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Visualizing landscape

My work with visualizations has two foci. From a research and collection point of view, I have dealt with historic and modern images of landscape change in Vermont. I use these images to examine how and where human and geologic forces have interacted over time and with what results. For teaching, I use whatever visualizations I can find from friends and on the web to illustrate my classes. I am almost exclusively a user of others' work in this regard although I have created a few powerpoint-based animations.

My research, gathering and interpreting images of landscape change, has helped me and others to understand the impact of humans on the New England landscape. We knew that clear cutting was widespread in postcolonial times; what we didn't know is how dramatic the landscape response was in terms of landsliding, erosion, and changing stream and river behavior. By collecting images of the past we help countless students and citizens understand more deeply the place they live, what it was, and what it can be.

My interest in visualizations is as a tool for communicating ideas. I am fascinated by the image as an object as well as the image as a conveyor of information. As a scientist studying Earth's surface, images are at the center of what I do; they are representations of the landscapes I study day in and day out. My work is founded on bringing landscape history, the thought that landscapes are dynamic, not static, to the widest audience possible.

Our work is featured on several web sites. Lots of abstracts but no publications so far...soon enough!

<http://www.uvm.edu/oakledge/> - a visual tour of a simple city park that was once the estate of Vermont's richest family; none of that history remains except in images – the buildings and grandeur are gone.

<http://www.uvm.edu/perkins/landscape/> -- a community archive of historic landscape images some of which are paired with modern images of the same scenes. Currently the archive holds over 2000 images from over 200 Vermont towns. Anyone can browse and anyone can submit images via the web.

Cognitive Processes and Visualization

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As a cognitive psychologist, my interest in visualizations has grown out of my previous research background in text comprehension and my overarching interest in human learning. Research in text comprehension has revealed a great deal about how people learn from text and about the complex, interacting factors that can predict a learner's ultimate comprehension (Butcher & Kintsch, 2003). However, text is a very simple type of material given the diverse media options that are increasingly available in learning situations. The use of visualizations in science learning highlights the potential of multimedia resources; visualizations represent a richer set of resources (extending far beyond text and even static pictures) that can support new learning activities. Opportunities for authentic discovery learning is just one example of the ways in which visualizations or other multimedia can provide a learning experience that is fundamentally different from traditional print materials.

Despite the promise of and excitement about visualizations for learning, relatively little is known about how individuals think or learn with visualizations and multimedia. As complex visualizations are increasingly used and available, more research is possible. But in order for visualizations to be optimally designed and applied in learning situations, we must know more about the cognitive processes involved in learning with visualizations. We also must study whether (and how) specific aspects of visualizations impact comprehension processes. My research approach specifically concerns the ways in which experts, intermediates, and novices process visualizations during learning and whether visualizations may be designed to scaffold cognitive processes necessary for comprehension.

In previous research (Butcher, 2004), I studied the cognitive processes and mental models of learners using visual diagrams in addition to a text. Participants studied with more or less detailed diagrams or text only. The more detailed diagrams emphasized correct structural information about the domain (the human heart and circulatory system) and the less detailed diagrams were simplified to emphasize functional relationships. The presence of diagrams significantly increased the number of inferences produced by participants, but did not influence any other (measured) learning process – monitoring, paraphrasing, or elaboration. In addition, participants who used diagrams demonstrated greater mental model development but the effect was most pronounced for students using the simplified diagrams. The interpretation of these results was that appropriately

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designed diagrams can successfully promote learning because they successfully guide the learner to engage in cognitive processes essential for comprehension.

Other research also has supported the conclusion that successful visual resources support important cognitive processes. Ainsworth and Loizou (2003) found that students using diagrams generated more self-explanations and, consequently, learned more than students using only text. Narayanan and Hegarty (2002) have demonstrated that multimedia presentations supporting their proposed model of multimodal comprehension (Narayanan & Hegarty, 1998) facilitate learning to a greater extent than do presentations that do not match the cognitive model. Although these studies approach the issue from different theoretical and methodological approaches, the conclusions are similar: visual resources must effectively support specific cognitive processes in order to promote learning.

The previously mentioned studies use relatively simple visualizations as a form of multimedia. However, geoscience education often involves more complex visualizations that may pose unique questions and challenges. For example, the function of animation in learning from visualizations is an open issue. An excellent review on this topic is provided by Tversky, Morrison, and Betrancourt (2002). These authors point out that existing research on visual animation is far from conclusive; most previous work has confounded interactivity with animation and has failed to ensure informational equivalency in multiple presentations.

Another issue raised by Tversky et al. (2002) is the issue of perception, specifically that complex visualizations can be difficult to perceive and interpret. Indeed, studies of perception and visualizations (Lowe, 1999, 2003) have shown that perceptual features of visualizations can interfere with successful comprehension. Although Lowe (2003) did find an advantage for predictions drawn from animation, the advantage was limited to perceptually salient features. Lowe (1999) also found that novice learners often were distracted by perceptually salient features of an animation at the expense of more important content information. Thus, the interpretation and use of visualizations may be greatly affected by perceptual qualities of the visualization as well as by the expertise of the individual. Understanding how learners with different background knowledge perceive, process, and use visual information (particularly from complex visualizations) are fundamental issues that form the current focus of my research agenda. Specifically, I am interested in the use of visualization by experts and the cognitive processes that must be supported for lower-knowledge students to achieve meaningful learning with visualizations.

Scientists at the National Center for Atmospheric Research (NCAR) use visualization tools for a variety of scientific tasks. Example visualizations produced at NCAR can be explored on the Visualization and Enabling Technologies website (<http://www.vets.ucar.edu/>). Currently, I am beginning exploratory work to assess when and how NCAR scientists use visualization in their work. More formal work is also planned to assess differences between the cognitive processes of experts, intermediates, and novices as they work with visualizations, with the intention that this work will highlight cognitive processes that must be scaffolded for novices in order to promote

meaningful learning. My work also deals closely with the Digital Library for Earth System Education (DLESE: www.dlese.org). As a digital library tool, DLESE provides multimedia content – including visualizations – in its available resources. At the present time, I am reviewing the extent to which DLESE resources conform to design principles from existing multimedia research. Ultimately, we also plan to test comprehension performance with DLESE resources based on cognitive principles of learning.

It is clear that much needs to be learned for successful use of visualizations in education and that collaboration between researchers, educators, and developers will be necessary to better understand when, how, and why to use visualizations. But it is equally clear that the potential impact of visualizations in science education makes the effort worthwhile.

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An Earth Data File is Worth a Thousand Pictures:
going beyond multimedia for education
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This essay explores how incorporating data files into “multimedia” educational applications changes the usefulness of these applications. Giving students direct access to data files through a dedicated “rich-client” (which sounds better than a “thick” client) opens up the possibility of independent discovery, and the beginnings of data literacy.



In the beginning was Macromedia Director™. And it was, well, pretty good, considering. This was in the mid 1980s, and the whole idea of multimedia was emerging as fast as the hardware and content formats could grow. While other multimedia authoring programs (notably Hypercard) would come and go, Director™ developed into the most widely used authoring software for educational (and commercial) multimedia CD-ROMs. John Thompson (pictured on the left; source: http://inventors.about.com/library/inventors/bl_Lingo_programming.htm), the chief scientist at Macromedia, developed the Lingo code that brought interactivity to the software. This meant that pedagogical feedbacks were possible, and the user (the student) could be given a number of pathways through the educational content. As the Internet developed, Macromedia has been migrating the capabilities of Director™ from CD-ROM delivery to this new media. First came Shockwave™, which allowed the user to play a “shocked” Director™ file. And later came Flash™, based on a new vector file format. But the idea was the same: create an authoring platform that can deliver an interactive, multimedia-rich user experience.

At roughly the same time (from the mid 1980s), earth science researchers were using their computers to create images and models and build data resources of data from newly launched earth orbiting remote sensors. The growth of research software, such as MATLAB, IDL, and ARCinfo, enabled a new generation of graduate students to explore data and models in ways their professors had never dreamed a generation before. A new cadre of scientists emerged, and a new science that was data-driven. These scientists were computer and software—and, of course, model and data literate. They would discover new knowledge about the earth system. But their tools, while powerful, grew enormously complex, being built to handle a wide range of data access, visualization and analysis methods.

The output of the science, in terms of graphics, has been enormous. NASA’s Visible Earth website [<http://visibleearth.nasa.gov/>], for example, boasts more than 6000 images. And NASA alone has thousands of other WebPages that offer tens of thousands of images. So when it comes to creating a multimedia educational application that contains pictures of the subject under study, there is, at last, a wealth of images available. However, if the goal is to help the student understand not only the content, but also the science that created it, new problems emerge.

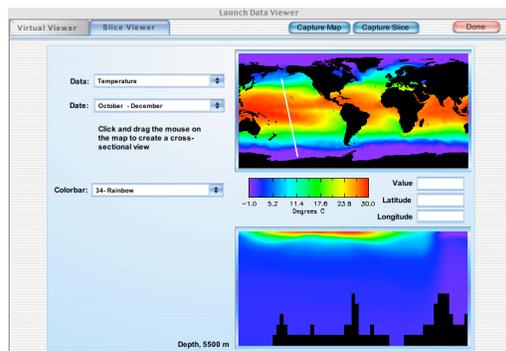
In the mid 1990s, under a NASA cooperative agreement, I managed a team that was developing middle-school courseware that included NASA data resources. [NOTE: These are still available: <http://www.planeteearthscience.com./products.html>]. These products were developed using Director™, and were designed to guide the student through the scientific process of data access, visualization, and analysis. For this purpose, the NASA data files were brought into IDL™, visualized, and then images—dozens, hundreds, thousands—were output. These images were then

integrated into the product to simulate the various choices that a scientist would make in using the data. But even with thousands of images, the software could only simulate a small subset of an actual data use case: any decision tree more than a few steps long and with a few interactively available parameters, would create the need for not just thousands but potentially millions of images. In another project designed to simulate a local land-use decision model, we determined that several hundred million graphic images would be needed. It appeared that we had hit the limit on where interactive multimedia could go.

We had been exploring the notion of building a data access and visualization tool for education using Java™, but the task seemed far too ambitious. Stepping back from the problem and looking at the possibility of extending Director™ (rather than starting from scratch), we hit on the possibility of developing a plug-in to this program. And since we were already using IDL™, I wondered if it might be possible to create a “plug-out” of IDL™ that could connect to our plug-in to Director.™ The goal was to have an IDL™ data window (or more than one) inside a Director™ authored application. This window would offer the students the same data analysis capabilities of IDL, but would be preprogrammed for the task at hand.

This data window would give the student a research-level tool in an interactive educational user interface. And the result would be an application where the students can discover data in much the same way as the scientist does. And since a single data set can be re-visualized any number of times, there is no need to pre-script what that

choices were for the student. The actual tool would replace the simulation of the tool. [At Left: a data page from our latest tool. The data displays are from actual data sets and the students can get data values using their mouse.] To produce this application we would not need thousands of (pretty) pictures for each data file, but only the one file. And since the data would be on the desktop, the response time would fall in the under one-second range (instead of the multiple



second—or even multiple minute—response time typical for thin-clients).

With support from the NSF (DUE #0121550), and from NASA and the ESIP Federation, the Data Discovery Toolkit technology was created. This is now being updated, upgraded, and enlarged to bring new data access, visualization, and analysis capabilities into Director™ and soon into Flash™. The code resources for this technology are freely available on the Data Discovery Toolkit and Foundry NSDL site [<http://www.newmediastudio.org/DataDiscovery/>]. This is the next generation of multimedia, where media might include images, sound, and video, and also data and links to models.

However, the promise of putting real data into the hands of students can only be fulfilled through an active partnership with teachers and curriculum builders. Giving students an ability to actively discover data in a real tool also means that students will need to learn about real data use and misuse. Data literacy becomes both possible and necessary for the students to learn about the earth through the data they can now manipulate. A data file is certainly worth a thousand pictures, but only to those who have learned to pull information properly from these data.

Simulations in Science Courses for Non-science Majors

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As a graduate student in geochemistry at the University of Washington in the 1970's, I found that my real interest in life was teaching introductory students. The faculty members at UW were supportive of this change in my direction and I was able to get a Ph.D. in a joint effort between the Geosciences Department and the College of Education. Part of my research involved assessing the spatial and mechanical reasoning aptitudes of introductory students and how these aptitudes interacted with different methods of instruction.

In 1993, I attended Project Update Geoscience, organized by the late Dottie Stout. At this meeting I was introduced to several computer-based simulations that I was able to use in my introductory geology classroom and lab. At this same meeting, Gary Novak (California State University- Los Angeles) demonstrated several science labs that are now available on the web. I use parts of his Virtual River lab frequently to help students understand how we determine the discharge of a local stream.

In 1999, Green River Community College (GRCC) received a CETP grant from NSF to prepare materials for a series of interdisciplinary science classes for non-science majors, including pre-service primary teachers. We developed a sequence of three Interdisciplinary Science courses (IDS). The cohort of students remains the same through the year, but we have a variety of science instructors from physics, chemistry, geology, and biology instructors that team-teach the class through the year.

To determine what we were going to teach in this IDS sequence, we polled the Science faculty at Green River and asked "What should students majoring in fields outside of science be able to do upon completion of their science requirement?" and "What should these same students know upon completion of their science requirements?" Although the list of skills and subject matter to be mastered was several pages long, there was a consistent opinion that these students should develop the ability to set up an experiment to answer a scientific question, interpret graphs, and develop confidence that they can answer scientific questions.

Since we wanted the students to gain skills in doing science, we decided that the fundamental approach of the course should be centered around of a series of guided-inquiry modules. If you are familiar with the work of Lillian McDermott (University of Washington) and her text, Physics by Inquiry, you will recognize the style of the class sessions.

We selected the overall theme of climate and global change to be the organizing thread for the three courses. The topics of the first quarter are measurement and basic physics

including several sections from Physics by Inquiry. The second quarter includes temperature, pressure, atmospheric science, climate change, and geological changes in the Earth over time. The third quarter contains biological and environmental science topics.

Computer simulations seem to be an effective means of helping students investigate some IDS concepts. One of my GRCC physics colleagues, Keith Clay, has used “Physlets” to construct several animations of elementary, but poorly understood concepts, such as intensity of light, why the earth has seasons, and the phases of the moon. Keith developed companion handouts to help guide the students through these simulations. Keith and I taught the class last winter and I am currently teaching the class with Mary Whitfield, from the chemistry department. The home page for the Interdisciplinary Science courses and links to the simulations used in some of our modules are referenced at the end of this essay.

We also use animations developed by other people in our modules. For example, we want our students to understand the role of trace gases in the atmosphere in influencing the Earth’s climate; this requires that the students learn about emission, absorption, and filtering of light. Our students visit a University of California-Berkeley site that permits them to mix colors of light in emission and absorption as well as try different filters.

It seems to us that interactive simulations are more effective than animations that simply run the same movie over and over. When the students can change variables and test ideas, they ask better questions and seem more interested in the process.

My goals related to visualization are to learn to develop interactive simulations and to write guided-inquiry modules to use in geology and Interdisciplinary Science courses.

General URL for the Interdisciplinary Science courses at Green River Community College:

<http://www.instruction.greenriver.edu/ids/>

Handout for Trace Gases in the Atmosphere module:

<http://www.instruction.greenriver.edu/ids/102/Modulesw04/TraceGases.pdf>

Simulations used in this module:

<http://mc2.cchem.berkeley.edu/Java/emission/Java%20Classes/emission.html>

<http://mc2.cchem.berkeley.edu/Java/absorption/Java%20Classes/absorption.html>

<http://mc2.cchem.berkeley.edu/Java/single/Java%20Classes/single.html>

Handout for Intensity of Light and Seasons on Earth module:

<http://www.instruction.greenriver.edu/ids/102/Modulesw04/IntensitySeasonsw04.pdf>

Simulations used in this module:

<http://www.instruction.greenriver.edu/physics/intensity/>

<http://www.instruction.greenriver.edu/physics/seasons/>

Handout for Phases of the Moon module:

<http://www.instruction.greenriver.edu/ids/102/Modulesw04/Phases%20of%20the%20Moonw04.pdf>

Simulations used in this module:

<http://www.instruction.greenriver.edu/physics/moon/>

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Filson, R., 1979, Instruction in college-level, introductory geology: Interactions of two teaching methods and selected student characteristics, unpublished Ph.D. dissertation University of Washington, 169 p.

Harnessing technology to support on-line model building and peer collaboration ¹

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Summary

A large scale design study in which 3000 middle and high school students from California and Massachusetts collaborated on-line about plate tectonic activity in their respective location. The students, demographically diverse, participated in this curriculum using WISE, Web-based Inquiry Science Environment (Linn, 1998), an integrated set of software resources designed to engage students in rich inquiry activities.

The curriculum engaged students in many inquiry-oriented, model-based activities. For example, students were scaffolded by WISE as they: a) drew initial models of plate tectonic phenomena in their respective area using WISE; b) wrote explanations of their models and shared their models and explanations with students on the opposite coast (east vs. west); c) were scaffolded to critique their peers' models; d) revised their models based on this feedback; and e) discussed the differences between E and W coast geology in an on-line forum.

Data analysis focussed on measuring content gains and characterizing the nature of students' models and model revisions, as well as their discourse. Results suggest that this curriculum was successful in fostering deep content learning. The task of evaluating and critiquing their peers' models provides some insight into students' learning.

Grounded in research in Science Education and Cognitive Science

The "What's on your plate?" curriculum is based on students' misconceptions of plate tectonics of both the inside structure of the earth and of the causal mechanisms underlying plate tectonic-related phenomena (Gobert & Clement, 1999; Gobert, 2000), as well as students' knowledge integration difficulties (Gobert & Clement, 1994). It emphasizes students' active model-building and scaffolded interpretation of rich visualizations (Kindfield, 1993; Gobert & Clement, 1999; Gobert, 2000; Gobert & Buckley, in prep.) as strategies to promote deep learning. The curriculum is implemented in WISE (Web-based Inquiry Science Environment) developed by Marcia Linn & Jim Slotta at UC-Berkeley, which is based on 15 years of research in science education (Linn & Hsi, 2000).

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Previous cognitive research on Earth Science

There has been some previous cognitively-oriented work on earth science in general, including:

- the earth as a cosmic body (Vosniadou & Brewer, 1992; Nussbaum, 1979, Nussbaum & Novak, 1976; Sneider & Pulos, 1983);
- knowledge of rock-cycle processes (Stofflett, 1994);
- conceptions of earth and space as it relates to seasons and phases of the moon, (Schoon, 1992; Bisard et al, 1994);
- sea floor dynamics (Bencloski and Heyl, 1985);
- earth's gravitational field (Arnold, Sarge, and Worrall, 1995);
- misconceptions about mountain formation (Muthukrishna, et al., 1993); and
- modeling the geosphere, hydrosphere, atmosphere, and biosphere (Tallon & Audet, 1999);

As well, there has been previous research on misconceptions in Plate tectonics in particular, including:

- Ross & Shuell (1993) investigated children from K - 6th grade regarding their beliefs about the causes of earthquakes. Responses included: “the core gets too hot and hits the surface of the earth”; “the earth is letting out air like a sneeze”; and “earthquakes are caused by the wind, thunder and rain, or by mountains”.
- Asked about what happens below the surface when there is an earthquake, again, a large proportion of the children answered that they did not know. Responses included: “roots underground pop”; “the plants might get “screwed up” because the seeds would jiggle around”; and “the earth has too much energy just like children who need to get rid of it”.
- 1450 adults interviewed from southern California, many held the misconception that earthquakes could be predicted by “earthquake weather” (Turner, Nigg, & Daz, 1986).
- Research with graduate students in geology showed that many students at this level in their education still do not understand geologic time (Jacobi et al, 1996).

This research, where relevant, was used to inform pilot studies as background to design of the “What’s on your plate?” curriculum. A study of students’ learning difficulties in this domain (Gobert, 2000 & Gobert & Clement, 1994, 1999) yielded three main difficulties in students’ model construction processes:

- (1) problems with setting up a correct static model of the layers,
- (2) difficulty understanding causal and dynamic information (e.g., heat as causal in forming convection currents, or currents causing plate movement), and
- (3) difficulties with the integration of several different types of knowledge including causal and dynamic knowledge into a causal chain in order to build an integrated mental model of the system.

Each of the three difficulties outlined above has different ramifications on model construction and revision processes, as well as the transfer and inference-making afforded on the basis of the model (for more detail, see Gobert, 2000).

See figure 1 for students’ typical models of structure of earth (Gobert, 2000). See figure 2 for students’ typical models of volcanic eruption (Gobert, 2000).

In addition, other research literature informed the design of the curriculum, namely, we drew on current findings from:

- causal models (White, 1993; Schauble et al, 1991; Raghavan & Glaser, 1995),
- model-based teaching and learning (Gilbert, S., 1991; Gilbert, J. 1993);
- model revising (Clement, 1993; Stewart & Hafner, 1991);
- diagram generation and comprehension (Gobert, 1994; Gobert & Frederiksen, 1988; Kindfield, 1993; Larkin & Simon, 1987; Lowe, 1989),
- the integration of text and diagrams (Hegarty & Just, 1993), and
- text comprehension (van Dijk & Kintsch, 1983; Kintsch, 1998).

Student Difficulty in Learning from Models

Previously it was thought that diagrams and models would facilitate students' understanding of difficult science concepts simply by "adding" a diagram or a model to the textbook's textual materials. However, research has shown that simply adding diagrams and models did not facilitate learning because it increased cognitive load on learners (Sweller, et al, 1990). Also, students lack the necessary domain knowledge in order to guide their search processes through diagrams/models in order to understand the relevant spatial, causal, dynamic, and temporal information (Lowe, 1989; Head, 1984; Gobert, 1994; Gobert & Clement, 1999). In particular, learning from models requires scaffolding of:

- search processes for acquiring rich spatial, dynamic, causal, and temporal information from models (especially with models in which all information is presented simultaneously).
- perceptual cues afforded by models in order to promote deep understanding.
- inference-making with models, again, to promote deep understanding (adapted from Larkin & Simon, 1987). For a fuller description of model-based teaching & learning (Gobert & Buckley, 2000).

Scaffolding Framework for Learning with Models in "What's on your plate?"

In the Making Thinking Visible project, we supported East and West coast students' collaborative on-line learning of plate tectonics using WISE (Web-based Inquiry Science Environment; Linn & Hsi, 2000).

The goal of the curriculum is that student learn:

- Content knowledge of the spatial, causal, dynamic, and temporal features underlying plate tectonics (data presented here).
- Inquiry skills for model-building and visualization (not presented here).

Epistemological understanding of the nature of scientific models (Gobert & Pallant, in press; (not presented here). Papers available at mtv.concord.org.

Overview of Model-based activities and scaffolding for unit: "What's on your plate?" (To see the unit, go to wise.berkeley.edu, click on Member entrance, and for login enter "TryA1"

and “wise” as your password. Click on “Plate Tectonics: What’s on Your Plate?”).

- Draw, in WISE, their own models of plate tectonics phenomena.
- Participate in an on-line “field trip” to explore differences between the East and West coast in terms of earthquakes, volcanoes, mountains (beginning with the most salient differences).
- Pose a question about their current understanding (to support knowledge integration and model-building)
- Learn about location of earth’s plates (to scaffold relationship between plate boundaries and plate tectonic phenomena).
- Reify important spatial and dynamic knowledge (integration of pieces of model) about transform, divergent, collisional, and convergent boundaries.
- Learn about causal mechanisms involved in plate tectonics, i.e., convection & subduction (scaffolded by reflection activities to integrate spatial, causal, dynamic, and temporal aspects of the domain).
- Learn to critically evaluate their peers’ models which in turn serves to help them think critically about their own models.
- Engage in model revision based on their peers’ critique of their model and what they have learned in the unit.
- Scaffolded reflection task to reify model revision which prompt them to reflect on how their model was changed and what it now helps explain. Prompts are:
 - “I changed my original model of... because it did not explain or include...”
 - “My model now includes or helps explain...”
 - “My model is now more useful for someone to learn from because it now includes...”
- Reflect and reify what they have learned by reviewing and summarizing responses to the questions they posed in Activity 3.
- Transfer what they have learned in the unit to answer intriguing points:
 - Why are there mountains on the East coast when there is no plate boundary there?
 - How will the coast of California look in the future?

METHOD

Participants. Approximately 1110 students participated in the Spring 2001 implementation of “What’s on your Plate?” These were drawn from 34 middle and high school classrooms across California and Massachusetts. From this large data set, data from 15 middle school classrooms was chosen for this paper; this represents data from three different teachers (1 in California and 2 in Massachusetts) each with five Science classes. The total number of students upon which this subset is based is approximately 360.

Procedure. Students were given a pencil and paper survey to assess both their content knowledge of the plate tectonics and their understanding of the nature of models both (this data is not described here); the same test was given before and after.

RESULTS & DISCUSSION

Pairs of students from one class on the West coast were partnered with pairs from two classes on the East coast because of the differences in class sizes. Five such sets or “virtual classrooms” (referred to as WISE periods) were created in WISE.

Data analysis. The data analysis is described in three parts. The first part describes the increases made in students’ understanding of the content as measured by pre-post gains. The second part provides some examples of students’ original models, their opposite coast partners’ critique, and the subsequent model revision.

Part. 1: Analysis of Variance of WISE periods 1-5 for content learning.

Analysis of variance was used on the total pre- and post-score on the content survey and computed for each WISE period (1-5). Again, since this is a design study, we are not comparing these groups to a control group, rather the goal is to iteratively revise the curriculum in response to data yielded. Thus, the purpose of the analysis of variance for content understanding is to get a general measure of whether the students’ understanding of the domain (as measured by the post-test) changed as a result the unit. It is also important to note that the teachers used the pre- and post-test scores for students’ grade on the unit; in this way, the implementation is also authentic.

In all of the WISE periods, the students made a significant gain on the post-test collapsing over teacher, meaning that all WISE periods acquired knowledge during the implementation of the “What’s on your plate?” unit. See Table 1 below for a summary of these findings.

Table 1. Summary of Content Gains for each WISE Period

	F value	p value
WISE Period 1	44.982	<.0001
WISE Period 2	39.473	<.0001
WISE Period 3	26.654	<.0001
WISE Period 4	25.019	<.0001
WISE Period 5	18.220	<.0001

Figures showing the pre-post differences, etc. can be found in the Appendix.

Part. 2: Examples of Students’ Original Models, Peer Critique, and Model Revision.

From this large data set, we selected some examples to get a sense of the types of critiques students were writing for their peers and how these critiques influenced students’ model revision. In the following examples, the model on the left is the students’ original model and explanation. On the bottom under “Critique” is their opposite coast learning partners’ critique of the model. On the right are students’ revised models and revised explanations.

EastWest East West PairID: 2 Names: _____
 CompleteID SP2G13941_5Wes Model Type Volcano

Model Picture




My model is of a volcano. It shows how a volcano erupt. and shows that lava spreads every where. Write a detailed explanation of what is happening inside Earth and on its surface. Inside it gets really hot and bubbly and on the outside smoke starts to rise and then lava flows out. When it dries it makes rocks.

