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Scientific Visualization as an Interpretive and Expressive Medium

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Introduction

As a powerful technique for the visual representation of complex data, scientific visualization offers the potential to help secondary school science students learn through active inquiry. Over a period of several years, we have been conducting research in the design of scientific visualization environments that support inquiry-based learning. The goal is to support students in a multi-stage learning process that culminates in open-ended research projects. In the early stages, learners should gain familiarity with scientific visualization techniques and the phenomena depicted. In the later stages, students conduct investigations that use scientific visualization techniques to explore open-ended questions. Through the process of conducting inquiry with scientific visualization students can gain an understanding of its usefulness for originating and answering scientific questions.

The use of scientific visualization, like other media, can be divided into two categories: *interpretive* and *expressive.* In interpretive use, the user is primarily a viewer who is attempting to extract meaning from visualizations. In *expressive* use, the user is an author who is attempting to convey meaning through the construction of visualizations. In the course of this research we have come to recognize the importance of both interpretive and expressive activities for learners. This paper traces our design of software and activities as we have shifted from a primary emphasis on the interpretation of visualizations to one that integrates interpretation and expression. Our initial software enabled students to view visualizations and our activities called for students to compare and contrast these images. Following a set of experiments in which we observed students drawing visualizations by hand, we have developed new software and activity designs that address some of the limitations of the initial design by incorporating expressive activities and a wider range of data. The more recent software design enables students to create data by “painting” visualizations, communicate a point by customizing the appearance of visualizations, and explore hypothetical scenarios by both creating and interpreting visualizations.

The setting for these activities is an investigation into global warming. The controversial nature of this subject can serve to enhance student motivation and demonstrate the dynamic quality of scientific knowledge [Linn & Songer 1993]. In addition, investigations of global warming can be substantially aided by scientific visualization, since these investigations requires analyzing large detailed data sets.

In the remainder of this paper, we present some experiences with design and use and explore their implications. First, we discuss our observations of the interpretive and expressive uses of visualization by students who were engaged in a unit on global warming. Second, we present three additional design goals based on these experiences. Finally, we describe our most recent design that attempts to achieve these goals. The observations reported in this paper were made in classes that were engaged in a unit on global warming as part of their participation in the Learning Through Collaborative Visualization (CoVis) Project [Pea 1993].

Interpretive Use of Visualization

Supporting student inquiry in global warming led to the design of the Greenhouse Effect Visualizer (GEV) [Gordin, Edelson, & Pea 1995] and introductory activities. The GEV was designed to give students access to atmospheric data describing the earth's energy cycle. The introductory activities focus on the current state of the atmosphere. These activities ask students to explore climatic processes through the interpretation of visualizations. In this section, we describe the design of the GEV and provide an example of its use.

The Greenhouse Effect Visualizer

The GEV was designed to provide students in a large number of classrooms meaningful access to a collection of visualizations depicting the connections between the earth's energy cycle and climate. It was also designed to scaffold students' interpretation of visualizations and to support them in the interpretive activity of comparison.

Some of the variables used by the GEV to describe the earth's energy cycle are incoming solar radiation, reflectivity of the earth-atmosphere system, surface temperature, and retention of energy due to greenhouse effect. These variables describe the process by which the earth's incoming and outgoing energy seek to attain dynamic equilibrium. These data are helpful to investigate global warming, since global warming will occur if this cycle results in a persistent net gain in energy The variables are highly inter-related through cause and effect relationships that can be investigated by comparing visualizations.

Delivering visualizations to a large number of classrooms was accomplished by implementing the GEV as a World Wide Web forms-based application[1]. This allowed any classroom with Internet-access to obtain these visualizations. The GEV scaffolds novices' understanding of visualization by making underlying representations and geographic context explicit. For example, numerical values are always displayed together with their units, an overlay is provided that shows continental outlines, and a legend that displays the mapping from colors to values accompanies every visualization. In addition, the GEV provides a variety of spatiotemporal resolutions (e.g., by 2.5° square or 20° square and by month or season) and access to the underlying data values. Meaningful comparison between visualizations is enabled by consistent rendering (e.g., all surface temperature visualizations were rendered using a scale from -40°C to +40°C).

The GEV achieved its goal of providing wide access to its visualizations. During the 1994-95 school year, the GEV served thousands of requests by middle and high school classes, university students and researchers. In addition, it has been included on lists of notable WWW-based Geoscience and educational resources.

