it possible for novice learners to pursue their open-ended research questions (e.g. weather prediction; causal patterns affiliated with global warming).
(6) CoVis telementoring database (e.g., forms for mentors to "profile expertise" and for teachers to search for it; automatic message handling for project participants, mentors, teachers)	Facilitates remote mentor participation and teacher identification of appropriate mentors.

In our initial work in developing distributed intelligent systems for science learning, we thus centered on creating tools and resources for learners. Since 1995, a great deal of our attention and effort shifted to the "social" aspects of distributed intelligence that are required to launch and sustain these efforts to reform science education toward a learner-centered, project-based pedagogy. Driven by teacher needs and a massive scale-up from 6 to over 100 teachers in geographically diverse sites from 1993 to 1995, we focused on creating activity structures that contextualized the uses of tools and resources by "seeding" the CoVis GeoSciences Web Server (http://www.covis.nwu.edu/geosciences/) with distributed science learning activities,

providing models for teachers to appropriate and adapt to their local circumstances (13). We called our sets of activity structures around a common topic "CIAs" or CoVis Interschool Activities (http://www.covis.nwu.edu/_geosciences/activities). They included multi-week resources on the topics of global climate change, water quality, land use management, weather prediction, and soil science. The World Wide Web was the primary medium through which these activities were shared with teachers, many of whom helped design them in face-to-face summer workshops and refine them in the context of their ongoing teaching. CoVis teachers using these activities formed communities of interest through listservs, to guide and support one another as they sought to interpret and extend the CoVis vision in new ways.

These predictably scheduled interschool activities help teachers think concretely about different aspects of project science, educational telecommunications, and collaboration, because each involve opportunities for telementoring, student collaborative learning, uses of the many Internet communication tools we have described, and such CoVis web resources as scientific visualization environments, datasets, collaborative support, and sample assessment rubrics. These activities provide a curriculum project "shell" or activity structure within which teachers can create specific projects that can be done across classrooms or within a classroom. Our central design challenge has been creating activities so as to provide enough structure so they may be feasibly conducted in a classroom context with limited time and workable classroom procedures, while also fostering enough freedom in the intellectual environment so that learners' questions may be developed as novel project directions (44).

Characterizing our aims and achievements in the design and implementation of scientific visualization environments for middle and high school learning in the CoVis Project and beyond helps make concrete what this work has been like.

The WorldWatcher Global Visualization Environment for Science Education[3]

Scientific visualization has dramatically changed scientists' practices in recent years by "using vision to think," exploiting human visual pattern perception for complex investigations in large datasets (e.g., 3, 5, 26, 43). Scientific visualization provides an image rendered through high-speed computer graphics that is based on a numerical dataset that describes some quantity in the world (e.g., global temperatures). Our goal in developing scientific visualization environments for pre-college education was to investigate the socio-technical conditions under which scientific visualization, integrated into inquiry-based learning activities, could enable students of diverse abilities (not only the most motivated and talented) to develop an understanding of complex scientific phenomena such as climate, weather and global climate change. We say "socio-technical" conditions because key components of the effective use of learning technologies include software functions that are readily learnable and usable—but also teacher-guided activities that are part of the social surround of technology use.