My new model is of a volcano. It shows what happens inside the earth and outside the earth when a volcanoes erupts. When the plates rub up against each other they create fection and then all of the heat exopleds out of the volcanoe and outside there is lava everywhere. Magma happens when the lava dries.

Original Model Score: 5 Score Difference: 4 Revised Model Score: 9

Critique Score: 6

Critique:

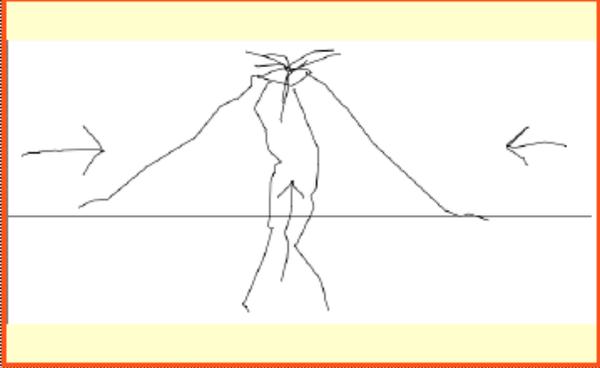
E2: Your model had a volcano and lava. But it did not include the following:

- Labels
- Cause
- Plates
- Types of volcano
- Interior
- Exterior

In this example, the students drew a model of volcanic eruption which includes only the crustal layer of the earth; that is, the inside layers of the earth are not depicted, nor are there any internal causal mechanisms responsible for volcanic eruption included in either the model or explanation. This type a model is called a “local” model and is consistent with previous research in this domain which showed that many students of this age group have models of plate tectonic phenomena which only include processes on the surface of the earth, i.e., they do not include the processes and mechanisms inside the earth (Gobert, 2000). The correct conceptions that are represented in the model and/or explanation are: hot magma, movement of magma beyond the volcanic cone, and magma forming new rock. The learning partners’ critique is very detailed in that it suggests that the students’ model needs “labels, cause, plates, types of volcano, interior, exterior, and what the volcano was doing”. The students’ revised model includes some the learning partners’ suggestions. The revised model includes plates and labels and the students have elaborated on one type of volcano as requested by their learning partners. More specifically, in their explanation it appears the students were trying to depict/describe volcanism due to plate convergence. The students have also included plate movement and plate friction as causal mechanisms responsible for volcanic eruption. The inclusion of more causal mechanisms is a significant advance over their original model.

EastWest East West PairID: 3 Names:
 CompleteID SP3G13928_5Wes Model Type Volcano

Model Picture





My model is of how volcanoes form and erupt. Write a detailed explanation of what is happening inside Earth and on its surface. First a mountain is formed by two plates colliding together. Magma come up through the inside of the mountain. When the magma cannot be held in the mountain, it erupts.

My new model is of how a volcano forms and erupts. Here is my revised explanation...first a mountain is formed (shown by the two arrows). One of the plates is pushed under the other and pushes magma up. When the pressure is too high, the magma is blown out of the volcano.

Original Model Score: 9

Score Difference: 2

Revised Model Score: 11

Critique:
 E3: The part that helped us to understand the process you were modeling is your explanation. The model was confusing but, with the explanation we understood it a little better. Maybe you could work out the explanation a little better so the model is easier to understand and to read. For your model you could maybe put color to represent the different parts of the model and to better explain what you are trying to teach us. It was quite sketchy so it was hard to read, but in its own way it was quite creative.

In this example the students' model represents a misconception, i.e., that a mountain is formed and fills up with lava and when it fills up, it erupts. Unfortunately, the learning partners' critique did not include much information upon which a revision could be based; this is possibly due to them not knowing what to do in the case of an "incorrect" model. In the revised model and explanation (which we assume is based on the content of the unit rather than the learning partners' critique), the students have added plate subduction and magma movement as a causal mechanism in how volcanoes are formed and have also included the concept of pressure as building up within the volcano. It is important to note that although their reasoning here is not entirely correct, intuitive conceptions such as pressure are rich, effective pieces of knowledge that can be effectively built upon (Clement, Brown, & Zietsman, 1989) and are usable anchors for developing understanding of convection (Gobert & Clement, 1994). As such the revised model represents gain in understanding.

EastWest East W PairID: 13
 CompleteID SP13G13805_5Ea
 Model Type Mountain Building

Model Picture

My model is of the creation of a fold mountain; the Appalachians were made this way. The lowest part of the green surface is called the syncline. The syncline is a downward fold in the rock. The top of the green surface is the anticline; the upward fold in the rock. Folds vary in size, some more than others. Sometimes you need a magnifying glass to see a fold clearly, while others are as big as mountains. Our fold mountain has 2 synclines and one anticline. The Appalachian mountains are made up of lots of anticlines and synclines; maybe thousands. There are too many to count.

There are also three other types of boundaries; divergent, where new crust is formed; collision boundaries where two land masses collide; and transform boundaries where two land masses slide against each other. Geological features are subduction. Subduction swallows up the ground so Earth doesn't grow. At a depth of 190-430 meters the rocks begin to melt. Some of the melted rock, now lava, goes up to the surface of ocean and creates volcanos. Most of it becomes a piece of the mantle, to reappear on the surface in a different boundary.

Original Model Score: 4 Score Difference: 10 Revised Model Score: 14
 Critique Score: 1

Critique:
 W13: We have evaluated your model. The parts that helped us to understand the process you were modeling were the labels that you had ("anticline and syncline"). We will also make the following suggestions that will help us better to understand your model. Label the colored part of your model. Put all the important labels on your model (enough for a person who hasn't learned this before to get the idea).

In this original model above (left), the students had focused on the crustal layer of the earth and had not included what happens inside the earth when mountains are formed; that is, there is no structural information or causal information about the inside of the earth. Again, this is a “local” model of plate tectonic phenomena (Gobert, 2000) because it does not include any processes or mechanisms inside the earth. In the critique that was done by their West coast partners, the learning partners requested that they label their model. The revised model includes labels (as suggested); it is also a much more detailed model, suggesting that the students learned a great deal from the content in the “What’s on your plate?” curriculum. Their new model includes the crustal layer as a “cut away” from the cross section view; it also includes convection as a causal mechanism in mountain building (in the original model there were no causal mechanisms included). The inclusion of convection as a causal mechanism, the relationship of the convection to the crustal movement and the location of the convection in the correct layers of the earth (the mantle), in their revised model represents a significant advance from their earlier model (Gobert, 2000).

EastWest East West PairID: 3 Names: _____
 CompleteID SP3G13824_5East Model Type Mountain Building

Model Picture

My model is of(name which geologic process it shows). the App. Mts. forming. Write a detailed explanation of what is happening inside Earth and on its surface. Two c.crusts are colliding together to form the App. Mts. The red box and the blue boxes are the continental crusts that are colliding together and the baby blue box is the App. Mts. forming.

My new model is of....two continental plates and mountains. Here is my revised explanation.....The two Continental plates are colliding and are forming a mountain range. The blue and the cyan are the plates colliding and the magenta is the mountains forming the red is the mantle which helps the plates move.

Original Model Score: 11

Score Difference
4

Revised Model Score: 15

3
 Critique Score

Critique:

W3: We have evaluated your model. The parts that helped us understand what you were modeling was the explanation. You could make your model more than some squares. Show the direction of movement of the plates. Instead of a birds eye view, give a cross section and show more detail.

In this example, the students' original model has two views: a cross section view, and a crustal layer view. Their model and explanation include no causal mechanisms in terms of what happens inside the earth when mountains are formed; thus, it is a local model (Gobert, 2000). In the critique from their learning partners', it was suggested that the students include the direction of movement of the plates. This is a high level comment in that it reflects that the reviewers knew that this information was important to the causality of the system being depicted. The critique also includes comments related to the model as a communication tool, i.e., they suggested that the students include a cross section view rather than a bird's eye view which is good comment regarding the model as a communication tool. The revised model includes the earth in cross section form with a cut away that includes information about the plates moving toward each other. In addition the students have added the mantle as a causal mechanism. Although not a significant advance from the point of view of including more detailed causal information, the revised model is a better model from a communication standpoint, as was requested by their learning partners.

SUMMARY & CONCLUSIONS

The purpose of the study was to effectively implement the “What’s on our plate?” curriculum into multiple middle school classrooms and investigate whether the curriculum, a rich, model-based inquiry unit could promote students’ content knowledge. We also sought to investigate whether students would be able to use what they learned about models in order to critique others’ models.

Results from the study thus suggest that students were able to achieve a deeper understanding of the domain, as evidenced by higher scores on the post-test for each of the five WISE periods. Thus, the unit appeared to foster students’ understanding of the content of the domain. Since the unit contained content knowledge as well tasks involving peer critiques, we can not state on the bases of these data what the relative contribution of the two possible causal factors, nor was the study designed for this purpose.

More analysis of the existing data is needed in order to tease out the relative contributions of the content in the unit and the learning partners’ critiques on model revision. Further data analysis is also necessary in order to characterize students’ reasoning with models as a possible index of how their understanding of models is used in situ. Additional analysis of this data (which is stored on the WISE server) will provide insight into this, in particular if those who have a very sophisticated understanding of models are also able to use this knowledge to drive their content understanding further (Gobert & Pallant, in press).

This research utilized a state-of the art science learning environment, WISE, in order to engage students from each coast of the United States in authentic and engaging tasks in which they learned why the coasts are different in terms of their geology. This unit served as an example to its student participants how science is a collaborative activity. This research on modeling fits within a current vein of science education which seeks to promote integrated understanding by use of model-based tasks. In some of these programs students are either presented with models to learn from (Raghavan & Glaser, 1995; White & Frederiksen, 1990); alternatively, they are given tasks which require them to construct their own models (Gobert, & Clement 1994, 1999; Gobert, 1999; Penner et al., 1997; Jackson, et al., 1994). In the “What’s on your plate?” curriculum, students are engaged in many authentic, model-based tasks, all of which were designed and scaffolded specifically to promote model construction and knowledge integration. Students were also scaffolded to critique their peers’ models from the opposite coast. This activity represents a novel approach to both deepening students understanding of the content (so that they may critique others’ work) as well as fostering an understanding of what models are and how they are used as learning tools. All told, the “What’s on your plate?” curriculum fostered deep content learning, as evidenced by large pre-post gain scores on both types of assessment tools. It is believed that having students construct, reason with, and critique each others’ models engages them in authentic scientific inquiry, and can significantly impact lifelong learning and scientific literacy on a broad scale (Linn & Muilenberg, 1996).

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APPENDICES

Table 1: Typical models of structure of earth by middle school students (Gobert, 2000),
Type 0= 10.6%, Type 1=89.4%

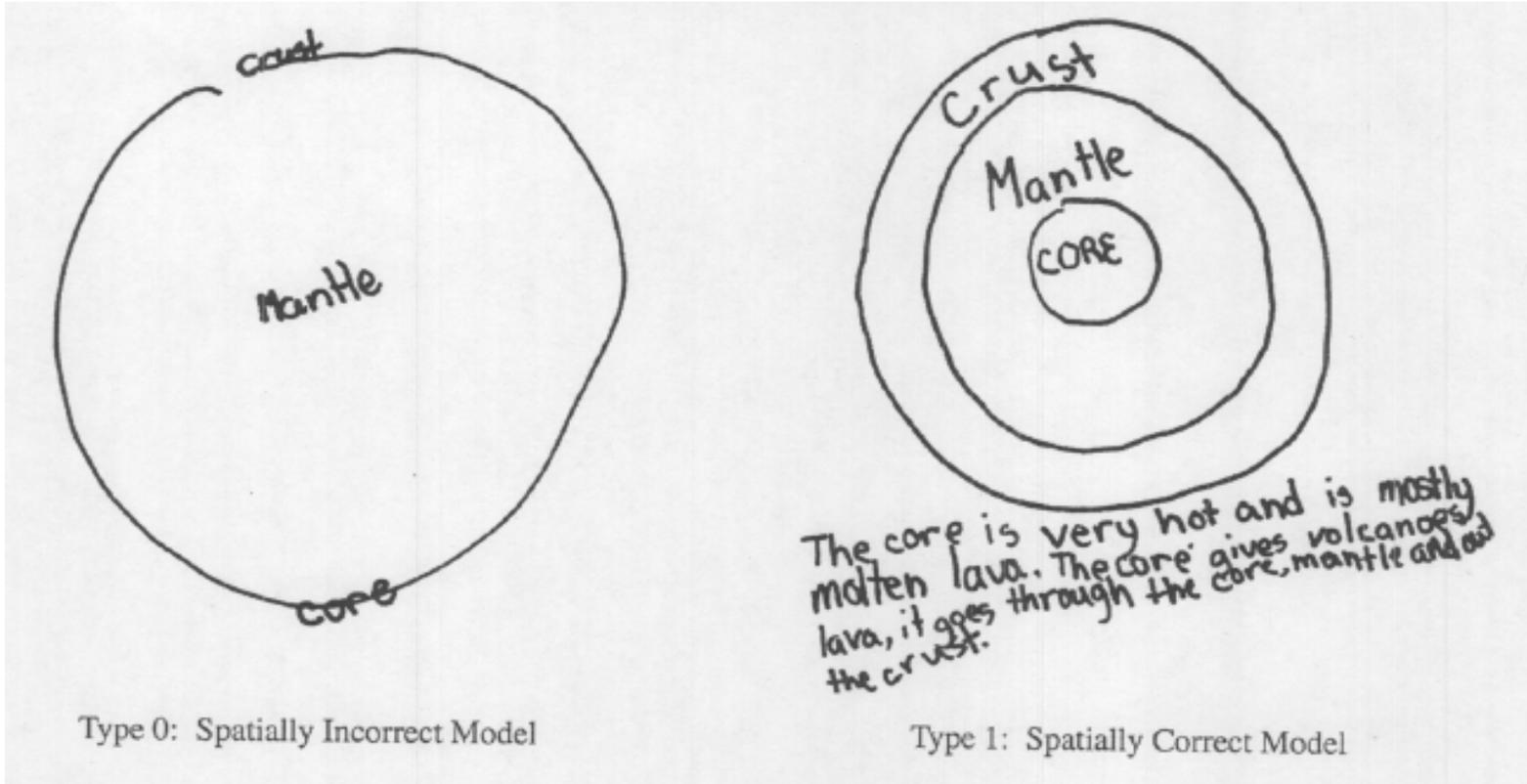
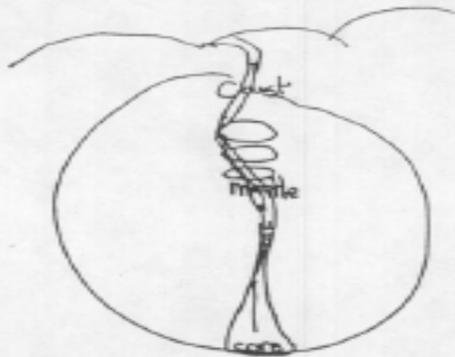
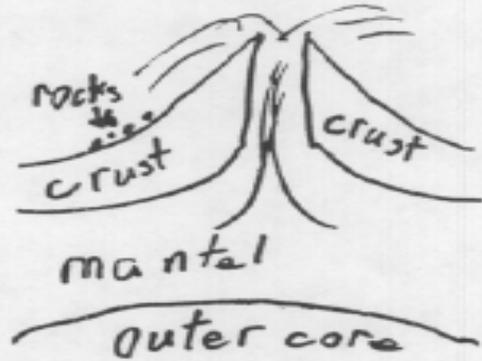


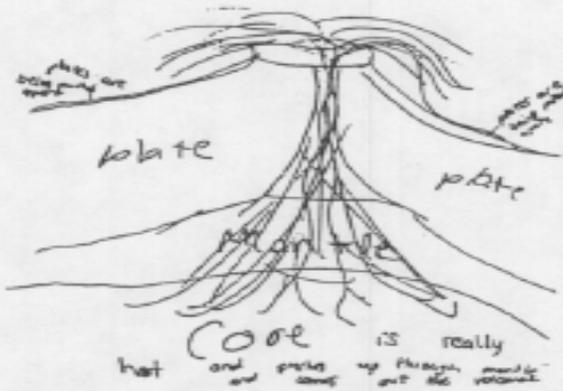
Table 2a: Typical models of volcanic eruption by middle school students (Gobert, 2000)



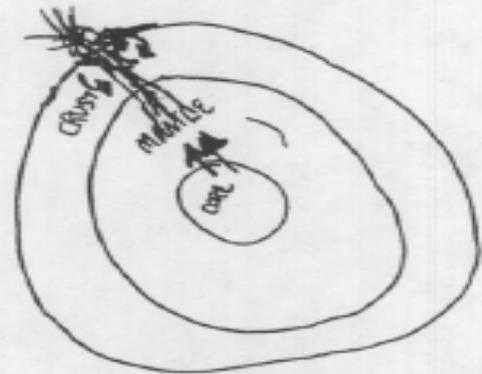
Type 1a: local 'Heat' model



Type 1b: Local 'Movement' model



Type 2: Mixed model



Type 3: Integrated model

Table 2b: Types of models of the causal and dynamic mechanisms in volcanic eruption by middle school students.

	<i>Type of Model</i>	<i>Characteristics</i>	<i>Frequency</i>	<i>Percentage</i>
TYPE 1a	Local 'Heat' Models	Heat-related mechanism(s) only; No movement-related mechanisms as causal	2	4.25%
TYPE 1b	Local 'Movement' Models	Movement-related mechanism(s) only; No heat as causal	29	61.7%
TYPE 2	Mixed Models	Few movement- and heat-related mechanisms; Notion(s) of heat and pressure	14	29.8%
TYPE 3	Integrated Models	Movement- and heat-related mechanisms; Includes heat as a causal agent	2	4.25%

Appendix B1: Statistics and Figure for Period 1 Content Gains

ANOVA Table for contentgain

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	17.231	8.615	.998	.3745	1.996	.208
Subject(Group)	61	526.577	8.632				
Category for contentgain	1	130.331	130.331	44.982	<.0001	44.982	1.000
Category for contentgain * teacher	2	22.548	11.274	3.891	.0257	7.782	.680
Category for contentgain * Subject(Group)	61	176.740	2.897				

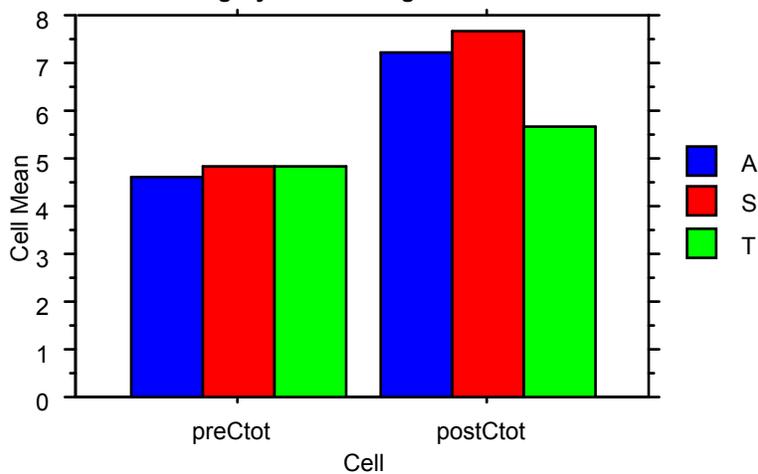
Means Table for contentgain

Effect: Category for contentgain * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preCtot	29	4.621	2.665	.495
A, postCtot	29	7.207	2.808	.521
S, preCtot	17	4.824	2.243	.544
S, postCtot	17	7.647	1.801	.437
T, preCtot	18	4.861	1.885	.444
T, postCtot	18	5.681	2.313	.545

Interaction Bar Plot for contentgain

Effect: Category for contentgain * teacher



A= Teacher A, West Coast
 S= Teacher S, East Coast
 T= Teacher T, East Coast

Fisher's PLSD for contentgain

Effect: teacher

Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value
A, S	-.322	1.130	.5745
A, T	.643	1.110	.2540
S, T	.964	1.252	.1298

Appendix B2: Statistics and Figure for Period 2 Content Gains

ANOVA Table for content gain

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	102.229	51.114	3.946	.0246	7.891	.687
Subject(Group)	60	777.298	12.955				
Category for content gain	1	115.695	115.695	39.473	<.0001	39.473	1.000
Category for content gain * teacher	2	38.791	19.396	6.617	.0025	13.235	.911
Category for content gain * Subject(Group)	60	175.860	2.931				

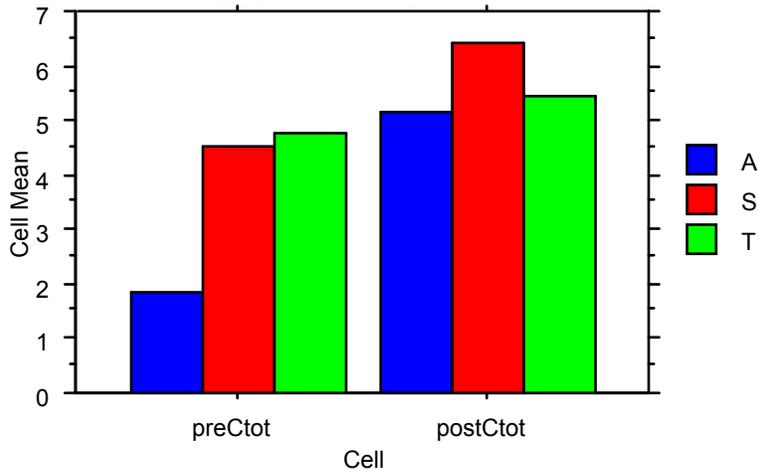
Means Table for content gain

Effect: Category for content gain * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preCtot	29	1.828	1.649	.306
A, postCtot	29	5.172	2.550	.474
S, preCtot	17	4.529	3.243	.786
S, postCtot	17	6.412	3.641	.883
T, preCtot	17	4.750	3.077	.746
T, postCtot	17	5.456	3.192	.774

Interaction Bar Plot for content gain

Effect: Category for content gain * teacher



A= Teacher A, West Coast
 S= Teacher S, East Coast
 T= Teacher T, East Coast

Fisher's PLSD for content gain

Effect: teacher

Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value	
A, S	-1.971	1.307	.0034	S
A, T	-1.603	1.307	.0167	S
S, T	.368	1.468	.6209	

Appendix B3: Statistics and Figure for Period 3 Content Gains

ANOVA Table for contentgain

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	60.752	30.376	2.525	.0883	5.050	.476
Subject(Group)	62	745.837	12.030				
Category for contentgain	1	85.178	85.178	26.654	<.0001	26.654	1.000
Category for contentgain * teacher	2	98.937	49.469	15.480	<.0001	30.960	1.000
Category for contentgain * Subject(Group)	62	198.133	3.196				

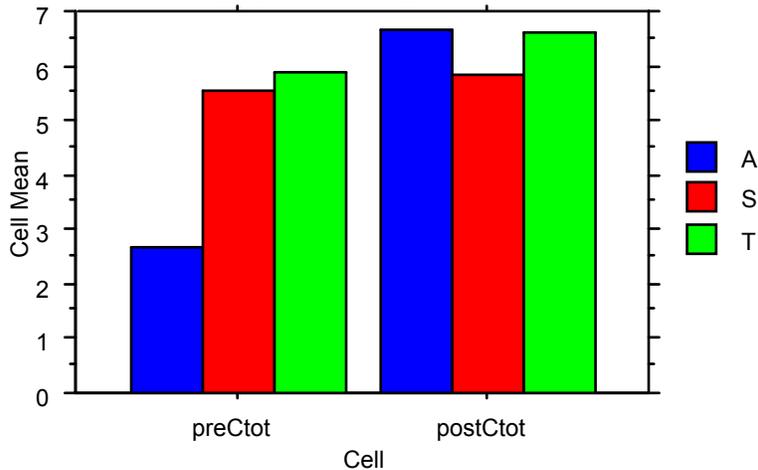
Means Table for contentgain

Effect: Category for contentgain * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preCtot	30	2.667	2.264	.413
A, postCtot	30	6.667	3.066	.560
S, preCtot	17	5.529	3.085	.748
S, postCtot	17	5.824	2.811	.682
T, preCtot	18	5.889	2.530	.596
T, postCtot	18	6.611	2.820	.665

Interaction Bar Plot for contentgain

Effect: Category for contentgain * teacher



A= Teacher A, West Coast
 S= Teacher S, East Coast
 T= Teacher T, East Coast

Fisher's PLSD for contentgain

Effect: teacher

Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value
A, S	-1.010	1.300	.1267
A, T	-1.583	1.277	.0155
S, T	-.574	1.448	.4347

Appendix B4: Statistics and Figure for Period 4 Content Gains

ANOVA Table for contentchange

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	97.656	48.828	3.898	.0254	7.796	.682
Subject(Group)	62	776.675	12.527				
Category for contentchange	1	130.942	130.942	25.019	<.0001	25.019	1.000
Category for contentchange * teacher	2	59.218	29.609	5.657	.0055	11.315	.855
Category for contentchange * Subject(Group)	62	324.487	5.234				

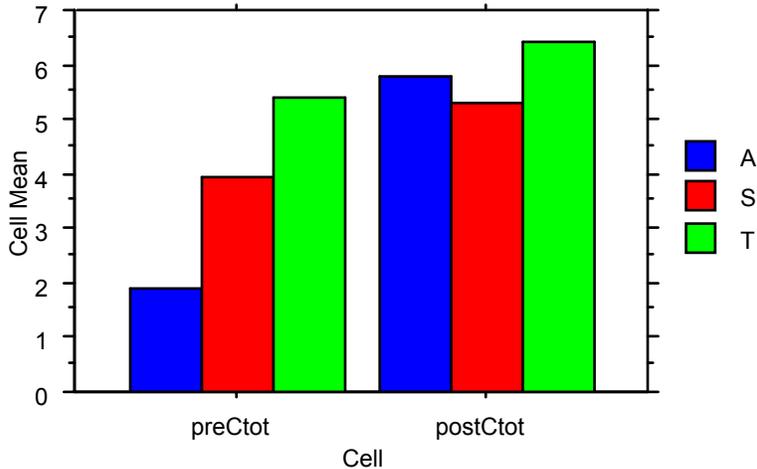
Means Table for contentchange

Effect: Category for contentchange * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preCtot	30	1.900	2.383	.435
A, postCtot	30	5.767	3.626	.662
S, preCtot	17	3.941	2.461	.597
S, postCtot	17	5.294	3.788	.919
T, preCtot	18	5.417	2.680	.632
T, postCtot	18	6.417	2.503	.590

Interaction Bar Plot for contentchange

Effect: Category for contentchange * teacher



A= Teacher A, West Coast
S= Teacher S, East Coast
T= Teacher T, East Coast

Fisher's PLSD for contentchange

Effect: teacher

Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value
A, S	-.784	1.385	.2645
A, T	-2.083	1.360	.0030
S, T	-1.299	1.543	.0982

S

Appendix B5: Statistics and Figure for Period 5 Content Gains

ANOVA Table for contentchange

	DF	Sum of Squares	Mean Square	F-Value	P-Value	Lambda	Power
teacher	2	256.450	128.225	13.509	<.0001	27.018	.999
Subject(Group)	60	569.514	9.492				
Category for contentchange	1	82.505	82.505	18.220	<.0001	18.220	.994
Category for contentchange * teacher	2	107.916	53.958	11.916	<.0001	23.832	.997
Category for contentchange * Subject(Group)	60	271.692	4.528				

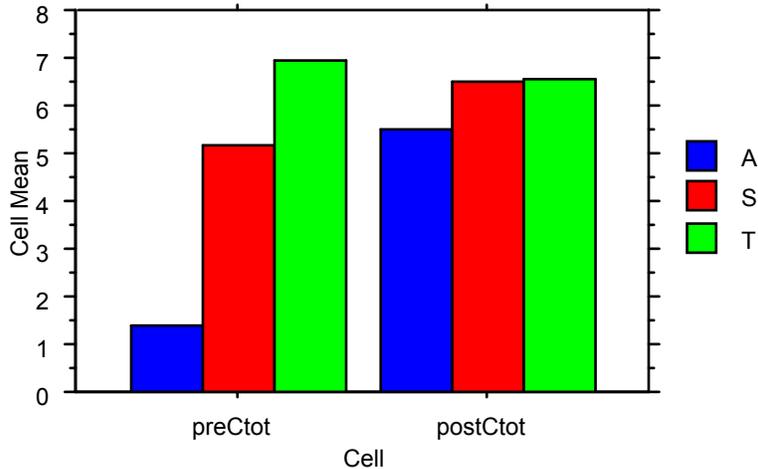
Means Table for contentchange

Effect: Category for contentchange * teacher

	Count	Mean	Std. Dev.	Std. Err.
A, preCtot	29	1.414	1.376	.256
A, postCtot	29	5.483	3.043	.565
S, preCtot	19	5.158	2.873	.659
S, postCtot	19	6.526	2.796	.641
T, preCtot	15	6.933	3.644	.941
T, postCtot	15	6.533	1.959	.506

Interaction Bar Plot for contentchange

Effect: Category for contentchange * teacher



A= Teacher A, West Coast
 S= Teacher S, East Coast
 T= Teacher T, East Coast

Fisher's PLSD for contentchange

Effect: teacher

Significance Level: 5 %

	Mean Diff.	Crit. Diff.	P-Value	
A, S	-2.394	1.236	.0002	S
A, T	-3.285	1.331	<.0001	S
S, T	-.891	1.446	.2248	

Some examples of my past, present, and future use of visualization in teaching (and research) in the Geosciences

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To me it would seem strange *to not* use visualizations in teaching. When I recall my days as a student, especially in mineralogy and structural geology, I was constantly building models. I built them mainly of toothpicks and clay to help me visualize the 3D relationships I was trying to learn in those classes. As a professor, this trend has shifted to me using those same sorts of real, as well as virtual (i.e., computer generated), models in my teaching. Over the past 15 years I've made extensive use of these "models" in teaching intro physical geology (Geol 101), a large lecture class with approximately 400 students, and in my mineralogy and optical mineralogy course with approximately 20 students.