Interpretive Use of the Greenhouse Effect Visualizer

In addition to the GEV software itself, we designed a set of structured activities designed to support the early stages of the multi-stage learning process described above, i.e., familiarization with scientific visualization and scientific phenomena. These activities encouraged students to match their understanding of climate to the patterns they saw in the GEV's visualizations. In the example below, a researcher and student discuss the cause of seasonal differences in a high school environmental science class. The class is working on a worksheet that asks students to compare visualizations from winter and summer. One question asks students to compare the amount of solar energy reaching the earth in January versus July. Brenda's answer surprised one of the authors (Gordin), leading to the following conversation[2]. Brenda had written, "The insolation in July is higher than in January, since July occurs during the summer-time."

G: "But, which one of them has higher values? Which is brighter and has more red in it?" (Pointing to the two visualizations.)
B: "January." (Pointing to the brighter one.)
G: "Right, and why do you think that is?"
B: "I don't know."
G: "Come on, take a guess. Why do you think it might be?"
B: "Maybe, because the sun is closer then?"
G: "Yes, that's right. The earth is somewhat closer to the sun during January than July, so it gets more energy then."
B: "But, if it's closer in January, why would it be summer in July? I guess I don't know what causes the seasons.... What *does* cause the seasons?"

The visualizations allowed Brenda to answer the initial question by investigating data, rather than being told facts. The overall line of questioning was designed to counter the common misconception that seasons are caused by the earth's distance from the sun. The strategy is to have students use this explanation (i.e., distance from the sun to account for varying energy) to correctly explain why more energy is received in January than July. When students have used this explanation to account for more energy arriving in January, it is difficult for them to turn around and use the same explanation for why it is summer in July. Initially this strategy failed, because Brenda apparently answered the question based on her beliefs, rather than what is shown in the visualizations. However, after her

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[1]The Greenhouse Effect Visualizer can be accessed at http://www.covis.nwu.edu/gev.html.

[2]This conversation is reconstructed from memory and was not recorded.

careful examination of the visualizations, Brenda becomes dissatisfied with her explanation of the seasons. This realization accomplishes a fundamental step in inquiry-based learning: understanding why a question is interesting.

While we judged the GEV and the interpretive activities it supports to be successful in engaging many students in inquiry learning, we identified two specific shortcomings of it. The first is that we found the GEV to be less successful in supporting the sort of open-ended projects that make up the later stages of our model of inquiry-based learning. In particular, we observed that students had difficulty finding questions that could be profitably explored using the GEV's data sets and capabilities. We are attempting to address this challenge in a number of ways that are discussed in [Design Implications] and [The Integration of Interpretation and Expression in the Global Warming Visualizer]. The second shortcoming is that the activities failed to engage students that might best be characterized as difficult to reach. This shortcoming led us to introduce a new, expressive activity.

Expressive Use of Scientific Visualization

Two settings in which we observed the GEV and its activities fail to engage students were with younger (elementary school age) students and in inner city schools. The challenge of reaching these students led us to design an activity in which students drew their own visualizations with crayons or colored pencils on paper. While these students had stared blankly at the visualizations in the GEV, we found them to be avid and imaginative drawers of their own visualizations. The instructions and materials were simple: Draw a visualization of any variable you like on a blank map of the world, using a small range of colors, and indicating the mapping between colors and numeric values. No data sources were provided, instead they were asked to based the visualizations on what they knew or could infer. The first choice for students was what variable they would draw. The variables chosen by students at two Chicago schools are listed in Table 1. We found it very significant that students prefer to draw variables depicting human geography and describe in Sections 3 and 4 how we have used that observation to inform our more recent software and activity designs.

Videogames	Crime	Temperature
People starving	Biomes	Population
Number of hurricanes	Elevation	Hanta Virus outbreak
Unemployment rate	Books read	Pneumonia
Teenage pregnancies	AIDs virus	Best looking men
Years basketball existed	Per capita income	Worlds best women

Table 1. Students choice of what variable to render as a Visualization.

These hand drawn visualizations can provide significant insight into students' thinking. For example, Figure 1 shows a student's rendering of the world's population drawn without reference to data. This visualization reveals the students' qualitatively accurate understanding of population distribution with, for example, China and India clearly appearing as most populous. In a variation on this activity, we asked students to draw visualizations of the earth's surface temperature on a blank map using only their own knowledge and reasoning ability. While students did not initially find this activity as engaging as when they were given a choice of what to draw, they appreciated the value of being able to compare their work to visualizations of actual data on the computer.

Our positive experiences with students' drawing visualizations on paper helped us realize the potential of expressive scientific visualization activities. The expressive activity engaged a wider variety of students than the interpretive uses of scientific visualization and gave students a creative outlet. The drawings that they produced helped provided data to help us better understand what kind of variables students find most interesting.