Our early investigations in CoVis revealed the need for specific supportive structures in a scientific visualization software architecture that can provide what learners need (15, 17, 18). Unfortunately, the tools and techniques scientists use presuppose significant prior knowledge in the canons of scientific inquiry, data exploration and systematic inquiry, and in strategies for search, analysis, and transformation of data using the capabilities of scientific visualization software programs. *Figure 1* exemplifies a scientific visualization environment developed for scientists, not science learners.
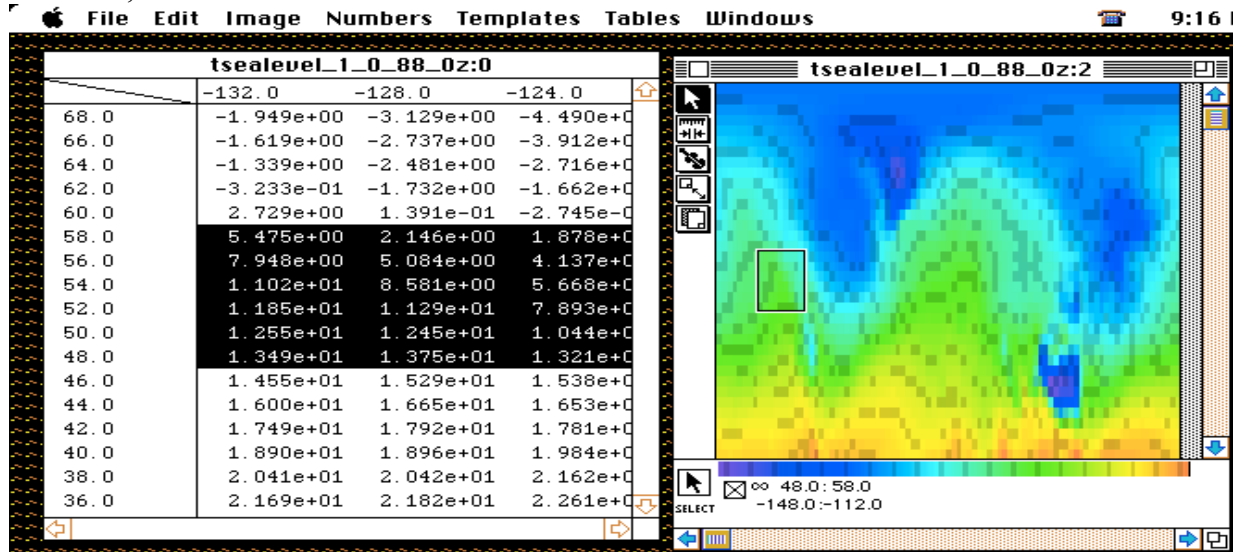

Figure 1: A visualization of surface temperature data for the Northern Hemisphere displayed by Transform, a powerful, general-purpose visualization environment widely used by scientific researchers (circa 1992)

WorldWatcher is a scientific visualization environment designed primarily for supporting student investigations of two-dimensional, gridded scientific data, and based on the ClimateWatcher software we first released in April 1996 (10). WorldWatcher built upon ClimateWatcher's aim to provide an accessible and supportive environment for students to explore, interpret, and analyze scientific data about the transfer of energy through the earth-atmosphere system and climate change in ways akin to scientists' inquiry activities. Data is distributed with WorldWatcher in data libraries that support educational activities centered around specific datasets, as used in interpretive, analytic and expressive visualization activities (http://www.worldwatcher.nwu.edu/).

Users of WorldWatcher can now create dynamic color visualizations of many different data types beyond those initial topics (from NASA and other public domain sources), and can import their own geo-gridded, as well as point datasets (using a standard spreadsheet format). WorldWatcher datasets for global climate change (insolation, albedo, absorbed/reflected solar energy, surface temperature, greenhouse effect/increase, outgoing long-wave radiation, net energy balance) are complemented by human and physical geography data to allow students to examine the causes and implications of climate change. Global climate data on precipitation and relative humidity are provided, as are physical geography data on elevation/bathymetry, soil type, dominant vegetation and ground cover, and plant energy absorption (FPAR). Students can also access global information on population magnitude and density, carbon emissions, and national boundaries.

Student access to the collections of WorldWatcher datasets is supported in two ways: (1) by

schematic diagrams that graphically depict relationships among variables—such as The Energy Balance in *Figure 2* — to foster students' conceptual development and which can be clicked
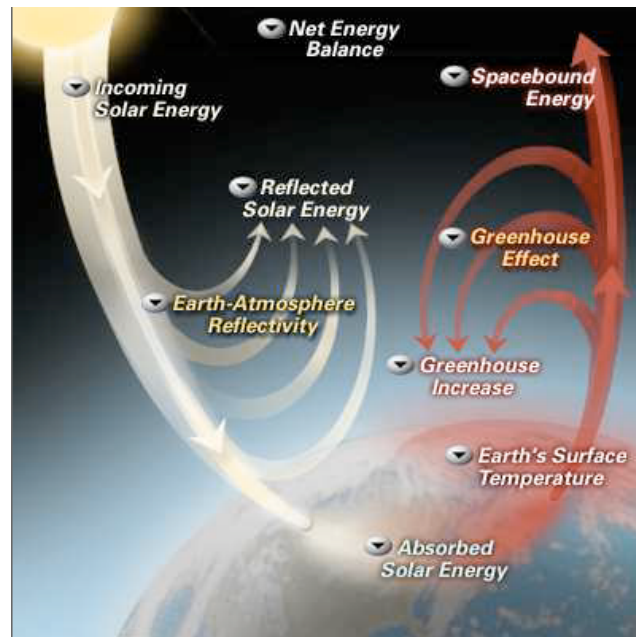

Figure 2: The Earth Energy Balance diagram user interface to WorldWatcher datasets

through directly to datasets for visualization, or by structured online notebook activities created by the teacher (see below).