When I first started teaching Geol 101 in 1989 I struggled for an organizational style to the present the material in the large lecture setting. At that time PowerPoint version 1.0 for the Mac was just released, so I used it to make overheads to present the material. However, I only put 10-20% of the material on the overhead – the rest I hand-wrote in real-time during class. (A pdf version of these notes can be found at www.webpages.uidaho.edu/~mgunter/geol101/notes/notes.html.) This seemed well received by the students then, and even more so now. I resist the current trend of placing all the material in PowerPoint and then using a computer projection system during class for static images. However, I developed computer animations in the early 1990's and used a black and white (not even grayscale!) LCD projection panel to show them in class. With time, I've evolved to a grayscale and then color LCD projection panels and finally the stand-alone projection systems. Gunter (1991) details early use of computer demonstrations and Gunter (1993) discusses how to integrate several methods, including visualizations, into teaching the large intro classes.

Along with the standard sort of visualizations used in the intro class, I started using concept maps (even though I had no idea they had a name!) as a visual method to introduce the linkages of different science disciplines. For instance, Figure 1 shows a concept map illustrating how geology is broken into different subdisciplines and, in turn, how one of those subdisciplines, mineralogy, is further linked to other areas outside the field of geology. This figure originally was presented in Gunter (1993). Figure 2 is another example of a concept map that shows some visual links for minerals; it's taken from Dyar et al. (2004) where we discuss several new methods for teaching mineralogy. A static concept map can also be dynamically hyperlinked to other maps, for examples see www.webpages.uidaho.edu/~mgunter/NAGT/vis.html.

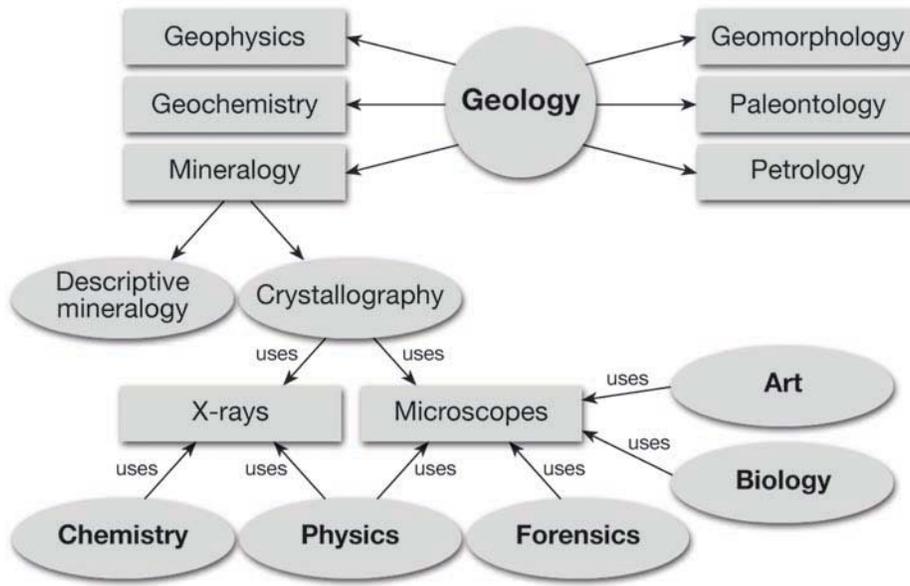


Figure 1: A concept map showing linkages of geology and mineralogy. (From Dyar et al. 2004.)

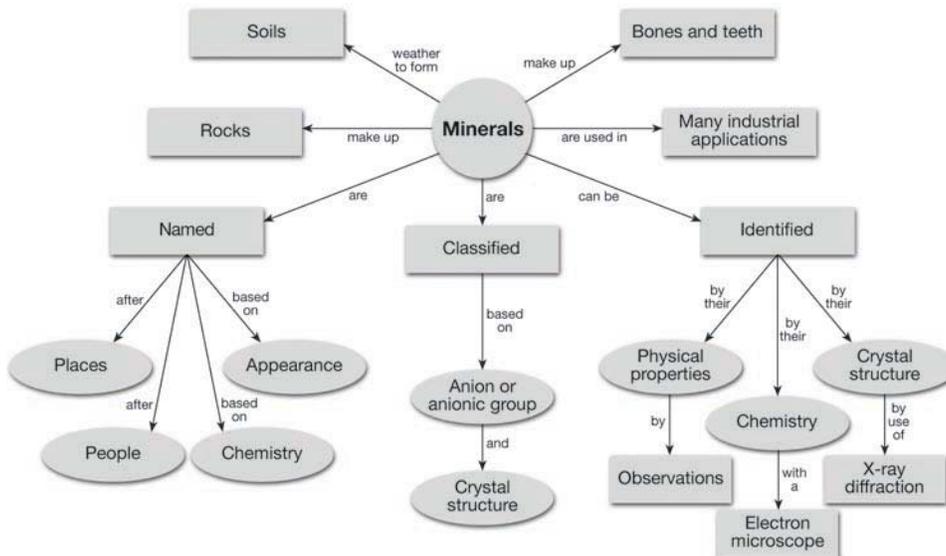


Figure 2: A concept map showing some of the basic linkages of minerals. (From Dyar et al. 2004.)

Currently my main teaching and research efforts are in mineralogy and optical mineralogy; it's really impossible for me to separate by teaching and research components. I am working in collaboration with Darby Dyar and Dennis Tasa on a new mineralogy and optical mineralogy textbook which will also contain animations of all of the images on an included DVD. A basic understanding of the crystal structures of materials is crucial in understanding mineralogy, thus we plan on having 100's of crystal structure drawings in the book and animations on the DVD. In the "old days" it was very time consuming to make such drawings, one drawing might take several hours, and

animations would be impossible. Back then we built 3D ball and spoke models as useful teaching and research aids, but it was even more time consuming to make these models, often taking several days to build one model (Gunter and Downs 1991). The ease of making animations of crystal structures should greatly aid in student's understanding of mineralogy. Figure 3 shows an example drawing of a zeolite before and after cation exchange. There are some examples of animated drawings at www.webpages.uidaho.edu/~mgunter/NAGT/vis.html.

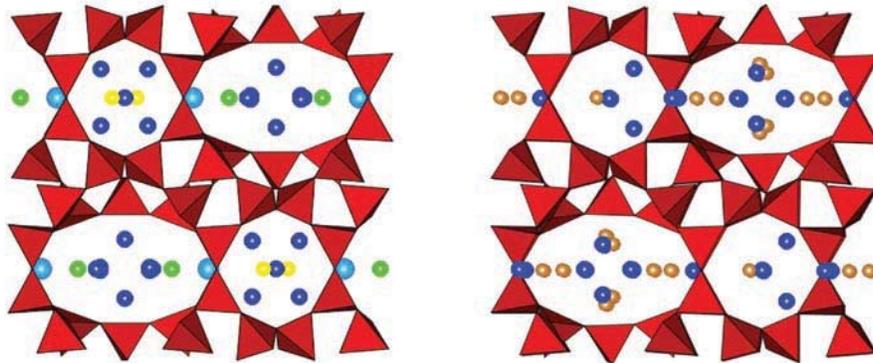


Figure 3: Example drawings of crystal structures of minerals. (left) A natural zeolite and (right) a Pb-exchanged zeolite. The red pyramids represent the tetrahedral framework and the small spheres are the cations and water molecules in the channels. Only by viewing the structure can one visualize the channels in these industrially important minerals. (Modified from Gunter et al. 1994.)

My major research interest still remains in interpretation of the optical properties of minerals, and probably less so with routine mineral identification as done in thin sections. Figure 4 below shows a very useful example of “interpretations.” During Pb-exchange experiments we found (Gunter et al. 1994) that the retardation of a zeolite increased drastically. We then used this method to visually determine the migration of Pb into the material with the aid of a polarizing light microscope (PLM). Given this observation, we could determine the diffusion coefficient for Pb, and several other cations.

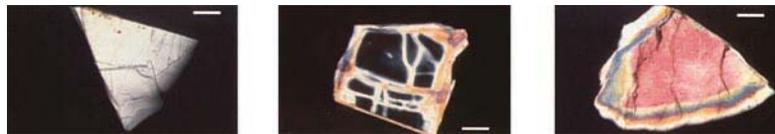


Figure 4: Photomicrographs of a natural (left), partially Pb-exchanged (middle), and fully Pb-exchanged zeolite (right). The changes in the retardation are directly related to the Pb content, thus chemistry can be mapped “visually.” (Scale bars are 100 μm , modified from Gunter et al. 1994.)

To aid in the understanding of the orientational dependence of the physical properties of minerals, I've made extensive use of the spindle stage (Gunter 2004), and then correlate these properties to their crystal structures. Also, use of the spindle stage is a major aid to show how optical properties change as a function of orientation (Gunter 1997). (Examples of this are at www.webpages.uidaho.edu/~mgunter/NAGT/vis.html.) The

spindle stage and the PLM are also the main tools for studying morphology of minerals, used mainly for asbestos minerals (Gunter 2004). For instance, an amphibole is considered as asbestos based on a “fibrous” morphology, and the best method to judge this morphology is by visual observations with the PLM (Brown and Gunter 2003). These methods can also be extended to 3D views of samples with an SEM (Bandli and Gunter 2001). Interestingly, as show in Figure 5, there is a gradation between non-asbestos amphibole (right side of grain) and asbestos amphibole (left side of grain). Again, the visualization of the image is the only way to distinguish these different morphologies.

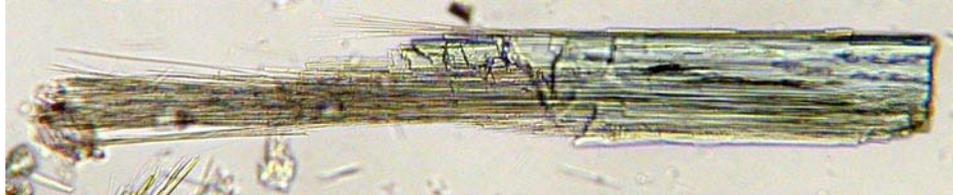


Figure 5: A single particle of amphibole (approximately 500 μm in length) as viewed in an immersion mount with the PLM. The left side of the grain would be considered asbestos based on its morphology, while the right side is non-asbestos. (Modified from Gunter 2004.)

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MICRODEM: GIS & Mapping Visualization



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Introduction

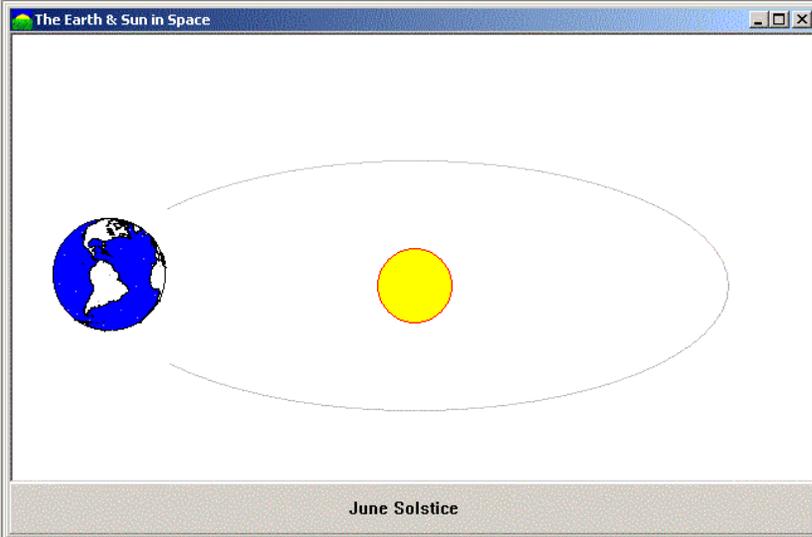
My background began as a structural geologist/field mapper, but for 15 years I've taught in an [oceanography department](#) at an undergraduate institution. Before that I spent three years in a department of geography and computer science, where I began my work in computer graphics and mapping. My research has centered around the MICRODEM GIS program, which has been evolving since 1984 (Guth and others, 1987). This program has been particularly strong in military GIS (it forms the basis of the Army's TerraBase II) and geologic applications (Guth, 1988), and has been applied to a number of other applications: spatial analysis of DEM error (Guth, 1992), slope and aspect algorithms (Guth, 1995), contour line ghosts in DEMs derived from digitized contour lines (Guth, 1999), eigenvector extraction of terrain fabric (Guth, 2001, 2003), and the computational parameters of the line-of-sight algorithm (Guth, 2003, 2004). The engine has also been used for web delivery of terrain visualizations (Thibaud and others, 2002; Guth and others, 2003).

From the start MICRODEM emphasized a simple, graphical interface. It now consists of about 220,000 lines of Delphi source code. While the military supplied much of the impetus and funding for the program, it has always maintained a strong earth science focus. In addition to MICRODEM, this essay will include examples from a number of visualization programs I have written for teaching oceanography. These share code and techniques with MICRODEM. All the programs use Borland's Delphi and run on the Windows platform. My bias leans toward software development used in teaching and my research.

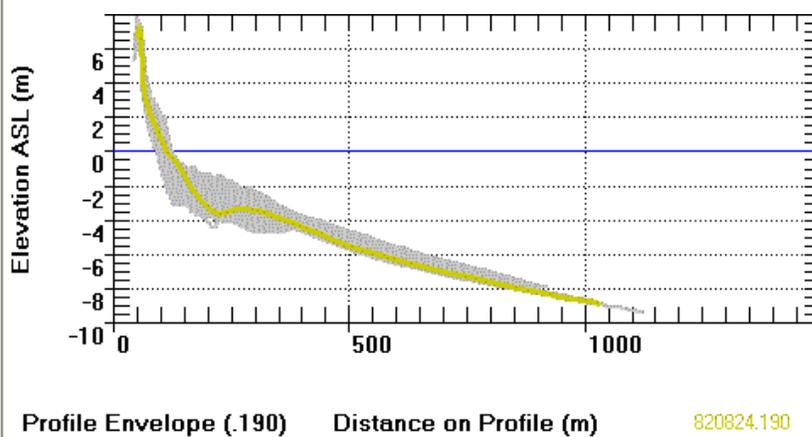
This essay borrows from Guth (1997). It shows a number of animations from lab programs I have written, to demonstrate graphically how computer graphics can bring the earth sciences to life. The animations shown here

use lower graphic and color resolution for improved download over the WWW; they run significantly better on a local PC. Local usage also allows student interactions and manipulation of the parameters of the animations.

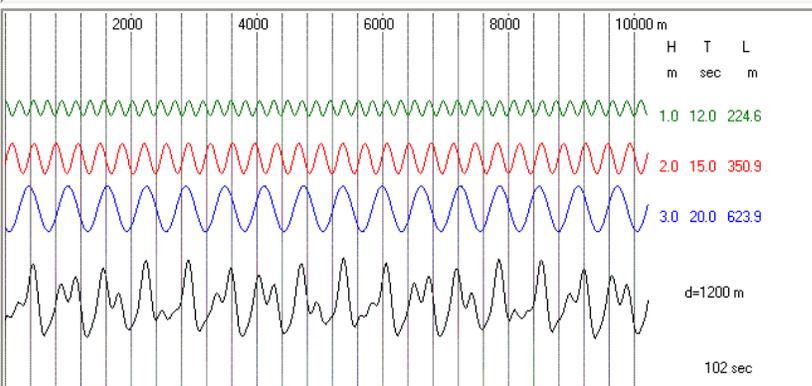
Role of Animations and Visualizations -- Visualization Examples Index



Tell Stories: this type of visualization depicts a relationship. With an animation, it can show how the relationship changes over time. This extract from the annual cycle shows the relationship between earth tilt and the June solistice ([Seasons & Climate](#)).



Explore and Understand Data: this type of visualization offer students the chance to manipulate and view complex data sets. Time series in the earth sciences provide one good example of this type of visualization. The diagram at the show shows an extract from over 250 profiles measured from the dunes and across the longshore bars at Duck, North Carolina. ([Beach Profiles](#)) While this may be similar to story telling, data exploration allows students to change the display, select parameters, and observe the changes.



Animate an Equation: this animation shows the relationship between wave period, speed, and water depth, and their affect on the [wave group's speed](#). Students can adjust the various parameters used in the equation, and see how they affect the results.

GIS

GIS relates data and maps. Any data that has a geographic component--essentially all of the earth sciences--benefits from GIS. The power of GIS lies in the ability to filter and query the data--restrict what will be displayed based on any criteria of interest, and to go rapidly from the map to the data. Furthermore, interactions with the GIS can occur graphically on the map

Microcomputer Labs

A well-designed computer lab serves five teaching goals. First and foremost, a lab should teach or reinforce key concepts from lecture. A lab that does not advance one of the course's major objectives should not be used. Secondly, labs can show the variability in nature. Textbooks and lectures usually employ "cartoon" figures and diagrams that show an idealized version of nature. Computer manipulation of actual data lets students see a variety of examples and develop an appreciation for how well the model fits the messy reality of nature. Third, the computer should encourage critical thinking and problem solving. Open-ended problems rather than cook book procedures force students to think about how they will use the computer as a tool to answer the question. Fourth, the lab will reinforce computer skills, something students will need in a technological world. Finally, the computer can reinforce writing across the curriculum because it removes the tedium from data analysis and visualization and lets students concentrate on understanding the processes involved and putting that understanding into words.

In designing my labs, I try to incorporate three fundamentals: avoid cookbook style exercises, maximize self-directed inquiry and problem solving, and provide hands-on and minds-on activities. I seek to provide a program that offers a set of tools to analyze data or a problem, and let the students decide which approach to use to answer a set of questions. Usually multiple approaches will work, because earth science data sets are typically multidimensional. As an example, the analysis of temperature in the Pacific Ocean becomes a five dimensional problem (latitude, longitude, depth, time, and temperature values) and we can easily display no more than two or three at a time. Students must learn the different ways earth scientists use to study such a problem, using map or profile views, colors, or contour lines.

Custom Programming

A good custom program requires a large commitment in time, effort, and maintenance. The learning curve to become proficient in programming, especially with event driven Windows programs, can be very steep. I have been programming almost as long as MS-DOS and Windows computers have been available, and have incrementally been upgrading the programs. When I started there was no educational software for the earth sciences, and there are still no commercial programs available for many of these functions. The available programs often prove less than fully satisfactory. Custom software can maximize the hardware capabilities in our labs and that our students have in their rooms.

Windows provides a common look and feel to programs, so that students can anticipate what to do (watching students use the program will often suggest better ways to handle the user interface). Each program has an integrated help file, and in addition to providing context sensitive help on demand, the help files offer hypertext instruction complete with graphics, indexes, and jumps to related topics. Window allows support for hardware,

especially printers; common tools like text and graphics editors; and easy export of graphic files to other programs.

MICRODEM GIS

MICRODEM can be [downloaded from the WWW](#). The [help file](#) is about 15 MB in size, and contains a number of tutorials, exercises, and graphics demonstrating the capabilities of the program. A [Delphi forum](#) provides user support.

GIS Alternatives

Alternatives to MICRODEM include [GMT](#) (Wessel and Smith, 1991, 1998) or commercial software like [ArcView from ESRI](#). While GMT remains a research standard in the geophysical community, its UNIX heritage with a command line and complex parameters does not work well for students. GMT is free. Other workers (Hall-Wallace and McAuliffe, 2002; [Saguaro Project](#)) have chosen to work within the confines of commercial ESRI software, which imposes a cost in both dollars and learning the complex interface. In addition, while ESRI software can be enhanced by the end user, it will never be as easy to customize for geoscience applications as MICRODEM.

Web GIS

I've also done some work with delivery of GIS graphics over the internet. There are a number of issues with this approach:

- IT organizations are not comfortable with the security issues of individual faculty running CGI programs with database access and reading and writing of files on the servers. From the IT organization perspective, it doesn't really matter whether you want to try to set this up on their hardware, or your hardware connected to their network.
- Most commercial web servers also will not let you run this type of application on their hardware; you will probably require a dedicated system.
- The large data files required for GIS operations have large download times, and in most cases I think local programs will provide the best response times for students. Many of the labs I use require several 100 MB of data files. As a one time download this is reasonable, and the response time thereafter is very fast.
- The user interface for a web application is much more limited than a Windows program, and porting the user interface to the web produces a large part of the required effort.

See Guth and others (2004) for an [description of web delivered GIS](#). You may also be able to run a [live web demonstration involving the location of forest fires](#) (this site is generally open for testing, but you should read the disclaimers). Both of these applications use the mapping and GIS core from MICRODEM.

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Presentation for "Teaching Geoscience with Visualizations: Using Images, Animations, and Models Effectively"
Carleton College, Northfield, MN, 26-28 Feb 2004

Last revision 2/18/2004

Visualize Venus

Vicki L. Hansen, Department of Geological Sciences, University of Minnesota Duluth

I use 3D visualization of radar and altimetry data for research and teaching aimed at understanding evolution of Venus, the major surface processes, and related geodynamical processes—in short, how Earth's sister planet gets rid of heat, currently, and how she had done so through time. 3D images are constructed using data from NASA's Magellan Mission. For a limited portion of the planet true stereo images (red-blue anaglyphs) can be constructed using different cycle radar data with varied illumination direction (e.g., Plaut 1993); for the rest of the planet we can construct synthetic stereo images (Kirk et al. 1992), which are lower resolution, yet cover immense areas of the planet allowing one essentially endless, free, helicopter time in this fantastic terrestrial world.

Venus is about the same size and density as Earth, was formed at the same time (a Thursday afternoon some 4.6 billion years ago), and resides at a similar distance from the Sun. And like Earth, Venus cools over time—that is, internal heat must escape. So the big question is: how does Venus cool—how does she get rid of her heat? Since Venus is devoid of water, sediments, and life (at least as far as we know), which on Earth mask evidence of heat escape processes, the cooling process should be evident. Earth currently cools through plate tectonic processes; Magellan mission data clearly indicate that Venus does not! Like many siblings, Venus followed a very different evolutionary path than Earth; the fun is to try and understand the path and contributing processes. But after more than ten years of study using data from NASA's Magellan orbiter mission Venus still holds many of her secrets, including the age of her crust and surface features, and the processes by which the majority of heat escapes to the surface.

Venus' current physical environment is also very different from Earth's current physical environment; Venus is hot (~500 °C), ultra dry (inside and out!), acidic, hosts surfaces of endless basalt and no granite so far as we know, and her CO₂-rich atmosphere has a density similar to Earth's oceans (~100 bars at the surface!). Thus Venus presents a wonderful playground for geological research—it is a rheological and tectonic laboratory beyond imagination. Venus also presents a wonderful playground for science talks at all levels of discovery.

Synthetic stereo radar images are not only the single most critical research tool for our work, they are also the single most exciting communication and teaching tool. From a research standpoint, synthetic stereo anaglyphs allow us to merge data constraints from radar backscatter (which basically indicates surface roughness and/or surface orientation) with topographic relief. Thanks to the NASA Magellan mission, and basic off the shelf software (and a talented graduate student who wrote nifty macros) we can produce stereo or synthetic stereo images for ninety-eight percent of Venus' incredible surface. Images are constructed using Magellan SAR (Synthetic Aperture Radar) data (available at NASA's PDS MAP-A-PLANET web site: <http://pdsmaps.wr.usgs.gov/maps.html>), and Magellan altimetry data. We now have at UMD the entire planet in synthetic stereo imagery (about 60 plus gigabytes of imagery). From a talk/presentation/teaching standpoint these images provide the single most critical aspect for talks at all levels, and with a wide range of goals. Stereo radar imagery allows the audience to directly participate in the discovery of Venus processes. Fundamentally every time I give a talk or lecture I hope to have the audience come away with a better understand of the scientific

process, information or a story about some particular topic or region, and most important perhaps, the joy of discovery or of understanding the beauty of logical thought. Visual images provide a wonderful tool toward achieving these goals.