Design Implications

These interpretive and expressive uses of visualization suggest three implications for the design of scientific visualization environments and activities: first, incorporate human geographic data sets; second, encourage students to engage in expressive activities by drawing visualizations; and third, integrate interpretive and expressive activities together by using student-drawn visualizations as a means to allow them to explore hypothetical scenarios scientifically. In general, we are trying to help students see visualization as a communication medium. As such, they need to see the interplay between expression and interpretation and how both are influenced by audience and problem. Finally, this mode of inquiry has to be motivated by issues they understand, like those that come from human geography.

Human Geographic Data Sets

The idea that students should study human geography before physical geography has a long history (Mitchell, 1934). Our experience with student drawn visualizations attests to this point (Table 1). When we discuss visualizations of human population with students they soon find questions that interest them (e.g., Students at one school asked: Why does Nigeria have so many more people than other areas of Africa?). This is important, since a critical part of fostering open-ended student inquiry is helping students to find a question to investigate. Answering questions about human geography will often lead students into issues of physical geography because patterns in human geography are often determined by patterns in temperature, precipitation, and terrain. Because students have more intuitive understanding of these sensible variables, working with them may serve as a helpful intermediate step to understanding more abstract and less experiential ones, such as energy.

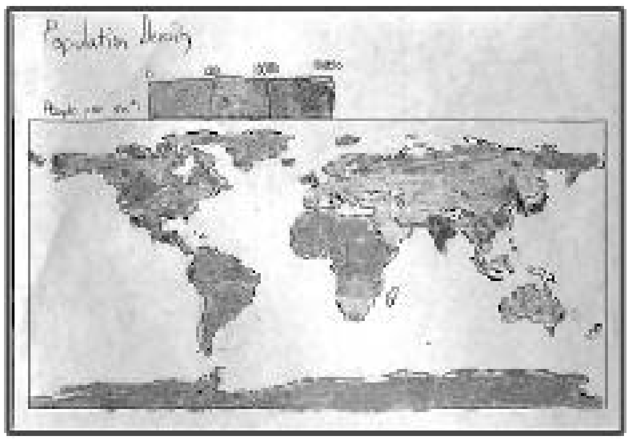

Figure 1: Student hand drawn visualization showing global population.

Expression through Drawing

Beyond its ability to engage students more than interpretive activities, drawing visualizations is a good beginning activity because it gets students to commit to paper what they believe. This articulation of their knowledge and beliefs can help to reveal gaps or conflicts in their understanding and can provide the basis for a discussion of their beliefs. Once they have articulated their beliefs, students have a new motivation to engage in interpretive activities. The record of their beliefs on paper provides them with a committed perspective from which to view visualizations based on measured data, compare their drawings to them, and to explain the differences they observe. For example, a student who drew a temperature visualization as horizontal bands, would see that she doesn't show different land and ocean temperatures.

Persuasive and Hypothetical Visualizations

Once students have had the opportunity to engage in both expressive and interpretive activities, they should have the opportunity to combine them in the form of authentic scientific inquiry. The skills that students gain in drawing and interpreting visualizations should allow them to engage in another expressive activity, the creation of persuasive visualizations. As students draw visualizations they will find the same data can be rendered in various ways. Also, as they interpret visualizations they will find some patterns easier to discern based on how the visualization has been rendered. Over time students may realize that no one rendering is best for all uses, rather visualizations need to be crafted to fit the use for which they are intended. This crafting uses expressive technique while taking account of how others will interpret it. For example, to aid a presentation a student will want a visualization that helps them to persuade their audience.

The ability to create data through drawing leads to a second way to integrate expressive and interpretive use of visualization. Students should be able to explore hypothetical scenarios by creating new data and then analyzing it scientifically. Computational modeling provides a mechanism to achieve this. Students can describe a hypothetical scenario by drawing it and then run a model to evaluate its consequences. Visualizations can be used to express a hypothetical scenario and to interpret and present the results. As students iteratively express and interpret visualizations they are engaging in scientific inquiry.

The Integration of Interpretation and Expression in the Global Warming Visualizer

The experiences and design implications described above have helped shape the design of our most recent visualization environment, the Global Warming Visualizer (GWV). Like the GEV, the GWV is an environment for exploring data related to climate and global warming. It provides access to the same data that is available in the GEV and supplements it with data corresponding to physical geography and human activity. The newer environment supports both interpretative and expressive use of visualization by providing a browsing and authoring environment. The first version of the GWV, called ClimateWatcher, is currently available, and the second version, EarthWatcher, will be available in June 1996.