WorldWatcher enables learners to examine and interpret datasets created by the scientific community and to create their own data using built-in arithmetic operations and climate models. WorldWatcher offers display features of visualization environments designed for scientific researchers, such as depicting 2-D global data in the form of false-color maps, but to provide geographical context for learners, these maps are displayed with latitude-longitude markings and an optional continent outline overlay (*Figure 3*). When a user interacts with the WorldWatcher visualization, a continually updating readout tracks the user's mouse as it moves over an image and displays current latitude, longitude, country or state/province, and data values. Users tailor visualizations by modifying color-scheme, mapping of colors to numerical values, spatial resolution, and magnification. WorldWatcher provides statistical summaries for user-selected regions[4] or whole maps.

Beyond these statistical summaries, WorldWatcher offers unary and binary mathematical operations for mathematical data analysis. Within an image, users can add, subtract, multiply, or divide all the values in a region or an entire image by a constant. They can normalize values in an image, and use the blackbody equation to convert energy values to temperature and temperature values to energy. WorldWatcher binary operators—enabling users to apply a function at each location in two images—are addition, subtraction, multiplication, division, maximum, minimum, and correlation, with the result displayed as a new visualization.

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[4] Regions can be selected using rectangular and irregular region selection tools, as well as by specifying geographic areas by name (e.g., South America in *Figure 3*), or data values by range (e.g., all areas with temperatures between 60 and 75 degrees F.).
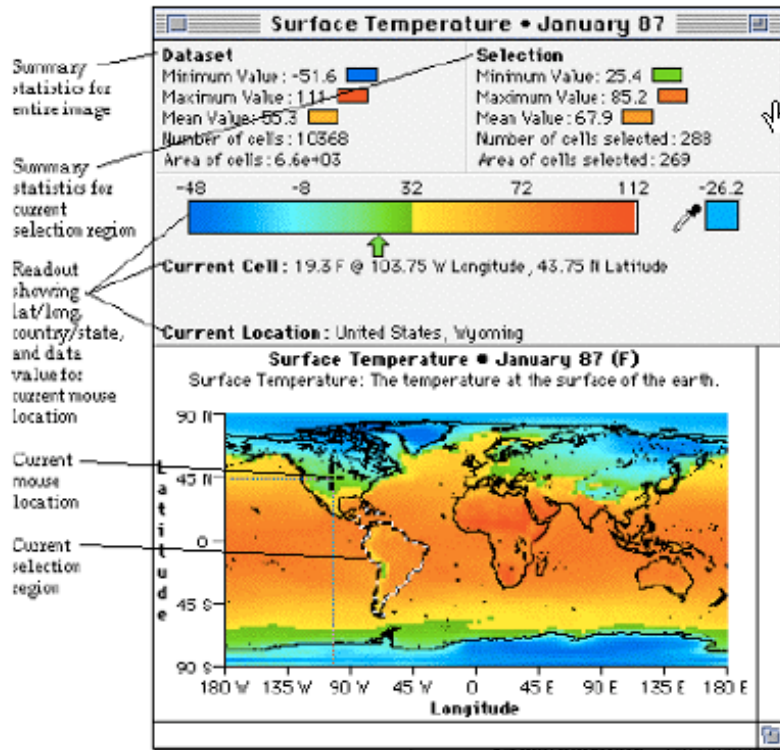
Figure 3: A WorldWatcher visualization window with key to what is represented