Puzzling about Venus evolution, Venus tectonics, Venus volcanism, how Venus might work are fantastic topics because we know so very little; perhaps it this general lack of knowledge that allows essentially all people the freedom to explore and discover processes that might have contributed to this planet's evolution. (One can hardly get down on his/herself or others for not knowing what this foreign planet is like, or how it works). As the audience, young to old, 'educated' or not, dons the fashionable red-blue glasses, they are transported to an imaginative world of discovery; they see 3D pictures that are recognizable, yet fantastic—almost magical. With a few ground rules of radar, chemistry, physics, and geology, dependent on audience expertise (or perceived expertise!) and goals of the particular talk, the audience immediately becomes explorers. Donning red-blue 3-D glasses, we can all digitally 'fly' above the surface and gaze down to the remarkable landscapes below. Flights reveal incredible views of surface folds, cracks, faults, fractures, lava flows, and impact craters that dwarf any such features on Earth. The patterns and interaction of features tell stories, and beg questions. Long, periodic ribbon-like ridges and troughs preserve a record of an ancient time when there was thin crust everywhere. Thin global crust led to increased volcanic activity and surface temperatures of roughly 1000 K (1340° Fahrenheit), insulated by thick volcanic greenhouse gases. Deep mantle plumes likely rose and interacted with the surface leaving evidence of their calling as well as evidence of thin, globally extensive crust. As Venus cooled internally over time, the crust thickened, thereby decreasing the levels of volcanism and greenhouse gases, leading as well to cooler surface conditions. Deep mantle plumes that rose to interact with this surface left a very different signature.

Once given a problem (or allowed to discover one on their own) the audience is off and running. The audience makes the observations, either guided or not (again, dependent in-part on overarching goals), and begins to assemble stories of how the scenes they observe came to be. All scientists that I know love their work because of the joy of discovery—facts mean little, discovery is everything. Visualizations, and 3D visualizations in particular, allow an audience to feel directly part of the discovery. Synthetic stereo radar images transport the audience (comfortably) to Venus hot, dry, acidic, high-pressure surface. The landscape is familiar enough to allow them to ask question, make critical observations, and assembly sequences of events, yet it is foreign enough to allow them complete freedom from preconceptions, and even their own egos. Curiously most of my talks bring the audience back to thinking about the earth, and how it works as a planet, and thus just as travels to other lands cause us to reflect on our world, forays to Venus cause students and the general public to see their own planet in a new light. I am convinced that the magic of Venus results from the visual images because people can immediately interact with the data sets, bringing their own experience (and questions and observations) to the table; they are an integral part of the exploration process; for my money, this is how we all really learn, and get excited about new worlds. Without visualization Venus research, and communication of Venus research would be a cold, dry, world with little atmosphere.

My Attempts to Use Maps (and Help Students use Maps) as a Tool For Visualizing, Synthesizing, Capturing and Conveying Information about the Earth

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Background essay for the workshop on *Teaching Geoscience with Visualizations*

I have chosen to center my essay and my talk around maps. Maps were the earliest technology humans developed to visualize portions of the Earth that were too big to see from a single vantage point. Geoscientists use maps to organize, record and convey information about the Earth—today’s Earth, as well as hypothesized ancient Earths, and forecast future Earths.

From 1975 through 1993, I was a sea-going marine geologist. That means I went to sea and made maps of the bottom of the ocean, and then tried to figure out the sedimentary and tectonic processes that caused the mapped seafloor to be the way it was. I made observational maps: bathymetric maps, maps of sediment type, fault distribution, and seafloor bedforms. I made interpretive maps, showing, for example, tectonic processes at various moments in a region’s geological history. I published maps of portions of Long Island Sound, the Tamayo Transform Faulty, the Clipperton Fracture Zone, the Siqueiros Transform Fault, the Vema Fracture Zone, the Mississippi Fan, the Ebro Fan, and the Mediterranean Ridge. I used maps to reveal places that no human eye had ever seen. I lived and breathed maps. Maps made me feel close to the secrets of the universe.

In 1991, I began to co-teach Planet Earth, a course for non-science majors at Columbia and Barnard Colleges. I noticed that maps, which were such a powerful tool for me to organize my own understanding of the Earth and convey my insights to my colleagues, had no such power for many of my students. Most were not adept at extracting insights from maps, and were completely inexperienced at using maps to organize and convey information. Some were shaky on the difference between a map and a profile; when asked to draw a profile, some would draw a map, and vice versa. When asked to sketch and label a map of the Earth’s oceans and continents from memory¹, many students left out whole continents, or misplaced continents in the wrong hemisphere.

¹ This exercise was developed by the originator of the Columbia Planet Earth course, Roger N. Anderson, who used it on the first day of class. It proved to be an excellent predictor of performance in the course.

Beginning around 1993, I became fascinated by the power of instructional technology. I had an opportunity, in collaboration with Columbia's Institute for Learning Technology (ILT), to apply for some seed-money funding to create an educational software application using a new authoring tool. I saw an opportunity to go from admirer and user of this new technology to creator. The only condition was that the application had to be for K-12 education. I asked myself how the K-12 education system had failed my undergraduate students. I came back to maps: too many of my students had passed through the K-12 educational system without learning how to use maps in any but the most simplistic fashion.

I tried to figure out what was wrong with how my students had been exposed to maps in their pre-college education. I noticed that most map-skills curriculum material for elementary schools did not require the student to "translate" between the map and the real world. In fact, many of the exercises could be done entirely in the frame of reference of the map, without thinking about the real world at all.

So, with colleagues at ILT, I designed and authored a prototype version of the *Where are We?* software (Kastens et al, 1996) and associated lessons. The goal was to set up situations in which the student would have to translate back and forth between the intricate, horizontally-viewed, constantly-changing view that you see as you stand in a terrain, and the schematic, vertically-viewed, unchanging view of the map of the same terrain. *Where are We?* shows a map of a park on one side of the screen, and video filmed within the park on the other side. Students can "move" through the park by clicking "turn left", "turn right" or "move forward" buttons at each intersection. The video responds appropriately. Users can interact with the software in four modes: In *Exploring the Park*, a red dot and arrow on the map indicate the user's position and view direction, moving and rotating as one steers a route through the environment. The red dot plays the role of the finger of a parent or other mentor, who shows a child her location on a map during a walk. *Are We There Yet?* simulates the most common real world map task: using a map to find one's way from a known starting point to a desired destination. In *Lost!*, students are "dropped" at an unknown location on the map, and must figure out where they are from the information in the video. Colleagues from my marine geology days are amused to note that *Lost!* was based on my experience diving in the submersible *Alvin* in places without good transponder navigation. *Add to the Map* introduces maps as a tool for organizing information spatially, and is analogous to field-mapping tasks undertaken by geologists, hydrologists, ecologists, and other field scientists. After much refinement, *Where are We?* was published commercially (Kastens, 2000) and is now in use in schools across the country.

Although it was thrilling to watch children using *Where are We?*, and both teachers and students seemed excited about using the software, I found myself wondering what students were actually learning from *Where are We?* With no idea how difficult it is to do good educational research, I plunged into an attempt to find out. Working with an insightful 4th grade teacher, Kottie Christy-Blick, I developed a set of outdoor map skills tests to evaluate whether the skills children are learning from "*WAW?*" transfer to real-world situations. In the "world-to-map" test, we place colored flags around the Lamont-Doherty campus, and give students a paper map and colored stickers. Their task is to place each sticker on the map at the point corresponding to the similarly colored

flag. In the "map-to-world" test, each child is given a paper map with numbered stickers on it, and matching numbered dinner-plate-sized markers. Their task is to place the markers in the real world at the point corresponding to the stickers on their map. Just as "WAW?" is designed to exercise students' ability to go from the visually-perceived real world to the map and vice versa, our field-based tests are designed to test translation skills in both directions. Our early trials showed that average scores of WAW?-users improved on all of the scoring categories on both the world-to-map and map-to-world tests between pre-test and post-test (Kastens et al, 2001).

However, when we looked at individual students, we found huge student to student variation: some improved enormously, some not at all, and a few got worse. I was at a loss to say why "Where are We?" worked so well for some students but not for others. I was mystified about what could be going on in the minds of the students who put answers that seemed completely nonsensical to me (for example, putting a sticker on the map lawn to indicate the location of a flag that was on a building.) Fortunately, I found a collaborator with extensive expertise in the developmental psychology of how children acquire map skills: Lynn Liben of Penn State's Psychology department. Liben and I are now using extended versions of the field-based tests of map skills, plus classroom assessments, to dig into the relationship between children's spatial skills and their performance on the real-world map tasks, and the nature and causes of children's mistakes as they use maps (Liben et al, 2002, Kastens et al, 2004).

I have recently started one other project on how people understand maps. This project is a collaboration with posdoc Toru Ishikawa, Chet Ropelewski and Tony Barnston of the International Research Institute for Climate Prediction (IRI) and Pat Louchouart of the Environmental Policy program at Columbia's School of International and Policy Affairs. IRI produces forecasts of air temperature and precipitation three months into the future. Their mission includes disseminating their forecast results to decision-makers around the world for use in agricultural and land-use planning, and other societally-important purposes. The forecasts are disseminated in the form of maps, probability maps. Our project began by asking: how well do these maps communicate with the intended audience? In a pilot project (Ishikawa et al, 2003), we showed maps of forecast and actual precipitation to students in Columbia's masters degree program in environmental policy. We asked a series of questions designed to assess how well they understood the map, and found that many students misinterpreted the more subtle aspects of the maps. We also asked students to evaluate how well the forecast precip agreed with the actual precip for that same region and time interval, and to indicate how likely they would be to recommend that the forecasts be used in agricultural decision making. This last set of questions has impressed on me the importance of distinguishing between how well map-users *understand* a map and how much they *believe* the map.

In closing, I notice that one of the other essay-writers (Gunther, 2004) wrote about concept maps, which jogged my memory about another attempt I made to synthesize and symbolize a large amount of information into a visual display. At the time (circa 1985) I was working on oceanic transform faults, and I was asked to give an introductory talk at a workshop, laying out what was known and unknown on this topic. I did this by leading the group through the process of making a giant concept map (although I, like Mickey Gunther, did not yet know this term) on three adjacent

blackboards. I put quantifiable casual factors (such as spreading rate or age offset) on the left, connected by arrows through the grey zone of interpretation, connected by yet more arrows to observable outcomes (such as magnitude of the bathymetric step across the transform) on the far right side of the diagram. Dotted lines and question marks marked steps in the chain of causality that were still not understood. The workshop participants loved it, and as each subsequent speaker came up to speak, almost all of them began by going over to the blackboards and saying something like “I’m going to talk about this link from here to here”, using the concept map to show where their particular research topic fit into the grand scheme of things. At the end of the workshop, the concept map was used again to identify major unanswered questions. The workshop’s reception of this way of synthesizing and visualizing an entire research domain into one diagram was so positive, that I was inspired to publish it in a review paper (Kastens, 1987). The paper centered around an annotated version of the concept map; numbered notes spelled out the logic of each link in the diagram and provided citations to the relevant literature. As far as I can tell, this paper has had absolutely zero impact on either researchers or students. In retrospect, I’m convinced that the finished concept map, in all of its glorious complexity, was approximately useless in conveying information—other than the general impression that this field was hopelessly complicated. I believe that it was the process of constructing the concept map together that made it such a powerful tool for the workshop participants—not the communicative power of the final diagram. This matches my subsequent experience with concept maps; they are wonderful constructivist learning tools for the person who makes them, but mediocre as communication tools for complex ideas.

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Development of 3-D Interactive Visual Object Using the Scripps Institution of Oceanography's Visualization Center

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My primary interest in promoting visualization use in the classroom is to help strengthen our future generation of Earth scientists. To this aim I have found interactive 3D visualizations key tools for clearly explaining complex multidimensional problems in order to excite, engage and encourage students to explore the many unanswered questions in Earth Science. To use visualizations effectively in geosciences education it is crucial that we pool our resources, skills and abilities, in an organized fashion so that we do not duplicate efforts or fail to effectively share our end products and resources. For my contribution, I would like to introduce the interactive 3D 'visual objects' that we have developed at the SIO Visualization Center:

<http://www.siovizcenter.ucsd.edu/library/demos/index.html>

<http://www.siovizcenter.ucsd.edu/library/objects/index.html>

and obtain feedback on the usefulness of these tools in the classroom. The primary thing I would like to take away from this workshop is knowledge about what type of visualizations are being currently used in the classroom and a 'wish list' of what can be improved or newly developed.

As science director of the SIO Visualization Center, I use the technology at our center, to render visual objects that can be exported to almost any system (Windows NT, Mac OSX, SGI, Sun, PC Windows2000 and PC Linux). This allows access to high quality 3D interactive teaching tools, yet reduces hardware costs for an in-class visualization system to the cost of a low-end laptop (~\$1,500).

My teaching experience spans teaching university level math classes (calculus, linear algebra), and computer classes (which included computer graphics) at UCLA; I am part of the IGPP/SCEC/IRIS/USCS/SDSU/SDSC/BAS team that is developing an annual teacher workshop that incorporates interactive 3D visualizations (see <http://www.siovizcenter.ucsd.edu/workshop/index.html>); throughout the past 2 years I have led 1-hour to 1-day 'exploration of geophysical data' for a wide number of audiences including grade school, high school, college, university, graduate and undergraduate classes as well as interfacing with the general public, emergency response teams, and those in public office and integral in homeland security (see: http://www.siovizcenter.ucsd.edu/news_events.php). My experience in developing visualization tools specifically to meet curriculum needs is minimal, and one of my goals is to begin to partner with curriculum specialists to help them reach their goals. Within the last year I have made initial steps toward this objective, through working with members of the NSF sponsored OptIPuter program to develop Earth Science resources for K-12 Education (<http://education.sdsc.edu/optiputer/>).

For my other 'day job' I'm a crustal seismologist at IGPP/SIO/UCSD, with research interests that include: (1) The role of dynamic and static stress changes in aftershock generation; (2) Earthquake rupture initiation and earthquake source physics; (3) Heterogeneity of aftershock focal mechanisms; (4) Precise relative locations of microearthquakes (seismic waveform cross-correlation).

I expect I'm in a different situation than most that folks attending this workshop – my main focus is developing 3D interactive visualizations for use in the classroom and research. What I want to learn from this workshop is what it is that people need, what they find useful now and what is missing from their 'bag of tricks'. My hope is that this workshop will enhance my ability to successfully develop and distribute interactive 3D teaching tools.

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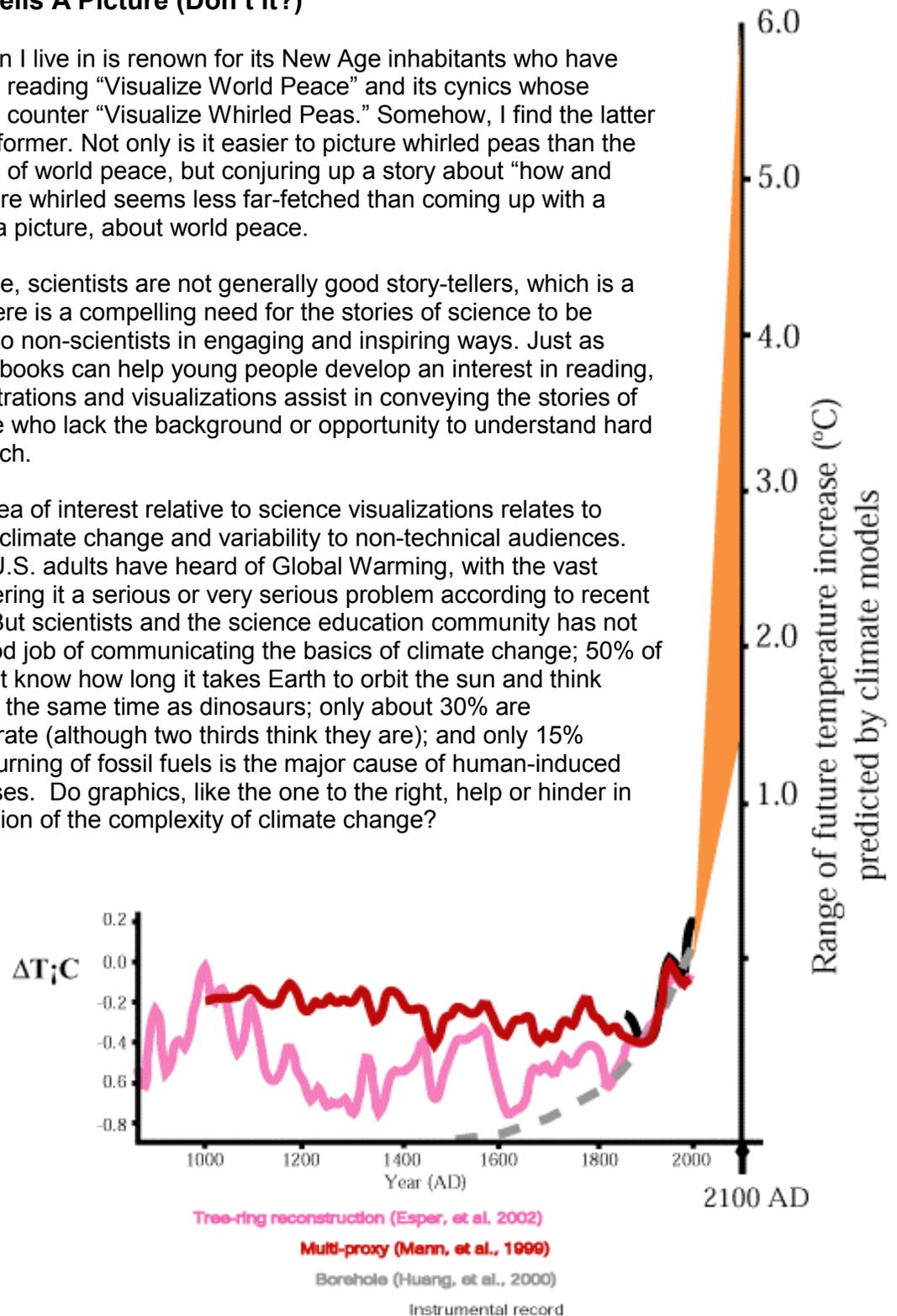
Essay for NAGT Visualization Workshop
Mark McCaffrey
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Every Story Tells A Picture (Don't it?)

The college town I live in is renown for its New Age inhabitants who have bumper stickers reading "Visualize World Peace" and its cynics whose bumper stickers counter "Visualize Whirled Peas." Somehow, I find the latter easier than the former. Not only is it easier to picture whirled peas than the nebulous notion of world peace, but conjuring up a story about "how and why" the peas are whirled seems less far-fetched than coming up with a story, let alone a picture, about world peace.

In my experience, scientists are not generally good story-tellers, which is a shame since there is a compelling need for the stories of science to be communicated to non-scientists in engaging and inspiring ways. Just as illustrated story books can help young people develop an interest in reading, so, too can illustrations and visualizations assist in conveying the stories of science to those who lack the background or opportunity to understand hard data and research.

My particular area of interest relative to science visualizations relates to communicating climate change and variability to non-technical audiences. Nearly 90% of U.S. adults have heard of Global Warming, with the vast majority considering it a serious or very serious problem according to recent NSF surveys. But scientists and the science education community has not done a very good job of communicating the basics of climate change; 50% of U.S. adults don't know how long it takes Earth to orbit the sun and think humans lived at the same time as dinosaurs; only about 30% are scientifically literate (although two thirds think they are); and only 15% recognize the burning of fossil fuels is the major cause of human-induced greenhouse gases. Do graphics, like the one to the right, help or hinder in the communication of the complexity of climate change?



Clearly, there is a huge gap between scientists studying past, present and future climate variations and the rest of the universe. In the U.S., some of the gap can be pinned on the media, which due in part to the power of the energy lobby tends to frame climate change as controversial and theoretical. (This is not the case in other parts of the world.) Some of the gap may also have to do with Americans' famously short attention span making it particularly difficult to convey scientific uncertainties and unknowns. Guilt about being responsible for more-than-out-fair-share of impact on the climate and environmental systems may also have triggered some degree of denial in the United States. But some of the gap in our collective climate change consciousness can be linked to the ineffective ways that scientists communicate, particularly with non-technical audiences.

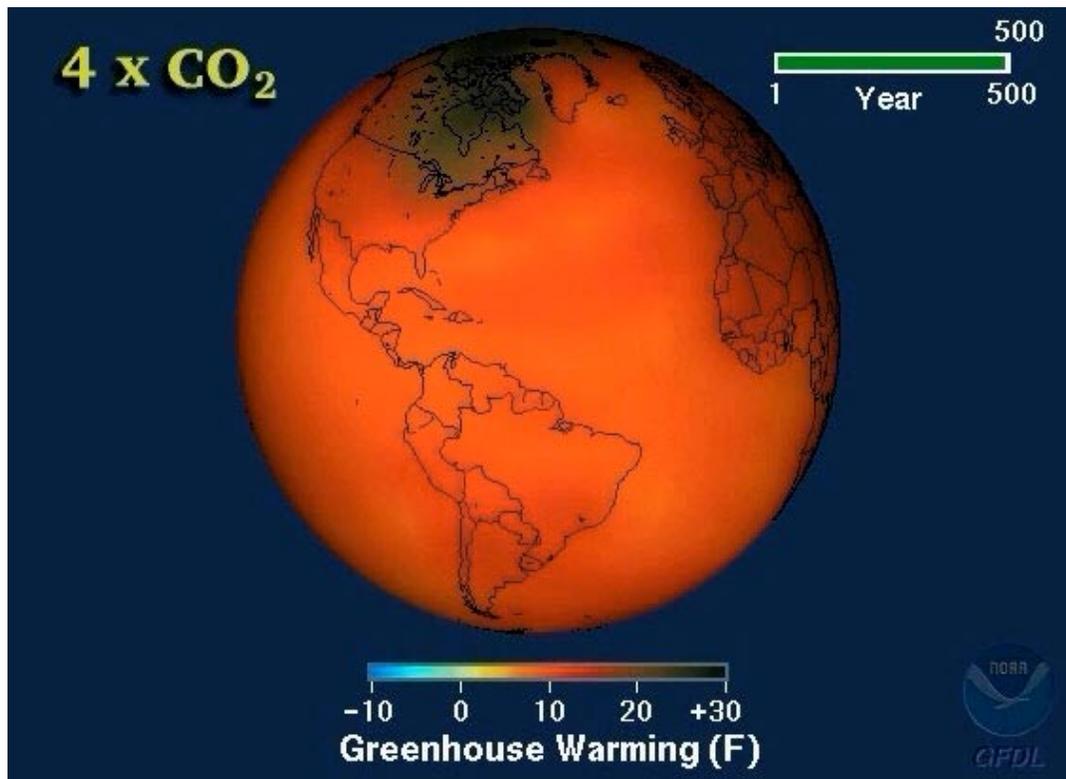
One of the problems that some scientists run into is that, in wanting to maintain an aura of "objectivity" above and beyond the messy details of politics and policy and avoid being labeled as "advocates", they simply don't bother communicating with non-technical audiences. Institutional pressure to "not rock the boat" can perpetuate this. But even when they communicate with each other with experts in their areas of expertise, scientists are often less than effective. When it comes to communicating with non-technical audiences (i.e. the vast majority of people), scientists often fail to know their audience or meet them at their own level. Moreover, in general scientists aren't skilled at storytelling nor at using effective visualizations and illustrations to communicate with the general public.

The proliferation of PowerPoint is also in part responsible for the communication conundrum. When it comes to presentations to peers and non-scientists, the medium of choice tends to be PowerPoint presentations which, according to Edward R. Tufte in his article "PowerPoint is Evil," "elevates format over content, betraying an attitude of commercialism that turns everything into a sales pitch." At professional meetings such as AGU, scientists model bad PowerPoint presentations to each other, often trying to zoom through thirty or forty slides of data visualizations in fifteen or twenty minutes. The graphics are often difficult to see due to the low resolution of PowerPoint, and complex ideas are often reduced to bullets. All too often, the PowerPoint slides are jammed with text, which the presenter then reads, word for word. No wonder many people are turned off by the dryness and complexity of science!

In a little National Academy booklet entitled "Communicating Uncertainties in Weather and Climate Information" (NAS, 2003) the authors examine several case studies in which weather and climate information was not-so-successfully communicated. One of the case studies relates to the National Academy responding to the White House's fast track request for a summary of scientific understanding of climate change in 2001. A report was pulled together in less than a month, resulting in President Bush's "Rose Garden" speech in which he admitted climate change is happening due to human activity, but that there are huge uncertainties that still need to be addressed. One of the "lessons learned" by the Academy was how important communication is, particularly with a topic like climate change:

If part of the goal of a scientific endeavor is to communicate the findings to the public and policy makers, then the charge and findings should be written with that audience in mind from the start. Dissemination should not be an afterthought. Executive summaries and press releases are helpful, but lay language should not be confined exclusively to these documents. (37)

Clearly, part of such communication should include graphics and other effective ways of helping people visualize the findings. But how effective are graphics, like the one below from an animation developed by the NOAA Geophysical Fluid Dynamic Laboratory for a Whitehouse briefing on climate change in 1997? (Animation shows one model's projections of surface temperatures if carbon dioxide levels increase four-fold beyond modern (1997) levels.)



Over the past decade, a paradigm shift has been occurring in the ways people construct knowledge, driven in part by the advent of the Internet. Memorizing and repeating information is “out” and being able to access and use information is “in.” This shift has profound implications for not only formal education, but also in providing the tools and support for “decision support” to diverse audiences. In the case of communicating the basics of climate change and providing tools and visualizations that can help people understand and plan for climate change and related socio-ecological dynamics, there is a compelling need to develop a new generation of materials and strategies that effectively meet users needs.

Climate change is perhaps the ideal interdisciplinary theme to weave together mathematics, sciences, ethics, philosophy and social discourse. Yet, making this a national or, better yet, international educational priority will require a degree of leadership and commitment that is currently lacking. If such leadership ever emerges, it will need to harness stellar visualizations and consummate storytelling from the scientific community in order to bridge the gap between the climate research science and the rest of the universe.

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**Teaching Geoscience with Visualizations:
Using Images, Animations, and Models Effectively**
February 26-28, 2004
Carleton College, Northfield, MN

My Interests and Research in Scientific Visualizations

Daniel R. Montello
February 2004

I am a geographer and psychologist, with research interests in many aspects of spatial and geographic perception, cognition, and behavior. My particular interest is in space and place at scales larger than the human body, including both built and natural spaces such as buildings, campuses, parks, cities, wilderness areas, states, countries, and the globe. These spaces include features and landscapes of direct interest to earth scientists, including physical geographers, geologists, oceanographers, climatologists, and ecologists. I am interested in knowledge acquisition, reasoning, problem solving, and communication via a variety of modalities, including direct sensorimotor apprehension, maps and other graphics, language, and virtual representations. Thus, while my major interest is in the psychology of (near) earth surface space, I am interested in the space of pictures and objects because they are a common means by which people interact with information about larger spaces—sometimes the only way.