Human and Physical Geography Data

The GWV contains a larger number of data sets and provides an improved interface to access data sets. While the GEV contained only atmospheric data sets and provided access to the data through a list of names, the GWV contains additional data sets describing physical and human geography and provides access to the data through schematic diagrams indicating relationships between variables. The new graphical interface is designed to help learners to place individual variables in the context of larger processes. The additional data sets are designed to better support students in conducting open-ended inquiry. Because they represent physical and human processes, these data sets can help students to connect atmospheric processes to phenomena with which they have experience. They also are designed to help students relate atmospheric processes and concerns about global warming to social issues. The additional data sets include population, carbon emissions due to burning fossil fuels, elevation, ground cover, and vegetation type. The inclusion of these data sets is designed to enable students to conduct investigations that relate human and physical geography.

Expressive Use of Visualization

The Global Warming Visualizer supports the expressive use of visualization in two ways. The first reproduces the experience of drawing a visualization on paper by enabling a user to “paint” a visualization on the screen. The second allows the user to customize the display of a visualization in a number of ways. The GWV provides an interface that allows students to create new data using a standard paint program interface. Students can “draw” on existing data sets or create new ones from scratch. The advantage of a computer interface is that 1) the resulting visualizations support direct visual comparison with actual, measured data; and 2) students can use built-in analytical operations, such as subtraction, to perform mathematical comparisons.

The second expressive capability that the Global Warming Visualizer provides is the ability to customize the display of any particular visualization. Students may change the magnification, the spatial resolution, and the mapping from numeric values to colors for any visualization. This ability supports interpretive use by enabling students to identify particular features that may be less visible at different settings, but it also supports expressive use by allowing students to highlight features that they want to emphasize in order to support an interpretation they are trying to communicate others. An example of this crafting of visualizations is the modification of the color scheme (the mapping from values to colors) to signify qualitative changes in a variable by hue discontinuities in the color display. Kuipers (1986) refers to such values at which qualitative changes take place as *landmark values*. For example, 0°C and 100°C are landmark values for the temperature of water, since at are those values water freezes and boils, respectively. Locating hue discontinuities at landmark values afford certain readings of a visualization.

Modeling

The most significant enhancement in the Global Warming Visualizer is the ability to investigate hypothetical climate change scenarios using a simple climate model. This facility will be available in EarthWatcher, the second version of the Global Warming Visualizer. Modeling in the GWV integrates expressive and interpretive use of visualizations by allowing students to create hypothetical data using the data creation interface and then use that data as input to the climate model to see how the new values affect other variables. For example, a student who wanted to explore the effect of a hotter sun could increase the incoming solar energy by drawing a higher insolation and then running the model to inspect the altered surface temperature. Similarly, a student could simulate a rise in atmospheric CO_2 concentrations by increasing the percent of energy retained in the atmosphere. In this use of the model, students cycle between expressive activities to set the initial conditions for a scenario and interpretive activities to analyze the results of running the model. This interpretation can lead to formulating another scenario or revising the initial one, and so on. The ability to conduct open-ended investigations provided by modeling is a critical element of the GWV's attempt to support open-ended inquiry projects.

Conclusion

We have explored the conjecture that scientific visualization can be an effective means to encourage inquiry learning on the part of science learners. The central question of this work is how to provide dynamic scientific media to students to promote scientific inquiry. This informal evaluation has provided some insight. First, we have seen that scientific visualization can promote inquiry conversations on the part of students. Further, we see from our interactions with students that visualization can be construed for them as both an interpretive medium and an expressive medium.

These early observations of student use of visualization environments have suggested several new design ideas to us for subsequent visualization environments. It is our hope that these ideas will make our new visualization environments more complete for student inquiry and communication. They will be both interpretive and expressive. They will also provide more data sets in an effort to help students see a tighter coupling between the world as they experience it and more abstract systems like global warming. The new designs described here will be the subject of continued formative design evaluation in school settings and elsewhere. As we proceed we will learn more about:

- How is visualization appropriated in school settings? For example, what mixture of interpretive and expressive activities do teachers and students choose?
- How are visualizations used in the conversations that students have with peers and others? For example, what are the key features of a visualization or the set of experience that students have with them that make it possible for them to use visualizations as a prop in explanation or argument.
- Where in the process of doing projects (e.g. developing a question, reporting results) do visualizations have the most value to student? And, where do they fail to add any value. In this effort we will continue to look carefully at student artifacts to see where students make productive use of visualization and where they do not.

The infusion of new media in school, or any other setting, is a slow process of design and redesign informed by use. Here we have just started down that road to help visualization find its appropriate role in supporting inquiry learning for students in science classrooms.

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