For example, examining the difference between global surface temperature values in January and July (all three visualizations included as *Figure 4*), students can observe the stability of ocean temperature and equatorial lands, in contrast to non-equatorial land masses, and the polar regions especially.
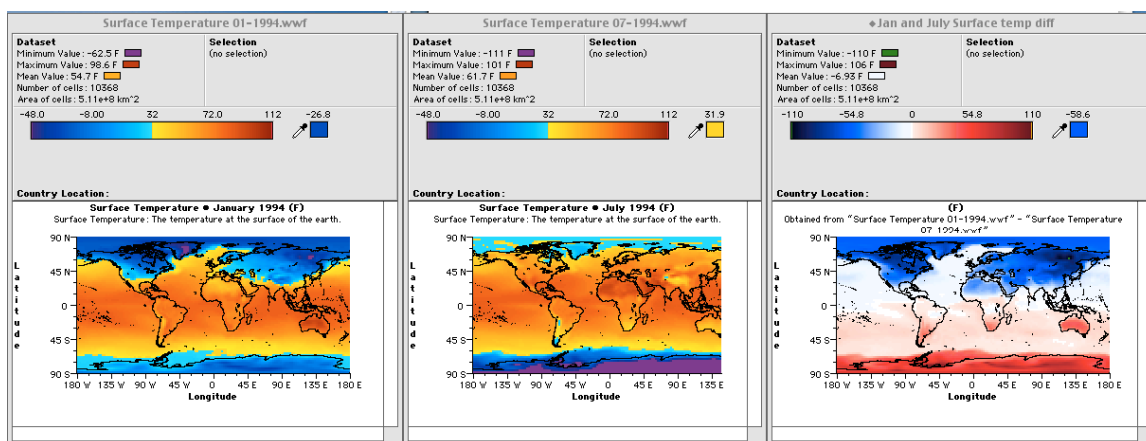
Figure 4: Three WorldWatcher visualization windows: Surface temperature for Jan-94, July-94 and the difference between Jan-94 and July-94

The functions of the WorldWatcher visualization environment allow students to view these data in the form of color maps at a variety of spatial and temporal resolutions, and to animate change over time. The activities are supported by a multimedia database of background and explanatory materials focusing on science topics and scientific visualization techniques.

WorldWatcher offers a simple on-line notebook feature that supports text, diagrams, multimedia, and clickable links to open specific datasets. Teachers are using the notebook to design and disseminate activities, and students are using it to create projects and record their cumulative progress in their projects, because they can annotate their visualizations

In today's uses of WorldWatcher advanced by LeTUS, the Center for Learning Technologies in Urban Schools (http://www.letus.org/), there are both middle school and high school curricula available, developed through a research center partnership, led by Northwestern University and involving the University of Michigan and 100 public schools throughout Chicago and Detroit. Scientific visualization is integrated into inquiry-oriented class work with hands-on labs, teamwork, and class discussions to develop learner understanding of both the scientific and social issues affiliated with changes in the environment. For middle school, *The Global Warming Project* is an eight-week unit centered on scientific factors contributing to the controversial global warming debate. The unit closes with student investigations considering scientific evidence and social concerns as they appraise potential solutions to issues raised by the global warming debate. *Looking At The Environment (LATE)* is a year long, inquiry-based, visually intensive environmental science curriculum for high school centered on three key issues: (1) The relationship between population growth and resource availability; (2) Electricity generation and meeting the demand for energy; and (3) Managing water resources for agricultural use and human consumption.

Conclusion

In the CoVis Project, we had several key objectives:

(1) To demonstrate the feasibility, opportunities, and challenges of establishing a distributed multimedia learning environment—the "CoVis testbed"—in which high school students could learn science by doing science over the Internet, using real scientific data and scientific visualization environments, as well as groupware and desktop videoconferencing tools for collaborative learning and virtual visits to labs, museums and other schools;

(2) To create a collaborative partnership in the development of the CoVis testbed of university researchers in the sciences of learning and learning environment design with a science education museum, a university scientific research group (UIUC/NCSA), multiple public schools, and industry partners;

(3) To investigate in detail how to make a powerfully general framework for scientific visualization in learning and teaching that could adapt scientists' tools, create software tools and curriculum to exploit that framework, and study how teachers and learners could come to use it productively in their learning and teaching activities.

When we began these efforts, the vision of establishing a high-end learning collaboratory for students to learn science by doing science over the Internet, with university-scientist level computing and communications resources, and engaging scientist telementors and science education museums in "virtual visits" was considered improbable by many, and exceptionally costly. Today, we see many of the features of our CoVis vision for science education integrated in the day-to-day learning activities of urban classrooms, among the most challenging settings for educational reform using technologies. While these achievements have been gratifying, we have only begun to explore the transformative roles for advanced computing and communications in supporting learning and teaching that taps the distributed intelligence available, so that anyone, anytime, anywhere, and at any pace, can advance their lifelong learning hopes and dreams.

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