I believe that many of my research activities over the past two decades have at least an indirect relevance to the study, creation, and use of scientific visualizations. In particular, I have collaborated on various research projects, and written several reviews of research, that have examined perceptual and cognitive aspects of cartographic and virtual information displays, including their role in information acquisition and knowledge development, and their similarities and differences from other modes of knowledge acquisition such as direct sensorimotor experience in the environment (Montello, 1998, 2002; Montello et al., 1994, 2004; Montello & Friendschuh, 1995; Pick et al., 1995; Slocum et al., 2001). Two ongoing lines of research are directly relevant to scientific visualization.

First is research being conducted with primary collaborators Drs. Sara Fabrikant and David Mark. This project investigates how users of information spatializations interpret spatial and nonspatial graphical variables as representing similarity relationships among documents represented in the display. “Information spatializations” are computer visualizations in which nonspatial information is depicted spatially. For example, a “point-display spatialization” depicts documents (or other information-bearing entities) as collections (clouds) of points in 2- or 3-dimensional space. Common examples include point displays, network displays, region displays, natural land surfaces, urban land surfaces, and more (<http://www.kartoo.com>, <http://www.touchgraph.com>, see Links at <http://www.geog.ucsb.edu/~sara/html/research/spacecast/spacecast.html>). Spatializations of large databases commonly use distance as a metaphor to depict semantic (nonspatial) similarities among data items. We call this the *Distance-Similarity Metaphor*.

Our results so far show that this metaphor operates differently depending on the type of graphical metaphor (e.g., points vs. regions) and whether nonspatial visual variables (such as color hue or value) are manipulated. For example, straight-line

distance in point displays is equated quantitatively with similarity when the display is a fairly homogeneous field of points (Montello et al., 2003). In heterogeneous fields in which points are more aggregated, people perceive emergent linear or cluster features that induce judgments of greater similarity for documents within a common emergent feature. In network displays, similarity is spontaneously judged as equivalent to metric distance along network links, not to straight-line distance across the links or to nonmetric distance, such as node counts (Fabrikant et al., in preparation). Link hue, value, and width all moderate this relationship, however. For example, homogeneously hued links are seen to connect more similar documents than are heterogeneously hued links. We also have data on region displays. Currently, we are designing studies of 3-D dynamic and interactive displays (such as “clouds of points”).

As part of this research project, we have recently begun to investigate the use of spatializations that appear more like natural or urban landscape surfaces. In our first study, we had participants view what appeared to be a hilly or mountainous landscape surface surrounded by water. Half the participants were told they were looking at a landscape surface; the other half were told they were looking at an information visualization designed to appear like a landscape. Qualitative responses to these displays suggest some interesting things about how lay people interpret geomorphologic surfaces (“common-sense geomorphology”) and about how they interpret such surfaces to represent information about the semantic content and similarity of documents. A specific example: The role of denudation is rarely considered by lay people to play as important a role as it does in “creating” what appear to be mountainous surfaces, such as those found in many mature plateau areas around the world. An urban version of this study is under way.

A second line of research in which I am involved, and that is relevant to scientific visualization, involves the use of visualizations in medical education, including both laparoscopic surgery and dentistry. My collaborators on this research are Drs. Mary Hegarty, Madeleine Keehner, and Frank Tendick. As part of its interest in medical informatics, the medical establishment is increasingly turning to computer-supported interactive visualizations (virtual technology) for training purposes. But there have been few systematic studies of how people interact with and learn from 3-D computer visualizations. Initial studies in the medical domain, including some of our own, suggest that rather than augmenting cognition for all learners, 3-D interactive models may actually be disadvantageous to some individuals.

Our overall goal in this research is to explore issues relating to the use of 3-D computer visualizations in teaching anatomy. Our research has three main objectives. The first is to explore the correlation between spatial ability and anatomy learning. In the initial phase of our research, we have examined how this correlation is modulated by the use of interactive computer visualizations. The second objective is to test the effectiveness of different aspects of computer visualizations for learning anatomy. Here we plan to manipulate variables relating to the computer visualization itself, such as depth cues (monoscopic vs. stereoscopic), interactivity (active vs. passive control), and haptic cues (a hand held manipulation device vs. a traditional interface), to see whether they affect learning. The third objective is to apply our findings to medical education by developing and testing training methodologies that incorporate the types of simulations that we show to be most effective.

While computer visualizations are often conceived as having the potential to enhance or support cognition, it is not known whether these hypothesized benefits are equal for all learners, or whether they differ for individuals with varying levels of spatial ability. Interactive computer visualizations might “augment” cognition equally for high-spatial and low-spatial individuals, or they might act as a type of “prosthetic” for those with poor internal visualization ability, so that interacting with them improves the performance of low-spatial learners more than that of high-spatial learners. Alternatively, however, it is possible that some minimum level of spatial ability is a necessary prerequisite for learning from these types of representations, that is, effective *internal* representations are needed to support the comprehension of *external* visual representations. If spatial ability proves to mediate the comprehension of 3-D computer visualizations in critical ways, understanding this mediation and exploring potential ways of supporting low-spatial learners or classes of learners will be important.

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Investigating the Underlying Processes of Visualization Experiences
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The major goal of my research has been to examine the processes underlying discourse comprehension (e.g., Rapp & Gerrig, 2002; Rapp & Taylor, in press). Discourse comprehension requires the construction of a mental representation built from the information in text, speech, images and multimedia sources. Much of my work has focused on the role of the reader in comprehending text. Currently I am extending this work beyond text to assess how reader expectations and strategies influence spatial and multimedia comprehension. It is this interest which is most directly related to the use of visualization as a tool for learning.

I am currently working in conjunction with the Perseus Digital Library group at Tufts University and the GEOWALL group at the University of Minnesota to examine the utility of multimedia systems for facilitating learning (an area which has traditionally ignored the processes, expectations, biases, and belief systems that are brought to such situations). Our projects examine whether theories of text comprehension are useful for outlining the potential effectiveness of these presentation systems in educational situations. To this end, we have focused on how users construct and apply mental models for multimedia experiences. Digital libraries and multimedia systems provide a fertile test-bed for implementing theories of comprehension in the design of educational software, as well as for evaluating the cognitive processes necessary for comprehension during hypermedia and multimedia experiences (Rapp, Taylor, & Crane, 2003).

In collaboration with the GEOWALL group, I am currently investigating whether 3-dimensional presentations of map information (constructed using stereo visualizations) may influence the speed with which students learn to read and use topographic maps, and the resulting memory representations that are encoded into long-term memory as a function of those experiences (Rapp & Kendeou, 2003). This work is largely exploratory, as we are concerned with the degree to which stereo visualizations may help students learn information beyond that conveyed using traditional flat map presentations found in most earth science coursework. Despite an increasing use of GEOWALL as a tool in earth science curricula, it has remained, up until this point, largely untested. This project begins a formal evaluation of the educational implications of the system. Visualizations have been offered as worthwhile tools for helping students understand complex systems and processes in science classrooms. The nature of scientific visualizations on cognition remains unclear, and as such we anticipate our collaboration will begin to outline the underlying cognitive processes that are influenced by multimedia visualizations.

In a related vein, I am particularly interested in addressing techniques that effectively reduce students' misconceptions about scientific principles and theories. As readers encode information into memory, this information continues to exert an influence on ongoing comprehension. While this is usually not a problem (and in fact, critical to ongoing comprehension), it can easily create difficulties if the initial information is

incorrect and is revised at a later point in time. In addition, the inaccurate prior knowledge that students may bring to learning situations are often resistant to change in a similar way (see Kendeou, Rapp, & van den Broek, in press, for a review). Specifically, evidence in psychology and education has demonstrated that students often have difficulty overcoming such naïve beliefs in domains such as physics, biology, and chemistry. Figuring out how to overcome or replace such misinformation is a major challenge; restructuring them requires focused attention, an awareness of errors, the motivation to make changes, and an explicit understanding of why the misinformation is incorrect. Therefore, we are currently investigating whether 3-dimensional visualizations can help students revise faulty prior knowledge for geological information. Of course, the effectiveness of these visualizations will depend not only on the types of visualizations presented, but also whether students' misconceptions are essentially 'visual' in nature. Examples of these types of misconceptions may include the rotation of the earth, earthquakes and plate tectonics, and the eruption of volcanoes.

To date, my research has focused on the cognitive processes necessary to understand language, texts, maps, and integrated multimedia. By focusing on these processes, I hope to develop more robust, naturalistic theories that account for comprehension across a variety of situations and experiences. The components of such a theory have important implications for describing the content, structure, and application of mental representations that are critical for higher-order cognitive processing. They also have direct implications for diverse research areas including the geographical sciences, human-factors design, and educational technology.

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Visualizing the Hidden Earth - Learning with Interactive Animations

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Beginning with my origins as a field geologist and my more recent work in geoscience-education research, I have always appreciated the huge role visualization plays in all aspects of geologic research, geologic reasoning, communication, and teaching. Visualization is a critical control of what we and our students see and think about in the field, on maps, and from the many types of geologic diagrams we use. Yet we know very little about what our students actually see and how they learn from these different representations.

As part of my two NSF-funded Hidden Earth Projects, we have been developing interactive animations, building curriculum around these, and researching how students use and learn from these. Our research results indicate that these interactive animations are indeed very effective in helping students learn key concepts and skills, such as how to visualize topography from contours maps and how to visualize the 3D geometry of geologic structures. Also, using such visual materials increases the general spatial abilities of all types of students and can eliminate differences in performance between males and females.

Our more recent work has involved research and curriculum development into how students visualize the deposition of rock layers and how such layers are expressed in the landscape. We documented some student preconceptions that should be shocking to any introductory geology teacher, such as students thinking that limestone layers in the Grand Canyon were formed when seas came into the already existent canyon and coated the walls with limestone. Also, many students see stratigraphic sections as maps. We simply must do more research into what our students see from the many photographs, maps, and geologic diagrams we show in our classes – it is not what we think they are seeing! A preliminary version of some of the visualizations is at <http://reynolds.asu.edu/seas>.

Some of the visualization-rich websites we have created are:

Arizona Geology 3D – QTVR movies of the Geologic Map of Arizona draped over digital topography for each 1° X 1° quadrangle.

Arizona Geophysics 3D – Interactive QTVR movies of gravity, magnetic, and depth-to-bedrock maps draped over digital topography

Arizona Satellite 3D – Interactive QTVR movies of thematic map images draped over digital topography

Arizona Topo 3D – Interactive QTVR movies of 1x1 degree topographic maps draped over digital topography

Biosphere3D: Interactive globes showing factors of the environment, such as precipitation, soil pH, and rainfall.

Geologic Scenery: Images and movies showing how landscape features form

Interactive 3D Geologic Blocks – An educational module with QTVReality (QTVR) movies of interactive geologic blocks containing layer, folds, and faults. Spin them, cut into them, erode them, make them transparent, and move their faults.

Painted Canyon – A Geologic Wonderland: A virtual world used in GLG 103 labs at ASU

Structure Map 3D Gallery – QTVR 3D perspectives of geologic features on digital topography.

Southwest 3D – 3D perspectives, presented as pictures and QuickTime movies, depicting the landscape of the Desert Southwest with colors showing different elevations.

Interactive 3D Geologic Maps – Classic, quadrangle-scale geologic maps draped over digital topography for various regions and geologic features.

Visualizing Topography – Educational module to teach students about contours and visualizing topography.

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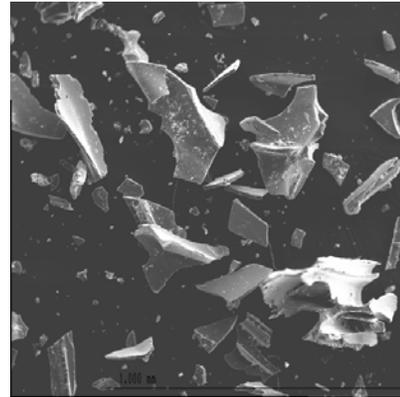
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From Popcorn to GIS: My Adventures in Using Visualizations for Geoscience

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Geology is a visual science. Visualizations are essential to understanding geoscience concepts and communicating concepts to others. They capture students' attention and get the creative juices flowing. At every stage of my career, visualizations have played an important role.

I started thinking about ways to use visualizations when I was in graduate school. At the time, I was studying volcanic ash particles using a scanning electron microscope (see image at right), and using remote sensing imagery and computer modeling to study volcanic plumes. I was bored by the lectures in college classes and wanted to pep up the classes I taught. I wanted to move from abstract concepts to something more tangible. At this time, I also started giving geoscience talks to local schools and realized the importance of visual examples (props, demonstrations, imagery, computer animations) to communicate complex science



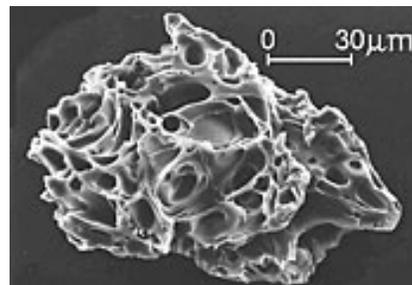
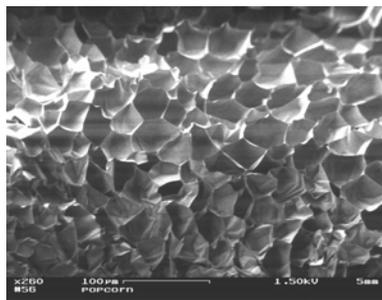
topics to K-12 students. The visualizations (defined in the broadest sense) were simple: remote sensing images of volcanic plumes, video clips of volcanic mudflows, wooden blocks on long metal rods to show earthquake frequency, fritos to show how ash particles fall.

One of these primitive visualizations demonstrated the movement of lava flows and mudflows. Students often think lava flows move fast and are the most dangerous volcanic hazard, and few students can imagine a mudflow. Karo syrup (representing lava) traveling down a tilted board, quickly demonstrates that lava flows don't move as fast as most students would imagine. A race between the karo syrup (lava) and a dirt-water mixture reminiscent of a mudflow, shows students that mudflows move swiftly down the flanks of a volcano and travel much farther. Students easily draw the conclusion that mudflows are the more dangerous volcanic hazards. This example showed me how important visual representations are to learning and that even primitive visualizations can be effective. I also came to realize how developing visualizations for students helped me think out of the box and be more creative with my own research. On a trip to El Salvador, I used the same lava flow/mudflow demonstration in K-12 classes. Gasps from the students as they witnessed the mudflow, showed understanding and how visualizations can even overcome language barriers.

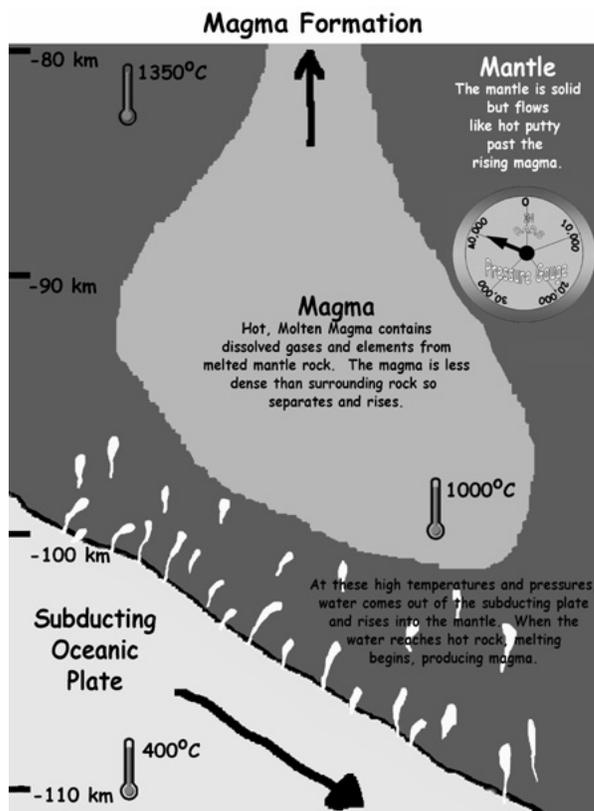
While in El Salvador, I asked K-12 students to tell me the names of volcanoes in their country. Consistently, students would not include volcanic lakes, and when we tried to tell them that they were volcanoes, our explanations were met with disbelief. Again, visualizations were required to demonstrate this important concept. We used a red water balloon to represent the magma under a volcano. The balloon was buried under a pile of sand (the volcano). Then we popped the balloon and watched what happened as the "magma" erupted from the volcano. Concentric cracks developed around the volcano's summit as the magma was extruded and eventually the summit

collapsed to form a crater. I synthesized rainstorms to fill the crater with water, and student disbelief was washed away. This experience showed me how important visualizations can be in convincing populations about the reality of volcanic hazards. No amount of words could communicate what this demonstration did in only 5 minutes.

These experiences served me well when I started writing volcanic hazards curriculum for the US Geological Survey's Cascade Volcano Observatory and Mount Rainier National Park. Some of the challenges we faced were getting middle school and high school students to understand how gas bubble expansion in magma leads to an eruption, and how magma travels from the subducted plate to the earth's surface. We popped corn to illustrate gas bubble formation, and used SEM photos of the popped corn to show the microscopic holes made when the corn popped (students compare these features to gas bubble holes in pumice).

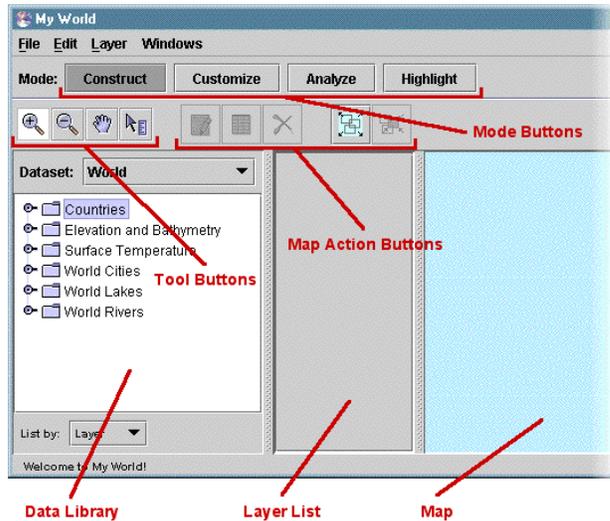


Scanning Electron Microscope images of gas bubbles in popped corn (left) and gas bubbles in volcanic ash (right).



How magma travels to the earth's surface was the hardest concept to demonstrate. By working with educators, we realized how important it was to make this abstract process real by relating it to things the students were familiar with. *How hot would it be at 500 km below the earth? What is the texture of magma like at that depth? (oatmeal-like) How many cars would you have to stack on top of each other to equal the pressure felt at this location?* We developed a series of cartoons to show the process, annotated the cartoons with fun facts, and wrote a teacher narrative to go with the cartoons. I found that my own understanding of this geological process was enriched as I was forced to describe the process in lay-person's or familiar terms.

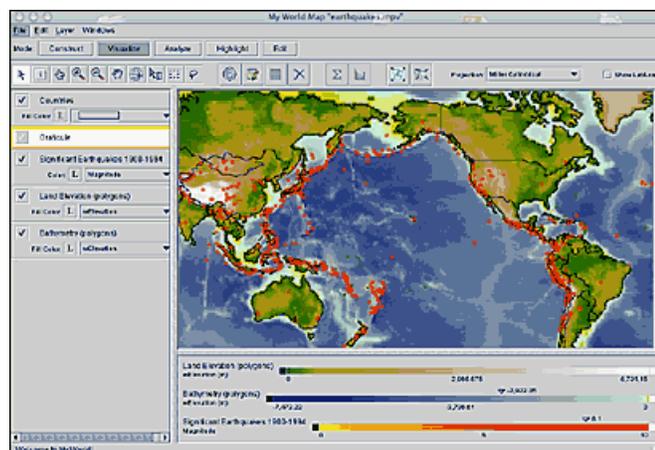
As a post-doc researcher, I've been exposed to a whole new set of visualization tools, as well as, a new way of teaching geoscience concepts using inquiry. Prior to my coming to Northwestern, a Geographic Information System (GIS) called *My World*, was developed by Danny Edelson, Eric Russell, and others. This system was designed to be more user-friendly (less complicated) than professional GIS programs, so that middle school to entry-level college students could use it easily. Lessons learned from developing other visualization tools (like *World Watcher*) guided the design of *My World*. Edelson and others designed *My World* to be practical, compatible with school



infrastructure, and easy to install. The options in *My World* are segmented into user modes, and queries are structured to help users easily understand the functions in the program. Edelson and others sought to build a GIS that could be used as a tool in science investigations, but not be so complicated that the tool becomes the learning focus. Gridded and vector data can be imported and displayed using *My World*. The software was written in Java and runs on Mac's, PC's, and Linux computers. Currently the software is licensed to a commercial publisher (PASCO: <http://www.pasco.com/myworld>)

My World is an excellent visualization tool. The software allows students to explore and analyze data at different resolutions. The software helps students plot large amounts of data that would otherwise take too long for students to plot on their own. Students can use the software to view the world in different ways using various map projections. Databases allow students to analyze data rather than get bogged down in formatting and processing data. The software makes it easy to compare data sets spatially or by data attribute. Darlene Slusher (an atmospheric chemist and post-doc at NU) and I are currently developing curriculum that uses *My World* GIS. Lessons are designed to demonstrate the power of GIS as a visualization tool versus the more conventional paper maps or spreadsheets used in many classrooms.

The major objective of the curriculum is to allow students to do science investigations using real data with a tool commonly used by scientists. The lessons are designed to expose students to nature of science processes—developing hypotheses, selecting data, analyzing data, evaluating data quality, putting limitations on data, using evidence to support conclusions, debating ideas using evidence, thinking critically, and dealing with open-ended questions. The lessons are inquiry-based and follow the “Learning for Use”



design structure of: motivate, construct, refine. Student motivation is accomplished by asking an interesting driving question. The question is designed to elicit curiosity. In addition, lessons sometimes include a narrative that sets up an interesting problem or causes the student to realize he/she lacks knowledge in an important area (elicit demand). The lessons are designed so that students construct knowledge as they use the *My World* software. It is assumed that students haven't used *My World* before, so detailed instructions are given for unfamiliar operations as the student works through the lesson. Lessons contain supports for guided inquiry. In places where an understanding of specific science concepts are needed to progress further with the lesson, definitions, a short paragraph, or a student reading is included. Students are asked to analyze data displayed in *My World* or use the software to manipulate data with the expectation of solving a problem related to the driving question. Students refine their knowledge by interpreting the data and applying what they've learned to answer the driving question.

Six lessons were written to cover a broad range of disciplines including: environmental science, geography, and earth science. These lessons are described in more detail on the poster, along with current and future research plans, problems encountered during lesson development, and database descriptions. While developing these lessons, the following questions arose:

- How can we format data faster and easier?
- How do we keep databases up to date?
- How should we test the software in classes?

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Links:

USGS Cascade Volcano Observatory Education Outreach

<http://vulcan.wr.usgs.gov/Outreach>

Download World Watcher at:

<http://www.worldwatcher.nwu.edu/software.htm>

To learn more about My World and download a trial version:

<http://www.worldwatcher.nwu.edu/myworld>

Visualizations, Maps, and Symbolic Development

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I am a developmental psychologist by training, and for most of my career I have focused on the development of children's understanding of symbols. I am interested both in how children come to understand symbols and in the cognitive consequences of symbol use. I have found that studying children's developing understanding of maps provides a window onto both issues. In addition, maps are perhaps the historically earliest and most frequently used form of visualization. Therefore, research on map use may be directly relevant to understanding how students' comprehension of visualizations. For these reasons, much of my experimental work has been on the development of children's understanding and use of maps.

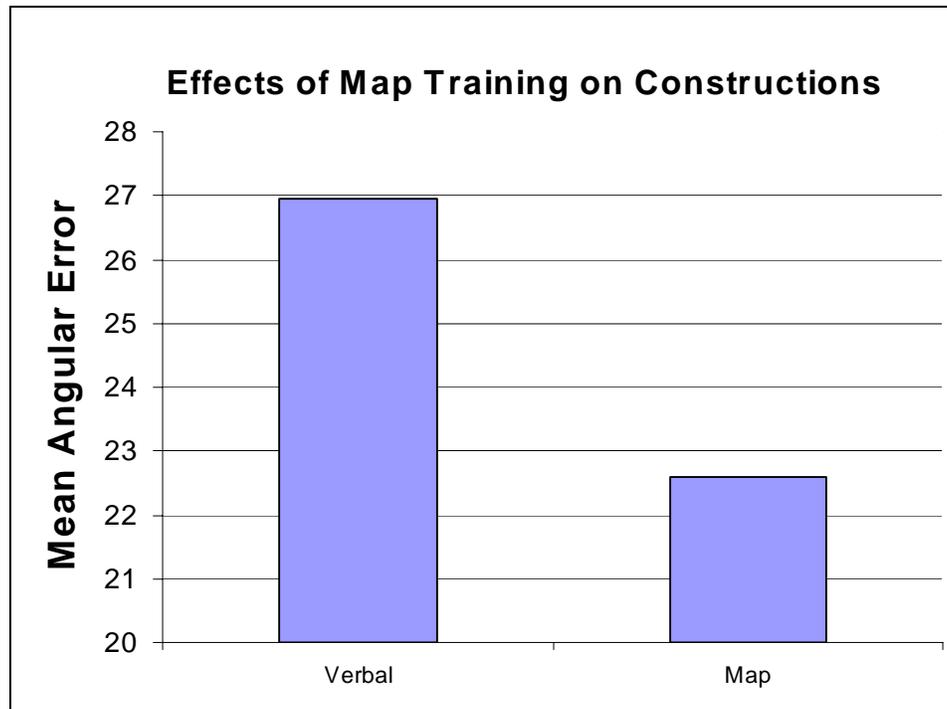
In this essay, I first report on a study that I am currently conducting that illustrates the kind of research that I do. I then discuss the relevance of my research to work on understanding of visualizations. I end with a call for research on students understanding of visualizations, arguing that there is an important opportunity for synergistic collaborations

Sample Research... With the help of Clare Davies (Davies & Uttal, 2003), I have studied how using a maps can affect children's developing conceptions of a familiar space, their neighborhood. Our specific focus is on whether studying a map helps children to think about spatial information in a manner that transcends how the information has been experienced. Put simply, does looking at a map help children to acquire survey-like knowledge of their neighborhoods? We studied children's knowledge of their neighborhoods because this provides a strong test of the idea that maps can influence children's thinking. We expected that children (ages 7 to 10) would already be familiar with their neighborhood. The question of interest was whether studying the maps could change *how* the children thought about and mentally represented the spatial relations among familiar landmarks.

We began in pilot testing by assessing children's familiarity with a set of potential landmarks. Our goal was to winnow a list of approximately 40 landmarks to a much smaller set of approximately 18 landmarks. We chose those landmarks that most children were familiar with as those that would appear in the main study.

We began the main study with a baseline of assessment of children's familiarity with the landmarks and of their knowledge of the relations among them. For example, we took children on a walk of the neighborhood and asked them to point to out-of-sight landmarks. After the baseline assessments, the children were assigned to either the *map* or *verbal* group. The map group studied maps of the neighborhood at the next two sessions. The verbal group provided a control for the effects of learning from the map. These children received extensive training about the locations, but they did not study a map. For example, we described the landmarks in detail, showed pictures, and asked the children about routes they might take between the landmarks.

The results show a substantial effect of exposure to the map on children's cognition of the large-scale neighborhood. As shown in the figure below, the children who saw the map were better able, for example, to construct map like representations, even for landmarks that were not included on the maps.



In other situations, however, the results interacted with the sex of the subjects. For example, for tasks that involving pointing to unseen locations differed substantially by sex. While boys benefited substantially from the map view, girls on the other hand actually benefited more from the verbal instructions.

Application to Visualization Research. My interest in natural science visualizations grew out of a conference on spatial thinking in chemistry that I attended a few years back.. I was struck by similarities in how novice chemistry students understand complex images and children's understanding of simpler visualizations, such as scale model or maps. In both cases, people must learn to view information in a new way. The assumption often has been that visualizations work by providing direct access to key spatial information that may be unobservable otherwise. But my work in symbolic and spatial development led to a different perspective, which is that even seemingly simple visualizations are symbolic representations, and neither students nor young children can be expected to “see through” the visualizations to the underlying concepts. I am interested in how students construct an understanding of what the visualization may represent.

Rather than viewing visualizations as an educational panacea, I see them as a powerful

tool that must be carefully matched to the user's level of understanding. Research on the development of symbolic understanding may be highly relevant to this endeavor. The results of several studies (e.g., DeLoache, Kohlstad, & Anderson, 1991) suggest that physical similarity is particularly important in early understanding of symbolic relations. If a map or model does not look much like the space that it represents, then children may have great trouble using it as a spatial representation. But at the same time, similarity may be something of a cognitive “trap”. Children often assume that the map or model *must* look like the object it represents, even when the correspondences are arbitrary and symbolic. This finding may have direct implications for understanding students' confusion in comprehending colors in using new visualizations in chemistry, the geosciences, or other natural sciences. If students continue to believe that the color of a symbolic representation must match its intended referent, then they may have difficulty understanding the abstract, symbolic correspondences that are entailed in using visualizations. Highly attractive and visual compelling images may actually be a dual-edged sword; vivid images may lead students to believe in correspondences that do not exist.

In attending this conference, I hope to move forward with establishing collaborations for research on the process of understanding scientific visualizations from the standpoint of symbolic development. I am interested in collaborating with researchers and educators in the geosciences and chemistry to establish a research program on the development of students' understanding of visualizations. I think such a program of research would be beneficial from an educational perspective, and it would also provide a forum for testing theoretical ideas in developmental and cognitive psychology.

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Acquisition and Use of 3D photorealistic models for virtual fieldtrips and exercises

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Dr. Xueming Xu and I have been developing a unique 3D photorealistic mapping of geology, creating virtual models at centimeter accuracy and resolution. We have used a variety of combinations of GPS, laser rangefinders and scanners and digital cameras. I am chairman of an NSF initiative INTERFACE (INTERdisciplinary alliance for digital Field data ACquisition and Exploration) to build a series of regionally distributed centers with key expertise and equipment who will then train other academic groups. Geologic virtual models have been created in Spain, Mexico and Ireland as well as the US. These are all at important geologic outcrops. Oil companies have used our models for reservoir characterization studies and virtual field trips. We have been working with our structural geologist by capturing virtually a series of very famous outcrops along I-35 in Oklahoma where schools from a long distance visit because they are such great examples of various aspects of geology. The concept is to utilize them for teaching thus demonstrating how these could be used. We assisted the Association of Engineering Geologists in Texas in building a virtual model of the geology in a famous area called Dobbs Valley near Mineral Wells. They wanted to use it when they had their geology field trip in July, to be able to take a computer in the field and virtually “fly around” the cliffs on the computer so that more could be seen. We worked on it with undergrad and graduate students and it was a great success, the first time this has ever been done. In addition in 2004 two fieldtrips being led by department faculty with the American Association of Exploration Geologists will use our models there and along I-35 in that manner as an assist in their visits to those locations. We have been unsuccessful in getting funding for educational applications since what we do is so unique these agencies do not know how such models can be used because such models have not been available previously. We are confident that what we do is unique in method and quality. The fact we actually model the camera geometry as opposed to rubber sheeting makes ours the most accurate method. That is the reason why we can seamlessly mosaic multiple images on 3D terrain rather than only a single image (as rubber sheeting does). Rubber sheeting was inadequate at an earlier stage of our research, and we eventually abandoned this approach. Projects with as many as 42 integrated photos in geology and over a hundred in man made structures have been successful. They have been viewed and interpreted in a variety of visualization systems including oil companies and universities with high end CAVE systems but are also effective in systems such as our own GeoWall. We have been also been capturing a variety of models besides geology. We have captured Mt. Rushmore very effectively, intending to create a virtual field trip. We have been working with the City of Rowlett forensic specialists in testing the use of our virtual modeling of crime scenes. A real crack house was setup with an officer acting as a body with fake blood to determine how that would be captured photorealistically in 3D. We mapped inside and out the Alamo in San Antonio cooperating with the Daughters of the Texas Republic and the curators. It was done as a test of the use of the virtual approach for historical documentation. The data set is complete to surfaces and photos are now being applied. Such a data set is extremely large and challenged our software and hardware. We also mapped part of a Dallas rapid

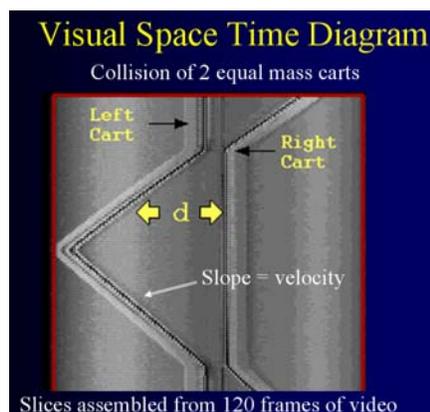
Transit (DART) railroad tunnel as a test of this application with their cooperation as well as their engineering contractors. Low cost visualization and geometric analysis software is not available which is a problem. We need to get feedback in ways to utilize this methodology and associated products.

Multiple Representations, Scientific Visualization and Student Learning of Science

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As a scientist trained in physics, who since graduate school has worked almost exclusively in problems of education, I have been really enjoying learning about visualization, cognitive processes in young adults and also about global climate change. In this essay, I would like to establish the background for my current research interests, share some of my influences and expand upon the title and its significance for college science instruction.

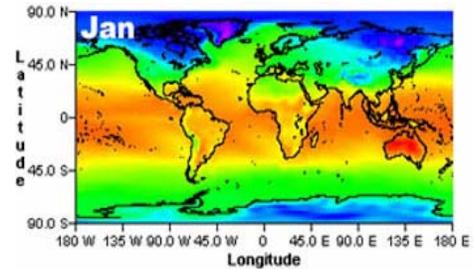
My interest in the use of visual media for learning science started with my involvement in a project looking at the uses of digital video for physics instruction. The idea was to treat digital video as a data stream and not just a VCR on the computer. Thus, one should be able to extract useful physical information from the digital video (e.g. the time rate of change of positions of certain objects within the frame) and in other ways manipulate the video information in space and time (Chaudhury & Zollman, 1994). On the right is an example of what we called a ‘Visual Space Time Diagram’ - because it compressed the physical information from several seconds of video (several dozen frames) into a single still image that still retained the essence of the physical phenomenon that had been captured on video originally (two carts on tracks colliding elastically in a straight line). Some manipulation of QuickTime video in space and time is now being done with software such as DIVER (Pea et. al., 2003)



While video presents one kind of challenge of a large data set – earth remote sensing data presents a whole other set of issues when it comes to usability in the classroom with the appropriate tools and curricula. Two dimensional line plots (whose application has been widely studied in the physics education research community) are no longer enough to represent the richness of data that describes aspects of the Earth’s environment. For the past several years, I have been working with tools and data from NASA’s Earth Observing System to meet the needs of two distinct audiences – undergraduates in a summer research program on Earth System Science and K-12 teachers. In our case, both groups were relative novices to the discipline and unfamiliar with the data products available (Chaudhury & Rodriguez, 2003; Chaudhury et.al., 1997). In rapid succession we escalated the type of data we handled from 3-D (e.g. false color images of ozone laid over a two dimensional world map), to 4-D (e.g. animation of a time series of false color images to show changes in ozone concentration over a period of several months) to Virtual Reality (e.g. the same ozone data rendered in an immersive environment where one could change perspectives and viewpoints).

As part of capacity building at NSU, we engaged scientists, undergraduates, graduate students (Education) and K-12 teachers in these endeavors. The early lesson we learned was that each

audience, each learning objective demanded its own tool and that NASA data (though there was plenty of it) was rarely in the form that was useable for meaningful interactive visualizations. WorldWatcher (Edelson, 2004) was one software tool that found applicability across multiple domains of users within the sphere of education – and visualizations created with it have been used on a number of occasions in my courses. This figure shows a WorldWatcher representation of global surface temperature (in January) is shown here. For undergraduate research purposes, however, the tools of scientists (IDL from RSI Inc.) became more critical simply because they could be programmed to accept data input from a variety of sources. From a purely visual perspective, IDL allows one to generate graphics and animations similar in many ways to what WorldWatcher does, though that is where the similarity ends. Our preliminary research in college science classes with visualizations such as the one shown here indicate that non-science major college students can be trained quite readily in the basic interpretation of such images. We have adapted instructional methodologies from the Physics Education Research literature and designed paper and pencil assessments for the use of scientific visualization tools and data in a traditional lecture setting (Chaudhury et. al., 2002)



As many others have mentioned in their essays – graphical visualizations are only part of the cognitive load that learners have to bear when dealing with topics in science. It is not easy to find ways to link natural phenomena to their graphical representation without introducing artifacts that could distract the student from the true concept to be learned. The stated goal of many scientific visualization projects is ‘enhanced student learning’ of topics in some particular domain – whether it be geology, meteorology, anatomy or chemistry. However – an issue that often gets overlooked in many of these discussions is that of the ‘multiple representations’ of phenomena that most scientists master along the way and that often brings clarity to their own mental models of the concepts. Within the context of a college science course, scientific representations of phenomena can be verbal (descriptions in the textbook), aural (professor’s lecture), numerical (data collected in lab), symbolic/mathematical (equations to be solved), diagrammatic (flowcharts/schematics) and finally graphical (charts/false-color plots etc.). Some of the issues for students are : when to use which representation? how to move between representations? are all representations equal in scientific merit? Challenging questions indeed! Within the realm of physics education, Van Heuvelen and others have paid special attention to student needs in this area and devised curricular strategies to help them make the representational transitions – especially at the calculus-based study of Newtonian mechanics. Within the overall sphere of geosciences education, I am not sure whether or not this issue has been addressed.

This year, as part of my work with the Carnegie Academy for the Scholarship of Teaching and Learning (CASTL), I am investigating how students in an introductory physical science course deal with issues of multiple representations – and especially focusing on whether or not they can be steered towards making maximum use of the visualizations provided in the textbook to overcome weakness in reading level (verbal representations) and math (symbolic and numerical representations). For example: my instruction on objects moving under the influence of gravity (in Week 3) and on the Solar System (Week 8) comprised *only* of a detailed discussion of certain

relevant diagrams in the textbook. Some of the assessment data were encouraging and some were surprising – I shall share my preliminary results in my poster.

In terms of this workshop, I would like to learn about what others are doing especially at the introductory college level and form collaborations with people who could bring to bear their expertise in areas such as cognitive science and psychology – something I sorely lack!

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Teaching Field Geology is all about Visualization
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University of New Mexico

I doubt that anyone would dispute the argument that an undergraduate (“capstone”) field geology course is of considerable importance in the academic experience of geoscience majors and that a student’s success in the course, measured in many ways, is dependent on their ability to accurately describe, portray, understand, and grasp the importance of field geologic relations. In other words, visualization of features in front of their eyes, at a range of scales, is critical to field geology; from a mechanical perspective, visualization is a critical component of the array of processes that, taken together, allow the student to make predictions (sort of a synonym for testable hypothesis) about what she or he should anticipate visualizing around the next hill, across the next valley, in the next drainage, etc. I have had the incredibly fortunate experience of teaching field geology for almost 30 years (this summer will be my 30th), having taken field geology in 1973. I taught the course as a graduate instructor at the University of Michigan, beginning in 1974, as a post-doctoral research scientist at the University of Toronto, and as a faculty member of the Colorado School of Mines, the University of New Mexico, and the University of Michigan.

So with this level of experience, there are several challenges in teaching field geology. A major one is, cognizant that each and every student is different, and each and every student has different levels of “comfort” in the field, how do you “work with” students to get them to develop a strategy for inspecting rock exposures in the field, visualizing the critical features of the exposure, and, close to last but certainly not least, recording this critical information for future use. To a degree, yes, visualization comes with experience, but the speed with which students pick up on essential techniques is highly variable.

What I have done in the field, and will continue to refine this approach (as all of this clearly is not rocket science), is to take a high-quality digital image of an outcrop, or field relation involving several outcrops, and print these out and carry them in the field. When I meet up with students, by chance or arrangement, I place us in the exact position/orientation that the image was taken. Then we describe what we see. In this part of the discussion, I emphasize to them....nothing but the facts.....no interpretation. As this process goes on, I pull out images of the feature we are considering, and have them marked up, with some (usually the most important) of our observations. With further discussion, I then pull out another image, with additional markings/details. The process may repeat itself several times, until the final image is one that focuses on interpretations. We close, at least for the moment, with the general question of whether the discussion made sense, and then talk about predictions.

I have found that the approach works quite well. Probably the very first field geology course taught emphasized the importance of accurate recording of

information, including sketches, in a field notebook. Students should not be expected to be their own good artist, but they should be able to accurately portray field relations, for their own use. Digital imaging helps with the process, step by step. Based on a fair amount of feedback, the very simple exercise I have outlined appears to be of use in facilitating students going through the process of visualization and accurately and neatly recording information, on their own.

I close with a question, based, no joking, on experience. What do you do when, on the last day of the last project in the field course, and you run into a student with that student's partner, and the first thing the student says is, "John, which way is north?". Do you (a) scream?, (b) recite the famous line outside the Vesuvio Bar, on Jack Kerouac alley in San Francisco (When the shadow of the grasshopper falls across the trail of the field mouse on green and slimey grass as a red sun rises above the western horizon silhouetting a gaunt and tautly muscled Indian warrior perched with bow and arrow cocked and aimed straight at you it's time for another martini), or (c) look the students in the eye with a smile and say, "ah, you two are doing such a great job, I am so very proud of how you have matured and grasped fundamental geologic principles and approaches during this course.....?????????

What is the impact of scientific visualizations on understanding of Earth processes?

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I am a geophysicist with research interests in design and development of technology-based curriculum to promote exploration of large geoscience datasets. Out of that experience, I have also begun to explore the development of spatial abilities in relation to working with visualizations of geoscience objects and processes, identification and remediation of scientific misconceptions, and knowledge acquisition. The focus of my work has been on students in high school through graduate school and my approach is that of a pragmatist trying to improve my teaching and in turn improve my students' learning potential.

Over the past four years, the SAGUARO team developed a series of GIS-based investigations of Earth processes for high school and college students. Our curriculum promotes inquiry of large data sets to relate patterns observed to the processes behind them. Because it is technology-driven and the technology requires a base level of expertise by the learner, the inquiry is guided; however, there are opportunities for students to freely investigate the data and relationships independently.

In developing the resources, we conducted extensive field tests and usability studies to determine the appropriate level of guidance needed on the technology, identify student misconceptions and measure knowledge acquisition. Through that process, I observed a number of things that I would like to investigate further, although I suspect some of the answers to my questions are already in the research literature.

Is it easier or more difficult to interpret shaded relief maps than contoured maps? Contour maps with color increments or line increments? What interventions are most effective in helping students read maps?

In our curriculum we have routinely used shaded relief maps or contour maps in which elevation increments were color coded rather than depicted with contour lines. In any case, significant numbers of students had difficulty recognizing the topographic features on the map. This is not unexpected and has been documented by many researchers. Interventions that included having students draw topographic profiles across different regions, explore block diagrams with topographic and related subsurface features, and view animations of slices through a block diagram to show how topography would look in a cross section addressed the problem for almost all students. Our approach was to add each of these interventions incrementally until we observed that all students were

successful in interpreting the shaded relief map, but we do not know what the impact of any one of these interventions had on student perception and understanding of the topographic surface and the different mechanisms for representing it. We also do not know which of the three representations of topography, shaded relief, colored contour intervals or contour lines, is most effective in helping students read topographic maps.

Can novice learners effectively interpret animations of processes that include two or more variables?

This question arises from the use of an animation (deemed by a group of expert scientists to be the most accurate and complete representation they had found) of the tsunami created by the 1964 Alaska earthquake. The animation shows changes in sea level in the open ocean and near shorelines from Alaska to California due to the tsunami wave and normal changes in the tide levels over a 14-hour period. In addition to showing the wave propagation across the ocean, graphs of shoreline sea level changes display in “real-time” as the wave animation progresses. Testing of this animation on freshman through senior undergraduate level science majors revealed that many freshman could not identify the coastline nor the initiation point of the tsunami wave, upper classmen who were more familiar with the concept of a tsunami could identify and describe the initial movement of the tsunami wave out from its source region but were confused by wave patterns in which large tides interacted with the tsunami wave. Few students at any level could correlate the shoreline sea level changes with the tsunami and tidal wave patterns. Alternatively, simple animations of tsunami waves on a more local scale and of shorter duration (thus, tides played a relatively small role), and in which the topography of the shoreline was shown in 3D shaded relief were easily described and interpreted by these same students. Tversky et al, 2003 have shown that a series of static visuals are as effective in animations with identical information, so it is possible that this animation could be broken down into a series of graphics that run slower and have more symbols to guide the learners’ observations. But what are the challenges for interpreting still visuals or animated visuals that have multiple variables changing at the same time, such as the tsunami wave height and the tide wave height?

How effective are 3D interactive models in helping learners visualize subsurface features such as the shape of a water table, fault zone, or magma body? What mental models need to be in place before these types of visualizations are effective?

In our investigations of water resources, it was necessary for our students to gain an understanding of how a water table responds to long term over-drafting of an aquifer. Three-dimensional interactive visualizations extending from the ground surface (shown with street grids and topography) to well below the top of the current water table were created. The visualizations also showed the location of pumping wells, which were color-coded to show length of time they had been in operation. It also showed the water table surface 20 years ago and 50 years ago. From this, students were expected to be able to identify and describe the shape of the water table at each point in time, how it had changed between these time periods, and the relationship between length of operation of a well and the top of the water table, among other things.

Most students had great difficulty orienting themselves with the ground surface and projecting observations of subsurface features to the surface. The depiction of the wells seemed to distract them from clearly seeing the water surfaces. And the relationship between the length of time a well had been operating and the level of the water table was generally not observed by the students. Expert scientists, especially in extractive industries such as water, petroleum and minerals, increasingly use these visualizations. What is the key for students to begin interpreting such diagrams? What are the key elements necessary to guide the novice learner through these complex visualizations?

Effective use of models, metaphors and analogies in teaching about Earth processes that occur over long time periods and scales not easily modeled in the laboratory.

In my presentation at the workshop, I will show a number of examples of visuals, models and analogies commonly used in the geosciences to teach about Earth processes that occur over long time periods and scales not easily modeled in the laboratory. It is the only way in many cases to teach about these concepts. However, it is clear we are introducing misconceptions to our students that propagate to different concepts and processes in the geosciences. I am interested in determining how we can improve the current models, analogies and visualizations to address these misconceptions.

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Our group at the University of Texas at El Paso has begun a research effort in visualization, both in terms of fundamental understanding of how subjects interact with and perceive visual displays, as well as using visualizations in the classroom. We have built a GeoWall to use in these studies. This past fall we conducted an experiment using the GeoWall to investigate the impact of stereo views on the Earth-Moon system on student ideas around the phases of the Moon. We also conducted a study of 2-D versus 3-D visualization; the abstract of the paper submitted on this topic is below.

Student Interpretations of 2-D and 3-D Renderings of the Substorm Current Wedge

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Abstract

In this paper we report the results of a study of eight subjects, all physics students with some exposure to space physics, who were provided with 2-D and 3-D depictions of the substorm current wedge. Student understanding of the current wedge was probed by asking them to determine the magnetic perturbations produced by the substorm current wedge system. None of the students were able to determine the complete correct set of north-south and east-west perturbations from the 2-D drawing, but all of them were able to do so from the 3-D rendering. Three students had, in fact, interpreted the 2-D drawing incorrectly and were able to correct the misconception on seeing the 3-D rendering. Other comments from students make it clear that the cognitive processing of mental images is a key factor in their ability to correctly determine the magnetic perturbation due to the current wedge and that the ability to determine the direction of a magnetic field from an arbitrary current is not an impediment. We also discuss the broader implications of this result for in general teaching about magnetism and the relationship to electric current.

The Power of an Interdisciplinary Approach: Bringing together the expertise we need to build stronger tools for visual communication in geoscience.

Cathy Manduca

Why am I interested in 'Teaching with Visualizations'?

Over the past several years, there has been increasing interest in creating visualizations for both scientific research and teaching in all of the sciences. This reflects the power of visualization tools in our research and the excitement we have for seeing our mental images of scientific processes captured on a computer screen. It is no wonder we are excited to use visualizations in our teaching. My interest in bringing together geoscience educators, learning scientists, and creators of visualizations comes from the convergence of four observations:

- 1) Faculty are really interested in using animations in their teaching. I often ask faculty what kinds of resources would be helpful to them, and frequently the answer is a library of animations. I would like to capitalize on this interest in using animations to help faculty be better teachers. This means providing them with access to “good” visualizations and help for how to use them effectively.
- 2) Research exploring the benefits of animations (Tversky, 2002) and the ways we learn from symbols (Uttal, 2002) contradicts our intuition about effective visualizations. Animations that are completely clear to geoscientists and capture all they know about an earth process may not be conveying the same information to students learning the topic and may not be very helpful. Further, creating symbols for objects that are too similar to the objects themselves may cause confusion – that is, diagrams depicting earth processes in a schematic way may be more confusing as the components in the diagram become more realistic.
- 3) Our science increasingly uses visualizations to display and interpret data, but we know very little about what either scientists or students are “seeing” when they interpret these visualizations. I was particularly struck by my own experience with the climate model visualization created by Don Middleton at NCAR that is displayed in our workshop website banner. When I saw this visualization for the first time, I felt that it answered many questions that I had about global atmospheric circulation. I had a very strong feeling of learning and understanding. However, when I thought carefully, I realized I didn't even know what the colors in the visualization represented. Was my new understanding correct or did I jump to an erroneous conclusion about what I was seeing? Given this power of visualizations to communicate we must learn to design and use them wisely so that we avoid misunderstandings. In my mind, this care is equally important for visualizations that enable scientists to communicate among one another as it is for teaching and communicating with the public.
- 4) Discussions about teaching and learning geoscience call out the importance of observation and making mental visualizations (e.g. Manduca, Mogk and Stillings, 2004). This resonates with my experience as a field geologist where I spent years making maps as an aid to developing my own complete three-dimensional mental

animation of the evolution of the geology of my field area through time with an integrated geographically referenced chemical data-set. This mental animation including the geochemical data was used to create and test theories about the origin and evolution of the rocks I was studying. Thus, I am particularly interested in what research on learning can tell us about how geoscientists use mental visualization and how we can assist students in gaining this skill. This information is particularly important as we discuss the future of field training in our discipline and take advantage of new opportunities to engage students with data.

Summing up these ideas, a major opportunity exists to enhance geoscience education through the effective use of visualizations because faculty are excited by animations that capture their knowledge of a topic and by visualizations that are powerful in their work as scientists. However, to effectively capitalize on the use of visualizations in teaching and research we need to know much more about how people learn from visualizations, how they develop their own mental visualizations, and how to design visualizations to effectively teach geoscience concepts.

How does this workshop build on past work?

The focus of my work is on improving geoscience education for undergraduates. My tools have primarily been conferences, reports, professional society meetings, and websites. In 1996, Frank Ireton, Dave Mogk, and I brought together geoscience educators from geology, ocean science and atmospheric science to consider the importance of working together to teach undergraduates about the complete Earth system and to outline the major challenges facing the discipline. The resulting report “Shaping the Future of Undergraduate Earth Science Education—Innovation and Change Using an Earth System Approach” (Ireton et al, 1997) articulates many of the high level goals of geoscience education while making recommendations for teaching strategies and ways to address other ongoing issues critical to improving student learning.

The focus on goals for geoscience education recurred as a major theme at the 2002 workshop “Bringing Research on Learning to the Geosciences” convened by Dave Mogk, Neil Stillings and myself. This workshop brought together leaders from geoscience education, learning science, and the application of learning science to specific science disciplines to initiate the development of a community engaged in applying learning science to the geosciences. The report from this workshop (serc.carleton.edu/research_on_learning/workshop02) outlines a three part strategy including research, dissemination and professional development to enhance geoscience learning by applying the results of research. A critical piece of the proposed research is the development of an understanding of geoscience expertise that can be used to establish well-articulated goals for geoscience education both at the level of the discipline, and by individual faculty in the design of their courses. Research is also recommended that addresses how students acquire geoscience expertise and the design of effective instructional environments.

The important role of observation and visualization in the practice of geoscience and in geoscience expertise was called out at the workshop. These fundamental skills underlie the ability of geoscientists to make sense of field observations, as well as of direct and remote observations on a wide variety of spatial scales, and of complex data sets. Workshop participants recommended increased research into the role of visualization in geoscience thinking and the use of visualizations in teaching. Our current workshop, “Teaching Geoscience with Visualizations” workshop is an exciting response to recommendations in the Bringing Research on Learning to the Geosciences report.

One of the major uses of visualizations in geoscience research and teaching is in displaying data: global observational data, calculated data from models, geographically referenced observations of multiple types (GIS data), representations of the chemical compositions of various earth materials, among others. To explore how faculty across the sciences teach with data and why they think it is important, Dave Mogk and I convened an interdisciplinary workshop and produced the subsequent report “Using Data in the Classroom” (serc.carleton.edu/usingdata). This report again returns to the idea of goals. By considering what we want our students to learn from their experiences with data, the workshop participants developed a set of recommendations for what students should be able to do with data that provide guidance for the developers of data services. These goals and recommendations are helpful as we discuss our use of visualizations in helping students explore and understand data.

This workshop provides for me an opportunity to build on earlier work by considering more specifically the research and questions surrounding teaching with visualizations. I believe that by working in this focused area of high interest, we can demonstrate how by bringing together expertise in geoscience, learning, and education with technical expertise we can improve our ability to do science, to communicate science and to teach science. Of particular interest are articulating principles that can help both developers and users of visualizations be more effective in their work; strategies that can help faculty understand what we know about effective use of visualizations; and research that can refine that understanding. My particular strength will be in assisting with dissemination and professional development, but I am equally excited to begin to engage the research questions, particularly in ways that involve broad community participation.

Acknowledgements

The National Science Foundation provided funding for all of the conferences and reports described above. In addition, “Bringing Research on Learning to the Geosciences” was hosted by the Johnson Foundation at the Wingspread Conference Center. The American Geophysical Union sponsored the “Shaping the Future” conference and published the report. The National Science Digital Library Core Integration Service sponsored the “Using Data in the Classroom” conference.

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Contour Memory Test

Sian Proctor

My work in visualization began with my master's thesis at Arizona State University. I created a virtual application called Volcano Island: A simulation of field geology. Upon completing my masters I enrolled into the PhD program in Curriculum and Instruction: Science Education. Working with Dr. Steve Reynolds (ASU), I have engaged in research looking at the strategies students use when given a contour memory task along with their ability to create mental models of contour maps. To date I have run a pilot study and I'm in the process of putting together my dissertation proposal.

Proposal Summary

An important part of geology is being able to visualize the landscape using contoured topographic maps. In an introductory geology class multiple lab exercises are devoted to topographic map skills and interpretation. For non-science majors the visual/spatial aspects of map interpretation can be difficult to grasp. Research by Eley (1993) has attempted to show subjects mental processes while interpreting contour patterns. Results have indicated that the mental processes of practiced map users are both strategic and flexible. The practiced map user appears to select contoured features that lead to a simplified mental representation of the landscape that are both sensitive and efficient to the task. According to Eley (1993), the practiced topographic map user acts under deliberate purposive action, guided by efficiency-oriented and task-sensitive strategic decisions. The mental processes undertaken by subjects have shown some commonalities but can be influenced by training or map-user predisposition. The purpose of this study is to determine how introductory geology students describe contour map features and to determine the relationship between mental models and memory.

The conventional pattern for studying mental processes set by Eley (1987 and 1993) has been to have subjects study standardized contour maps and then judge separately and subsequently presented three dimensional representations. The response time for studying the contour map and for judging the three dimensional representation is recorded along with the accuracy. That same format was used for this study except instead of recording reaction times subjects were given a time limit to choose their answer.

Computer technology has become an integral part of the learning process and provides a unique opportunity to present visual/spatial information to students. It has enabled geology instructors to improve student visual/spatial skills and understanding of topographic features through interactive multimedia activities. Computerized three dimensional models along with color layering techniques have been found to assist in the visualization and detection of landform features (Phillips, 1982). For this study, students were taught using a combination of concrete modeling, computer simulation, and paper map interpretation. These lessons were part of the Hidden Earth Curriculum developed at Arizona State University and are designed to help students visualize the topography which in turn should improve their ability to generate and manipulate mental models of the landscape.

Pilot Study Methodology

Subjects

The subjects were 31 university students enrolled in an introductory geology class. 19 subjects were female and 12 male.

Materials

The subjects were given a computerized test consisting of 32 multiple choice questions and 8 short answer questions. The test was broken into two parts with 16 multiple choice and 4 short answer questions per part. The test was created using MicroDEM and Authorware.

Procedure

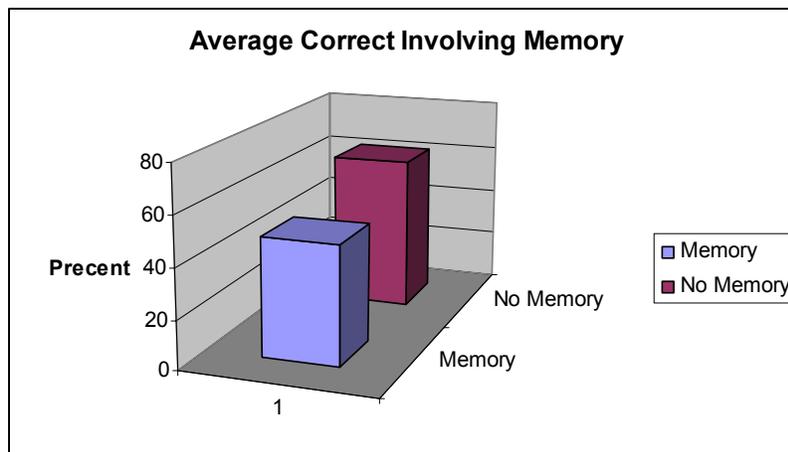
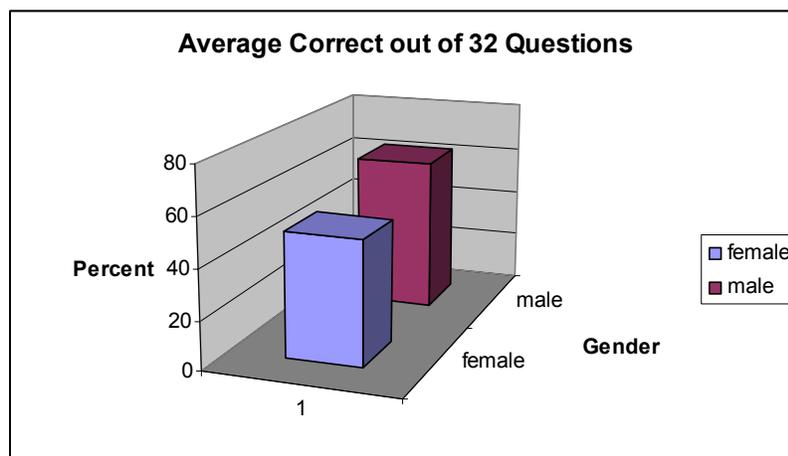
The test was administered as part of a laboratory assignment. Subjects were given a brief introduction stating the purpose of the test and told to follow the instructions. In Part 1, students were first shown four different contoured maps. For each map they were asked to describe how they would memorize the map. They were then given 16 multiple choice questions in which they are shown a contoured map for 5 seconds followed by 4 three-dimensional representations. Subjects were given 10 seconds to choose which representation correctly matched the contour map (see Figure 1). For half of the questions the contour map stayed on screen along with the representations. For the other half, the contour map disappeared and the subject had to rely on memory to determine the correct representation. Subjects did not know if the contour map would stay or disappear ahead of time. Part 2 was identical to Part 1 except for if the contour map remained on screen for a question in part 1 then it disappeared for the same question in Part 2.

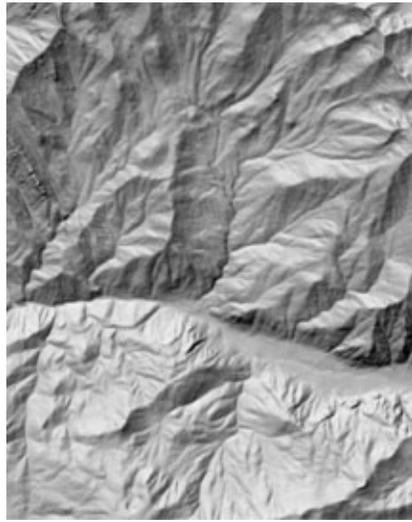
Data Collected

Gender, contour strategy, and the answers to the 32 multiple choice questions were collected.

Results

A two-tailed paired t-test was conducted for gender and memory. The corresponding p-value for gender was 0.032 and for memory was 0.047. There is a significant difference between genders and between no memory and memory. Further data analysis is still in progress including a qualitative assessment of subject's strategies.





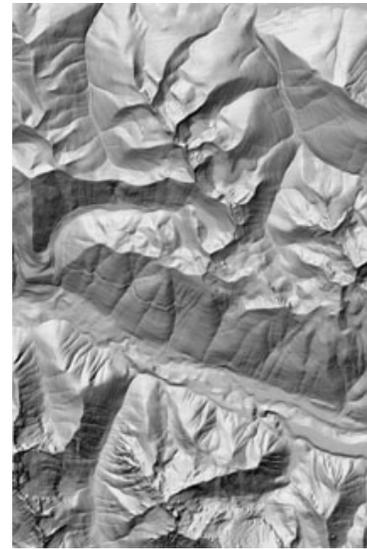
A



B



C



D

Figure 1: Test Question Design

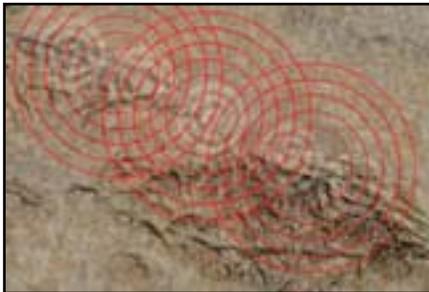
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Using Advanced Interactivity to Create Compelling Simulations for Immersive Earth Science Visualizations

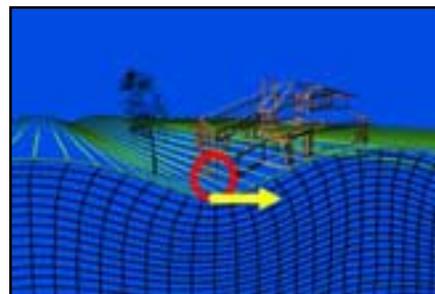
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I have worked closely with geoscience educators for the past five years helping them explore ways to apply technology to their educational efforts. My work has been in the role of education courseware development using tools that offer greater interactivity, accessibility, and scalability than those typically found in undergraduate education. In the past, high-end visualization tools such as AVS and OpenDX have been used to generate powerful visualizations for earth science education at San Diego State University, but have met with mixed results. It is extremely difficult to make these programs conveniently available to undergraduate students, and their non-intuitive interfaces only add to the challenge. Educators have a difficult enough time teaching complex concepts. The last thing they need is the challenge of teaching their students how to use a tool.



As a result, for the past few years I have developed a functional understanding of many tools useful for courseware development. My primary tool of choice is Macromedia Director®. It is the most powerful tool for prototyping and integrating instructional media available. For years, Director has been the leading tool for instructional courseware development. It offers advanced interactive features and cross-platform support. Now, with the addition of Shockwave 3D, a whole new realm of earth science modeling and simulation has opened up.

Still, Director cannot “do it all”. Perhaps my greatest strength is in identifying the appropriate tools for the job, and knowing how to integrate their results into a coherent and meaningful instructional experience. Other tools essential to Earth Science educational development include Discreet’s 3D Studio Max® or Corel’s Bryce® for more detailed



modeling, Macromedia's Flash®, Adobe's Photoshop®, and Apple's QuickTime®.

With these tools, I have recently developed an interactive stereoscopic flythrough capability for the GeoWall. The main feature that may be of greatest interest to the GeoWall community is that the stereo cameras can fly through a 3D space in much the same way our eyes do. In this regard, using simply a mouse as a navigation device, users can navigate a 3D space similarly to using a "magic wand" with a polhemus 3-space tracking device. GeoWall users who don't have such a device will find this very exciting.



With this new level of interactivity, we can introduce students to some compelling and profoundly realistic interactive experiences. Some relatively simple demonstrations of the capabilities have been developed and will be presented. These

demonstrations are only the beginning. Numerous other models developed and implemented with Shockwave 3D have been developed that run in a web browser using the Shockwave plugin, some with the ability to animate 3D objects by parsing XML data from a web site or by accessing a MySQL database. For those users without a GeoWall, additional demonstrations have been developed that can be "free-viewed" ("free-viewing" is a technique in which you cross your eyes to merge the two stereoscopic images and perceive depth). You can explore these and numerous other models that will soon be converted to stereoscopic versions for the GeoWall, at:



<http://www.edcenter.sdsu.edu/geowall/>

<http://www.edcenter.sdsu.edu/ssc/3d/>

<http://www.sci.sdsu.edu/volcano/>

<http://www.edcenter.sdsu.edu/3d/3dg/index.html>

<http://www.edcenter.sdsu.edu/dleseworkshop2004/3dearthquakes.htm>

Know the Flow: Exploring Ground Water Flow with Computer Modeling

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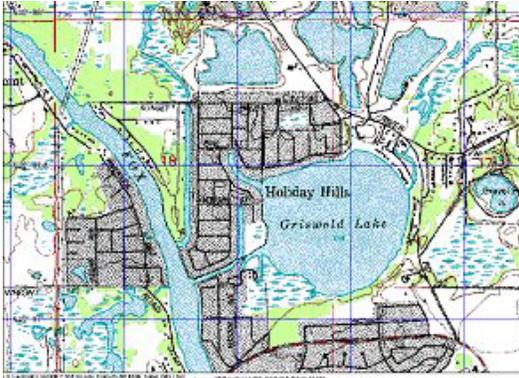
When someone asks a question of a geologist, they're likely to get an answer sketched on a napkin or the back of an envelope. Most of us talk with our students with pencils or chalk in our hands, drawing as we talk, illustrating our discussions with cross sections or crystal structures or geomorphologic time-lapse sequences. We "read" the figures before we read the article; we're visual learners; we think in pictures. It only stands to reason that we would look to visualization as an effective way to help students learn.

I'm a hydrogeologist, so I'll describe how I use visualization to help students understand ground water flow. I use two pre-packaged ground water flow models in my upper-level introductory hydrogeology course. The first, called FLOWNET, is packaged with the textbook. It animates water movement in 2-D layers of different hydraulic properties, and allows the user to change properties, layer characteristics, and hydrogeologic configuration.

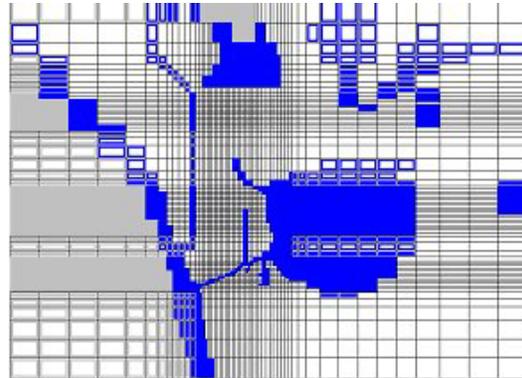
Once students figure out how to use FLOWNET (it is DOS-based and the learning curve is short, but steep for the Windows-dependent), they are fully engaged. I have seen them sit at a computer screen, transfixed, watching the animated "flow" of ground water for minutes at a time, as if it were an aquarium full of tropical fish.

FLOWNET is visually and graphically almost primitive, when compared to the look of even a simple web page. And yet it is effective. Why? I suspect it's because the program is thoroughly interactive, and because the results of any changes to the variables are immediately visible. It gives the student control of the flow system, so they can experiment, testing out hypotheses about how altering aquifer properties will affect the flow. A successful visualization tool should incorporate hands-on inquiry possibilities.

The second visualization tool I use extensively in my hydro class is Graphic Groundwater (GGW), shareware easily downloadable from the internet at the academic website of the author, Steve Esling at Southern Illinois University/Carbondale. (<http://bear.geo.siu.edu/GraphicGroundwaterPage.htm>). GGW is a graphical user interface for the USGS ground water modeling code MODFLOW. It allows the user to start with a topographic map, build a model grid directly on the map, enter hydraulic properties into grid cells as one would into a spreadsheet, click on the grid to enter the positions of water wells, and (among other things) track imaginary "particles" that would flow into the well from the surrounding area.



Students begin with borehole data and a topographic map like this.



They construct a model grid directly on the map, set well locations, and enter hydraulic properties in each grid cell (e.g. blue indicates a cell where surface water is connected to the aquifer).



The completed model allows students to track imaginary particles (the black “spiders” on this map) flowing to the three wells from the surrounding area within a five-year period. Community planners now know what area to designate a “wellhead protection area”.

My students use GGW to delineate the area from which a well will draw recharge during a five-year period. It’s a practical problem and one that allows them to put together geologic skills (reading maps, drawing cross sections) with hydrogeologic concepts (recharge area, ground water flow, hydraulic properties of earth materials) to produce something that would be meaningful to a community—say, a zoning or planning board.

If I’m successful, by the end of the project, the students have an intuitive grasp of the principles of ground water flow, and can describe how altering some of the variables—e.g. increasing pumping rates, decreasing recharge due to drought, or manipulating river levels by using locks and dams—will affect the size of the wellhead protection area. This visualization is successful because the students control the whole look and shape of it and can alter variables at will to experiment with how each change affects ground water flow.

Students in some scientific fields can combine two chemicals in a test tube and watch what happens. Geologists can’t always work that way, because often what we study is underground and hidden from view. Useful visualization tools allow our students to perform hands-on experimentation, creating a virtual laboratory for testing hypotheses that heretofore could not be easily explored in the geology classroom or lab.

Geovisualizations for pre-collegiate science education

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My academic training lies within the realm of educational technology research and instructional design. As a collaborator, I'm often paired with scientists or science educators, with a vision for research or product development but generally unable to implement ideas due to technical or educational research restrictions. In this capacity, I design, implement, and evaluate educational products and courses. Visualization products and tools (digital mapping, animations, and imagery) occupy a substantial position in my research and development efforts.

The context for visualization

My initial interests in visualizations grew from early involvement with an online science education community, The Kansas Collaborative Research Network (KanCRN – <http://pathfinderscience.net>), a 1997 Department of Education Technology Innovation Challenge Grant. KanCRN stressed project based learning through "meaningful, authentic science" for middle and high school students, using the Internet to establish discourse with a mentor/advisor and other participating students. A substantial effort of the grant involved student participation in the entire scientific research process, not simply one *decontextualized* piece of a scientific research process (for example, data collection). Student work at KanCRN was centered on one of several different project areas, some of which included: Global Warming, Tardigrades as bioindicators, Stream Monitoring, Lichens and Sulphur Dioxide, Particulate Monitoring and Phenology.

As students began study in a project, they would initially follow a well-defined framework for conducting research. Initially, student involvement was designed to *create a context*, providing basic subject-specific information and research skills necessary for promoting future, personally-meaning research. While students working in this initial stage, appropriately called *Creating the Context*, did not engage in scientific research, they were expected to gain the requisite facilities and expertise for doing research (working with a research question, collecting pertinent information, collecting relevant data, analyzing data, drawing conclusions, identifying potential social action, etc.).

Students who completed *Creating the Context* inevitably asked more questions, questions that grew from their new experiences and knowledge. These young researchers were directed into a new phase of study, *Guided Research*, where students were allowed to design and implement a study based on their own questions related to the project. Although stringent controls were in place, via Internet technologies, students had great liberty to pursue questions of personal interest. Following the same structure of scientific inquiry set forth in *Creating the Context*, students would ask questions, collect and analyze data, attempt to form conclusions, and most importantly devise further research questions.

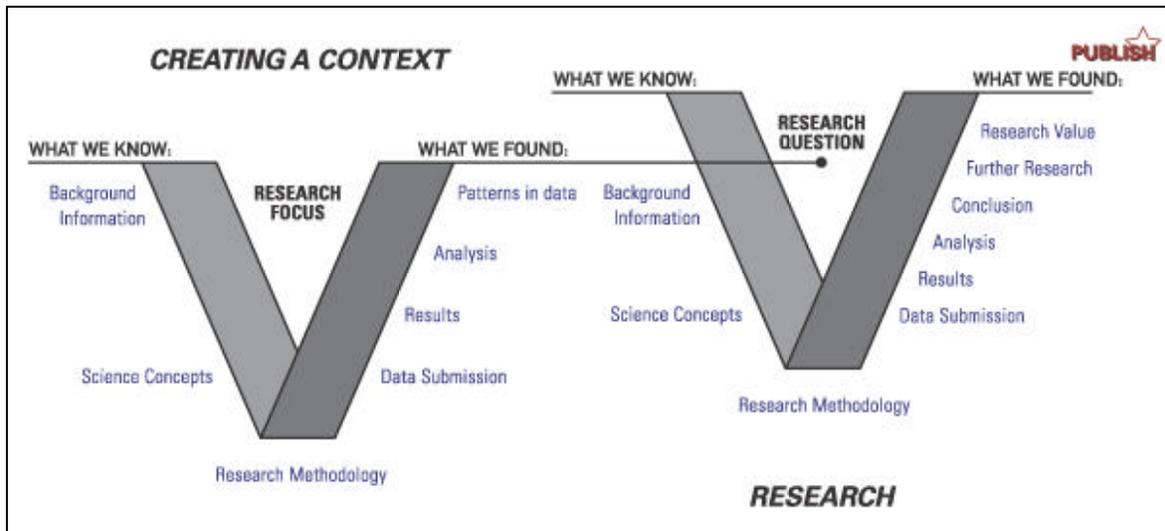


Figure 1: The KanCRN Double Vee-diagram, © Pathfinder Science, LLC

Throughout the development and implementation of KanCRN, it was apparent that some form of data visualization technology would be critical for successful data analysis. Many projects, particularly the *Creating the Context* side of many projects, had hundreds and even thousands of student-submitted data points. In many cases, the data were geographically-relevant making spreadsheet only partially useful and the choice of digital maps (or Geographic Information Systems) one apparent approach to providing students with a visual account of their data.

As a case in point, 120 middle school science students engaged in the KanCRN Lichen and Sulphur Dioxide project, an effort to measure relative air quality using tree lichen as a bioindicator of air quality. This research study used a non-equivalent quasi-experimental research design, wherein two versions of a two-week Project Based Learning unit were developed, implemented, and assessed. Students used a collaborative GIS or paper maps to support data analysis activities in this eighth grade Earth science unit. Attitude and self-efficacy in science and technology as well as student achievement in science process skills were measured. The study found significant improvement in attitudes toward technology, self-efficacy toward science, and modest, yet significant, improvements for geographic data analysis for students who used GIS (Baker & White, 2003; Smith & Baker, 2003).

Extending Scientific Inquiry through Collaborative GIS (ESIC-GIS)

Getting a professional-grade GIS to work for schools requires a substantial commitment of time and resources on the part of schools, teachers, and students. ESIC-GIS (<http://gis.kuscied.org>) is a teacher enhancement grant awarded to the University of Kansas to train in-service K-12 science educators in the use and integration of this data visualization tool. The program focuses on the development of curriculum in a combined online and onsite course along a developmental pathway to teaching *with* GIS and remote-sensing technologies in the science classroom (see Baker, 2000). The program has several ongoing, embedded research agendas, including investigating student learning

from cartographic animation, teacher content acquisition and GIS skills implementation, and teacher training motivation. ESIC-GIS is set to conclude during the fall of 2004.

As part of a research efforts associated with ESIC-GIS, a nationwide collection of data regarding students' learning and performance in understanding graphically rendered GIS data on a number of topics. One example of such GIS data concerns tornado reports across the U.S. over the last several decades. The locations of such reports are superimposed across a map of the continental U.S., and for each report, a dot is generated and placed on the appropriate point on the map. Several maps are presented, each representing a different month of the year. With this display, it is the student's task to draw content information and conclusions about the relative frequency of tornado activity as a function of geography (i.e., region of the U.S.) and time (month of the year). The material has been presented in one of three ways: (a) *static*, in which a list of links is presented, each representing a particular month, and where the student is free to click through each at his/her own pace, and in any particular order; (b) *animated with controls*, in which each monthly display is presented in a sequential fashion, producing apparent motion in which the density of tornado activity moves regionally month-by-month, but where the student has "buttons" that allow for the stopping, pausing, playing, reversing and fast-forward/fast-reverse of the sequential program; and (c) *animated*, in which each month-by-month display is presented in a sequential fashion, but without the buttons which allow students to control the flow of the map sequences. After viewing these exemplars for some amount of time, students are then asked rigorous content questions about the display in order to determine how much they have learned, and are asked to generate inferences and conclusions about the nature of the phenomenon represented as an index of the quality of inquiry the display has engendered.

In the course of conducting research on students' performance under different presentation systems, they observed a number of findings regarding the conditions under which students learn best. One particular finding contradicts the intuitive sense that the presentation of information in animated, dynamic displays should enhance or facilitate learning. Indeed, it was observed that students learned GIS-based information dramatically better under conditions where information is presented in a *static* format; the superiority of static displays yields performance that is approximately 80% better, relative to that seen for animated displays. As counterintuitive as this finding appears, it seems to support conclusions highlighted in a meta-analysis on the effects of the form of visual presentation and display on learning published by Tversky, Morrison, & Bettrancourt (2002), in which animation consistently produces either null or deleterious effects on learning from graphical displays. We believe these results offer immediate implications to the ESIC-GIS program, directing future curriculum development and visualization tool selection. Currently, efforts are underway to replicate, expand, and publish this study.

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Bringing GIS into the introductory Earth Science classroom
at Middle Tennessee State University

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I seek to help undergraduate non-science majors use geographic information systems (GIS) to learn Earth Science at Middle Tennessee State University (MTSU). The following paragraphs outline my goals, past efforts, future plans, and the wider significance of the planned work.

Three goals motivate my use of GIS in introductory Earth Science:

1. familiarizing large numbers of undergraduate non-majors with GIS;
2. recruiting students for GIS courses;
3. recruiting Geoscience majors.

The first goal is important because many disciplines need GIS. For example, at MTSU, GIS is used or discussed in geology, geography, biology, economics, sociology, anthropology, political science, history, recreation, and business. Many students majoring in these disciplines complete an introductory Earth Science course to fulfill part of a general studies science requirement. Consequently, this course can acquaint large numbers of non-majors with a problem-solving tool (GIS) encountered again during advanced study.

The second and third goals are important because the Geosciences Department has primary responsibility for instruction in GIS, geology, and geography at MTSU. For example, I teach GIS, Advanced GIS, introductory Earth Science, structural geology, and field geology. I have an ongoing need to bring non-Geoscience students into the GIS course because roughly two-thirds of current enrollees hail from outside the department and approximately half are completing degrees in the social sciences, humanities, or business. In addition, non-majors enrolled in the GIS and introductory Earth Science courses are recruited for the Geosciences major. If enrollment in the major grows, so will the department.

My interest in using GIS to teach introductory Earth Science blossomed during the last few years. Initially, I used GIS to create hardcopy shaded relief maps, radar images, and perspective views of volcanic landforms, and used these materials to teach introductory geology to majors at the California Institute of Technology (Abolins, 1997). Later, at MTSU, I used GIS and ancillary software to create animated block diagrams for a state-funded educational video on human-environment interactions in karst country (Jackson et al., 2001). Most recently, I used GIS to create hardcopy environmental maps for group-use in a large-lecture introductory Earth Science course (Abolins, in review; also, see the poster and demo at this meeting). Success in past efforts encourages continued use of GIS in teaching.

The efforts described in the previous paragraph benefited from access to a diverse suite of software. At MTSU, this suite includes:

- the full spectrum of Environmental Systems Research Institute (ESRI) GIS software;
- ERDAS Imagine, ER Mapper, and ENVI remote sensing software;
- the IDL programming language;
- Adobe Photoshop and Corel Photopaint graphics software;

- Macromedia Flash animation software.

To complete each step in a project, I used the most appropriate software. For example, I used remote sensing software to process images, GIS software to combine images with road maps, and Adobe Photoshop to polish the final product. Use of multiple software packages was more time-efficient than use of a single package.

In the near future, undergraduate non-majors in the introductory Earth Science course will use ESRI's Arcview GIS software to investigate water resources. I chose this topic because (A) it is a departmental emphasis and (B) an appropriate curriculum exists (Hall-Wallace et al., 2003). The Hall-Wallace et al. curriculum provides ready-to-use activities, and also provides a model for the development of original activities. An original activity will be developed at MTSU during early summer 2004, and will address two needs:

1. making the curriculum more relevant to students living in Middle Tennessee by including karst-related content;
2. showing students that they can create GIS-based educational products at MTSU.

I will pilot, evaluate, and improve the original activity by following the approach described in Hall-Wallace and McAuliffe (2002). Future students completing the curriculum will see how involvement with the MTSU Geosciences Department helps them understand their world.

The original activity will have significance beyond MTSU for two reasons. First, the karst-related content will be relevant to students living in other karst areas (e.g., much of Florida). Second, the planned work will show how the Hall-Wallace et al. curriculum can be used as a model for the development of an original activity focusing on the local environment. To reach a wider audience, project results will be disseminated on the web and through conference talks.

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Promoting Spatial and Temporal Visualization Literacy Among Introductory Earth Science Students

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As part of a Department of Education Fund for Improvement of Secondary Education (FIPSE) grant, I, along with my colleague Erin Campbell-Stone, am identifying those literacies (skills) students must master to be successful in introductory geology courses. In addition to subject content, we have identified six literacies that are important for students to master before they can successfully apply any scientific approach to a societal issue they may face later as citizens. For the Earth sciences, the technical literacies we have identified are:

- the power to interpret a *table, graph or chart*
- the facility to make qualitative assessments
- the capacity to perform simple *quantitative calculations*
- the skill to read different types of *maps*
- the ability to visualize in *three dimensions*
- the capacity to conceptualize *changes through time*.

Rather than identifying those students who lack these literacies and sending them to a campus resource center, e.g. math lab, reading center, etc, we are restructuring our introductory geology classes to incorporate these literacies into all activities associated with the class. By providing students with frequent and on-going practice with these literacies, we hope to foster their mastery by a much larger student population. To aid this development, labs, lecture activities, etc, will all contain a simple graphic that reminds students which literacies they are practicing while completing an activity.

Although one could argue that the first four literacies are common to all sciences, the last two, spatial and temporal visualization, are unique to the Earth sciences. Geology

instructors ask students to visualize structures on scales beyond their everyday experience and which they have had little personal contact. In addition, these visualizations are constructed not from direct observation, but from indirect evidence acquired by a variety of techniques, some of which are quite complex. Armed with this information, students must construct mental models that can never be checked authoritatively for accuracy, i.e. direct observation to compare interpretation and "real world". This type of mental activity is clearly different from say biology where students draw cross-sections and diagrams of objects they have had personal experience with or can directly observe. Given the level of sophistication we are asking of students and the limited practice we provide them, it is not surprising that many students leave geology courses with only the most rudimentary spatial and temporal visualization skills.

With support from the FIPSE grant, we are restructuring our courses so students are given abundant practice with these skills. To accomplish this, we are pursuing a three-prong approach. First, we have constructed lab and lecture activities that require students to apply visualization skills to solve a geologic problem that occurs in the real world. For example in one lecture activity, students construct geologic cross-sections from drill cores to identify hidden igneous intrusions and determine which may be a potential ore body. Another lecture exercise has students find a displaced silver vein in the footwall of a normal fault. (Other lecture activities focus on correlation, groundwater movement, the rock cycle, and determining the plate tectonics of a distant planet.) Second, we are developing a catalog of Flash computer simulations and animations for teaching spatial and temporal visualization. We use these media in the lecture activities as well as labs and extra credit problems. Some files are 3-D blocks students can rotate in space whereas others are animations showing tectonic motions and activity solutions. Because these multimedia are delivered via the Web, they can be used in an instructor-directed mode, e.g. in class, or by students working independently. Third, we are building physical models of the "geologic structures" students model to provide them with a "real " object on which to anchor their two-dimensional

results, i.e. cross-sections, maps, block diagrams, etc. Small models are being constructed for use in the lab whereas larger models are being built for use in a large, auditorium-style classroom. To help students visualize the interior of these models, they are constructed of clear plexiglass so the interiors can be directly observed. Although more difficult to construct, this design does not require students to imagine how strata on the faces of the model project into the interior, an ability some students do not have. As our project progresses, we plan on posting object movies of these models on the Web along with streaming video clips illustrating their use.

My primary goal in attending the visualization workshop is to learn more about how students learn spatially and visually. We will use this knowledge to refine our models and improve their effectiveness. In addition, I would like to share our work with others to get feedback on what works on a cognitive level and what doesn't.

Applications of GIS-based Laboratory Exercises In Entry-level Geoscience Courses

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As instructional lab manager in the Geosciences Department at Princeton, I develop the lab curricula used in our solid earth entry-level courses, train and supervise the graduate student lab instructors (while teaching some labs myself), provide general support for overall geoscience undergraduate instruction, and provide professional development for K-12 school teachers.

Integrating various visualization strategies is critical to education activities in all of these areas. Our classrooms, as are most geoscience classrooms, are littered with not only with rocks, minerals and fossils but also computers, globes, maps of all sorts, Styrofoam, Silly Putty, clay, string, pegboards and plastic syringes (for the ever popular “Jelloea” lab), slinkies, fault models, etc.

Over the last three years we have added computer labs using GIS to our educational bag of tricks, with great success. One technique has been to use GIS-based SAGUARO modules as launching pads for project-based lab exercises. This approach has allowed students to master significant science content at a level and pace far beyond our previous experience. Additionally, it has allowed students to model the process of doing scientific research; an important goal of our entry-level geoscience courses.

Note that I speak of “entry-level” geoscience courses. I have never been comfortable with the term “introductory” courses, because the vast majority of students taking such courses at Princeton our lower level courses are taking them to fulfill a distribution requirement and will likely not take another geoscience course. This is the case at many colleges and universities. The courses might just as aptly be called “terminal” geoscience courses.

This has greatly influenced the way we approach these courses in general, and the way I develop lab curricula in general. Just as important as teaching about the earth, are our goals of teaching students about the process of doing science and developing their critical thinking skills.

As an example, students in GEO210B: Earthquakes, Volcanoes and Other Natural Hazards have just completed one of these lab exercises titled Testing Plate Tectonics. About three weeks into the course and after lectures and assigned textbook readings on plate tectonics, students complete the lab which is organized in three parts

In Part A of the lab, students work through exercises from the SAGUARO Dynamic Earth module, in which they deduce plate movements by analyzing age data from the Mid Atlantic Ridge, East Pacific Rise, and Hawaiian/Emperor volcanic trend. We present this as data used to formulate a plate tectonic model, NUVEL1, which predicts plate motions based on certain assumptions and long-term average plate motions such as the ones they just calculated in the SAGUARO exercises.

In Part B of the lab, students are introduced to the technique of Very Long Baseline Interferometry (VLBI) and showed how to access on-line data from various radio telescope pairs that can be interpreted in terms of near-real time plate motions.

In Part C of the lab, student pairs are assigned either a plate boundary or plate interior to research. They use the SAGUARO GIS ArcView views to image their area of interest, and add geophysical data sets such as telescope locations, volcanoes and earthquake epicenters. They choose baselines that span their plate or plate boundary and compare VLBI rates of baseline length changes with NUVEL1 model rates. They conclude the lab by composing an essay which:

“(focuses) on your plate or plate boundary -- do not discuss the whole theory of plate tectonics...some points to consider (not an exhaustive list):

- Interpret your baseline length changes in terms of plate movements.
- How do your VLBI results agree with your NUVEL predictions?
- How well do your results fit with assumptions of stable plate interiors and active plate boundaries? What could account for discrepancies?
- Are plate velocities constant with time?
- Are your data consistent with the presence or absence of earthquakes, volcanoes and/or topographic features that occur along your plate boundaries or within your plate?”

The result of this exercise is that by the third week of their first (last?) geoscience course, students are working with actual data and testing a fundamental theory. We have developed several other exercises that are organized in a similar fashion. The exercises are well-received by students, who feel immediately engaged and empowered as they manipulate large three-dimensional geophysical data sets, and gain a sophisticated understanding of both geoscience content and the process of doing science.

Geo210B Spring 2004
Feb 16-19

Your Name _____

Lab Partner _____

Computer #(s) _____

Part C investigation: _____

Lab 2: Testing Plate Tectonics

Objectives:

- To understand how movements of lithospheric plates can be tracked through time.
- To distinguish between long-term average and near real-time rates of tectonic plate movements.
- To test plate tectonic theory.

In Part A, you will work through several GIS exercises which illustrate how age data from the ocean floor can be used to track long-term movements of tectonic plate over tens of millions of years.

This ocean floor age data, combined with information from transform fault orientations and earthquake slip data forms the basis of a plate tectonic model called **NUVEL-1** (DeMets et al., 1990, 1991; Argus et al., 1994). NUVEL-1 assumes that the earth's lithosphere is divided into 12 rigid plates that move relative to one another. Within NUVEL-1, plates are not allowed to deform internally, and all the action is assumed to occur along plate boundaries.

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In Part B, you will be introduced to a way to test the NUVEL-1 plate tectonic model. This method uses Very Long Baseline Interferometry (VLBI) from NASA radio telescopes to precisely measure actual changes in lengths of imaginary baselines over the past 20 years.

In Part C, you and a partner will be assigned a particular plate or plate boundary to investigate. You will compare and discuss actual plate motions measured by VLBI, to the motions predicted by the NUVEL-1 model.

Part A. Tracking Lithospheric Plates by Investigating Seafloor Age

Individual work : complete questions on pages 2-6 (*not included here*). This should take about one hour.

Launch ArcView GIS

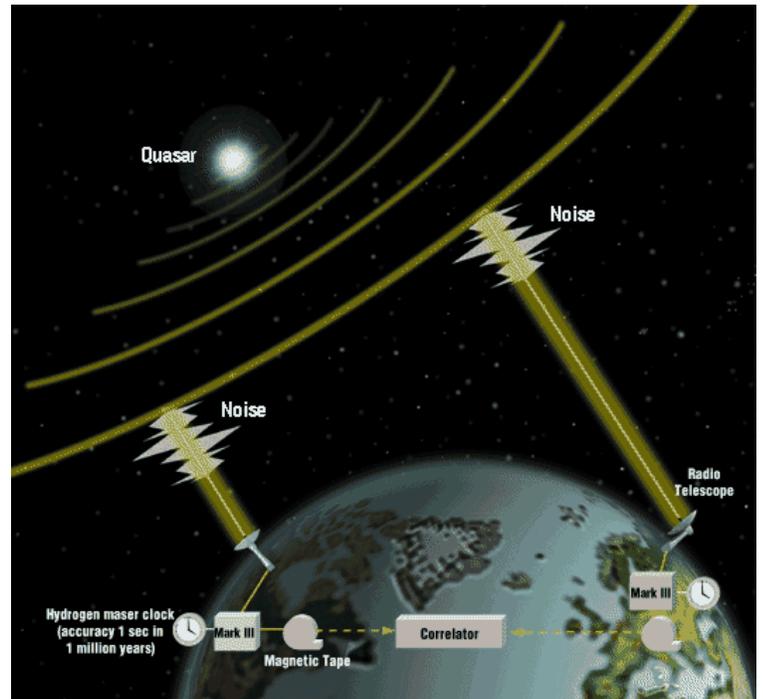
Open the existing project dynamic.apr which can be found via d:/saguaro/dynamic/dynamic.apr

Open the Changing Plates view (last week you worked with the Clues view)

Part B. Near real-time actual baseline length changes with VLBI (Very Long Baseline Interferometry)



Radiotelescope ORVO in the Owens Valley, California. See tiny lab manager at base of telescope for scale.



Class discussion:

- Review homework assignment.
- Add a theme with VLBI telescope locations to ArcView:
 - Go to View→Add→Theme and then find d:\users\geo210\lab2\location.shp and click ok.
 - You will have added the theme “locations” to the top of the legend.
 - Click and activate it.
 - Use zoom and the identity tool to identify individual telescopes and plates on which they sit.
- Using either Netscape or Internet Explorer, your instructor will show you how to access VLBI baseline data from <http://lupus.gsfc.nasa.gov/plots/baseline/gif>
 - Not all baselines have data: see provided list of available baselines.
 - See the following page for an example of the data you will collect.

Obtaining VLBI data and NUVEL rates for a baseline

Name of baseline. Both telescopes are in California: one in the Mojave Desert and the other at Vandenberg Air Force Base.

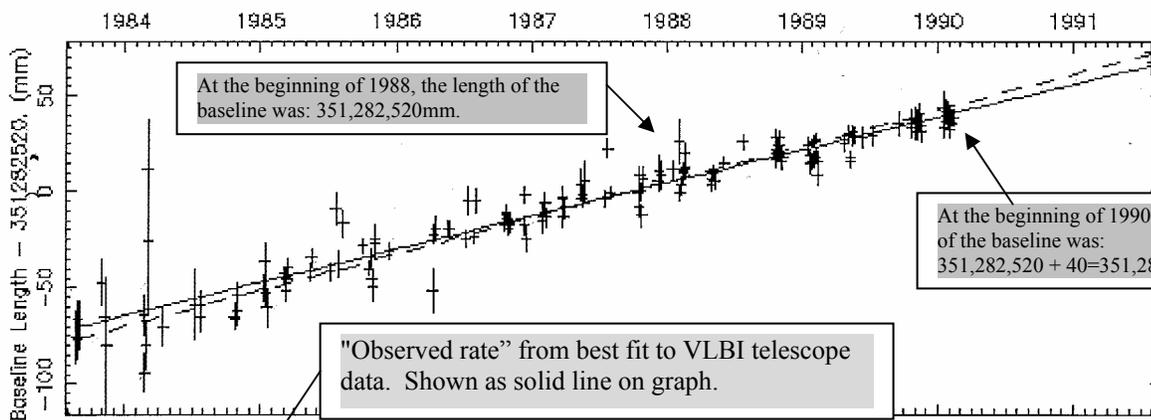
Vector baseline plots for MOJAVE12-VNDNBERG

GSFC VLBI Solution 2001ct03 - June 2001

Baseline length = 351 kilometers

Number of sessions = 181

Number of VLBI data points on graph.



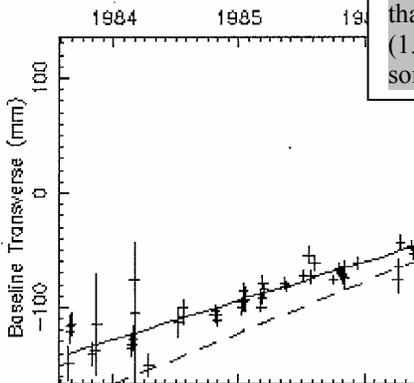
At the beginning of 1988, the length of the baseline was: 351,282,520mm.

At the beginning of 1990, the length of the baseline was: 351,282,520 + 40 = 351,282,560mm.

"Observed rate" from best fit to VLBI telescope data. Shown as solid line on graph.

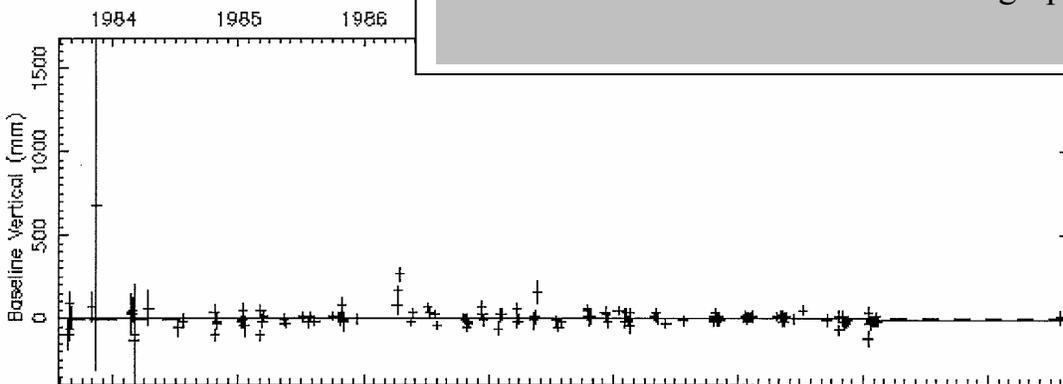
Observed Rate = $17.2 \pm .3$ mm/yr (scaled sig.) Wrms of fit = 8.4 mm Reduced_Chi-square = 2.01
 NUVEL model rate = 18.8 mm/yr Weighted mean length = 351282524.3 mm

Long term NUVEL model rate from ocean floor data (Part A). Shown as dashed line on graph. Both rates show that the baseline is lengthening. However, note that the NUVEL rate is about 7% faster than the upper bound of the VLBI rate ($1.3/17.5 \times 100$), indicating that this baseline is currently lengthening at a rate somewhat slower than the long-term average rate.



Observed Rate = $33.6 \pm .3$ mm/yr
 NUVEL model rate = 44.4 mm/yr

You do not need information from the second and third graphs.



Observed Rate = -1.5 ± 1.7 mm/yr Wrms of fit = 33.0 mm Reduced_Chi-square = 1.90
 NUVEL model rate = 1.3 mm/yr

Part C. Investigating your plate or plate boundary

Your plate or plate boundary: _____

C1 Hypothesis: The NUVEL-1 plate tectonic model proposes that plate interiors do not deform and that all the action happens at plate boundaries. What do you predict should happen to the lengths of baselines within your plate or across your plate boundary?

C2 Analysis and Results (*teamwork*)

- ⇒ Investigate the motions within your plate or across your plate boundary and fill out the chart provided; teammates can fill out one or two charts together. Find at least three baselines with data (different baselines can have one endpoint in common); the more, the better. Teams with more telescopes available to them should use four or more baselines. Don't choose baselines that cross more than one plate boundary. Do not print out the NASA data plots; just list the results in the chart.
- ⇒ On the map provided for your area, label your plate or plate boundary. Draw in the baselines that you list in your chart, and key them to your chart so you know which data refers to which baseline. Be sure to confirm the orientation of E/W trending baselines at mid to high latitudes; the baselines are great circle traces and may not be straight lines on a map. (Again, teammates compile their maps together.)
- ⇒ Answer the following questions about your data (a few sentences each). Print out one copy.
 1. Do both VLBI data and NUVEL rates indicate that your baselines are lengthening, shortening or not changing? Or do they contradict one another?
 2. Explain how well the magnitudes of the VLBI and NUVEL rates agree. Be sure to consider the +/- limits of the VLBI rates.
 3. Does the quality of the data give you more confidence in some VLBI rates than others? You might consider number of data points, time span over which data were collected, lengths of error bars, etc.
 4. Any other comments on your results.

C3 Discussion/Conclusions (individual work)

Prepare a one-page (maximum) discussion of your results. Be focused on your plate or plate boundary -- do not discuss the whole theory of plate tectonics! Confer with your teammate and your lab instructor as much as you like, but write your own discussion. Some points to consider (not an exhaustive list):

- Interpret your baseline length changes in terms of plate movements.
- How do your VLBI results agree with your NUVEL predictions?
- How well do your results fit with assumptions of stable plate interiors and active plate boundaries? What could account for discrepancies?
- Are plate velocities constant with time?
- Are your data consistent with the presence or absence of earthquakes, volcanos and/or topographic features that occur along your plate boundaries or within your plate? (Use the GIS database to see these features).

To finish up:

Compile a packet for your team (binder clips provided) that includes, in the following order:

- Lab handouts from each team member.
- Homework assignments from each team member.
- One copy of the C2 Analysis and Results for the team.
- C3 Discussion/Conclusions from each team member.

Close all programs

Click "Start" at bottom left and choose "Log Off geo210"

Animating Earth History: Plusses and Pitfalls in Creating/Using Educational Geo-animations

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I come to animation as a geo-science content provider; as an academic research scientist and teacher with a background in marine geophysics and plate tectonics. I lecture about plate tectonics in a great number of venues to a great range of audiences: university courses at all levels, national and local professional meetings, museum/naturalist groups, media groups, retirement homes, after-dinner for community organizations, etc, and, especially, lots of K-12 teacher development workshops. Plate tectonics is a profoundly visual subject, so every presentation I give is full of images: maps, landscape photos, graphs, and conceptual diagrams. I started animating out of pure frustration because plate tectonic stories are always four dimensional. I really needed my images to move and change with time. I was wearing out my arms, waving them in the air – trying to sketch out the mental animations that I had running in my head.

I started animating in the 1980s with the production of a twenty minute intro film, “Continental Drift and Plate Tectonics”. We made it with student artists and student shooters painting stacks of Disney-style plastic cels and shooting them: thirty frames per second, one frame at a time! Despite its drawbacks of this old film - very amateurish production, some important content mistakes (editing was nearly impossible with so many painted cels) - it is still used extensively in classrooms around the world and at many levels. I learned some lessons from this project. 1) The teaching world is hungry for clear, concise explanatory visual materials. 2) One set of simple, clear, moving images can communicate ideas across a surprisingly large span of cultures, ages, and knowledge levels; we were aiming at large freshman “intro” classes, but in fact the movie is used from graduate classes* to fifth grade**, and it is used by non-English speakers (with the sound turned off and the teacher narrating as needed).

The advent of user-friendly computer-animation programs in the 1990’s made me into an animation fanatic and the development of web-delivery opened a huge new set of opportunities. My recent passion has been to create basic geological information packages on local and regional scales and offer them to anyone who will use them.

* as a quick introduction to get everyone onto the “same page”.

** as a “capstone”-like experience to cement in what they have been studying.

The local aspect is crucial for the teaching of introductory geology since each locality has its own distinct, smallish subset of geological objects and processes, rendering much of the material in any textbook unfamiliar, alien and, some would say, irrelevant, at least for that important first taste.

Since there is no way that I can personally master the local/regional geological stories of more than a few places, I have set up a visitor's center (EMVC or Educational Multimedia Visualization Center). Colleagues are invited to visit, bringing their regional expertise and still images and leaving with animations and digital imagery. Thanks to an

NSF Distinguished Teaching Scholars Award, the center offers the services of a geo-artist, student animators, video and sound studios, dissemination possibilities, and good geological conversation; visitors' travel and living expenses are paid. For more information about the center and/or to download some of our products, visit our website at <http://emvc.geol.ucsb.edu>

Below is a listing of insights and problems that I hope to share and discuss at the meeting.

Some factors affecting effective communication using conceptual animations:

Medium to fast moving objects get the attention, hence the particular importance of ones choices for frames of reference and movie speeds.

Very slow motions or changes are invisible. (It is shockingly easy for the animator to cheat.)

Clutter is bad. Simple, cartoon-like images work best for getting concepts across, but you can include more sophisticated information if it is properly toned down (partially mollifying us scientists' anal need for "accuracy").

Animations are most powerful when imbedded among still landscape/data images (i.e., "Here is what we see" [best if it is a familiar object] "and here is how we think it came to be".) and when used as a complement to hands on activities and field trips.

In presentation, an animation needs to be repeated several times, preferably with the presenter suggesting different aspects to watch on each repetition. (After a single run-through, the viewers are often in a panic).

Settings where the viewer can control the repeats, stops, goes, frontward, backward, etc., are especially engaging and instructive, when they are included as parts of lab exercises, for example.

Moving images aren't a priori better than still ones. (For example, I don't think most fly-throughs convey information very well, though they do add a fun-factor.)

Creation of an animation always takes at least three drafts (like any serious figure or text). We are always surprised when we get the first draft up and running.

Viewers tend to attribute more authenticity to cartoons and animations than the makers intended. (Especially when the animation/cartoon was successful at teaching the concepts. Scary!)

Some technical problems that I'd like to hear about from anyone who is doing these things:

Transfer of computer and photographic images to VHS videotape = ugly and sad!

(And, for now, it is the only way to supply materials to many schools.

Hopefully this will solve itself some day soon.) Reds run, colored vertical lines turn black, edges blur, details crawl, edges are cropped.

Delivery of movies over the web. What works? Is streaming a realistic alternative to big downloads? What works for low end users?

Delivery of power-point conglomerations via the web. Narrated or not? Does written narration work? Other power point issues for telling a story.

Other ways to deliver mixes of imagery, animation, and narration/text.

Teaching With Projections in the Geosciences
David W. Mogk
Dept. of Earth Sciences
Montana State University

Geoscientists are trained to represent multi-component datasets by projecting onto relatively simple diagrams on two-dimensional surfaces. These projections are used to represent a variety of phenomena ranging from spatial relations to physico-chemical processes. By using projections, it is possible to create simple diagrams as models or analogs of complex and heterogeneous natural systems using a limited number of well-defined “end-member” or stylized variables. Although projections are widely used in professional practice, the construction, use and interpretation of these diagrams often presents formidable barriers to student learning. This is largely due to the fact that diagrams that display projected data are the composite product of underlying scientific and mathematical principles, spatial relations on the diagrams may serve as proxies for physical or chemical properties or processes (thus co-mingling spatial reasoning with conceptual reasoning), there are myriad hidden or understood assumptions in the creation of the projections, and projections seek to decrease the “dimensionality” (or degrees of freedom) of multi-component (or multi-variable) systems. Additional layers of information may be superposed on projected diagrams by contouring data, using color or other symbols to distinguish discrete populations of data, imposing gradients of related variables (e.g. isotherms on composition diagrams), or using multiple projections to demonstrate time sequences that elucidate processes (e.g. before/after relations; certain types of animations). Thus, the simple forms of graphical projections may belie numerous layers of information that attempt to explain complex and sophisticated relationships in nature. In striving for simplicity in presentation, diagrams that present projected data may confound student understanding due to lack of knowledge about the inherent complexities in their development. Recall Plato’s Myth of the Cave (Republic, Book 7): the shadow on the wall is at least one step (and probably more) removed from reality. So, too, are the abstract projections used to represent data of all kinds throughout the geosciences.

The following is a brief inventory of projections and their uses in the geosciences:

Maps. Topographic maps are perhaps the most familiar type of projection. Topography is represented by projecting contour lines onto the map surface, and landscapes can be “read” from maps by interpreting the spacing of contour intervals. Other physiographic (e.g. rivers, lakes, etc) and cultural features (e.g. roads, towns, political boundaries) are also superposed onto the topographic map surface, and of course, topographic maps serve as the base for other special types of geologic maps (bedrock, structure/tectonic, soils, hydrology). There are also numerous other map projections in common usage that present a variety of perspectives of the Earth for different purposes (e.g. minimizing distortion of spatial relations, etc). For a more complete description of map projections see <http://erg.usgs.gov/isb/pubs/MapProjections/projections.html>.

Stereonets. Spatial relations in the geosciences are commonly represented by projecting the orientation of planes and lines onto a horizontal surface. There are two main applications of stereonets in the geosciences:

- *Structural Geology.* The orientation of planar features (strike and dip of bedding, foliation, joints) and linear features (trend and plunge of lineations of all kinds) are the primary field data of structural geologists. Stereographic projections provide the means to aggregate these data to help interpret the overall structure of a field area. Structural data presented in this manner emphasize the angles between lines and planes rather than the relative positions of lines and planes in space (i.e. as an alternative to maps of structural data). Stereonets are created on an “equal area net” by plotting the intersection of a plane or line with respect to a reference sphere, as it is projected back to one of the poles of the sphere. The intersection of the line(s) of projection with the horizontal “primitive circle” represents the orientation of the structure. Thus, the number of dimensions are reduced by one, and planes in three-dimensional rock structures are represented by lines (great circles), lineations are represented by points (piercing the primitive circle), and planes may also be represented by the lines normal to their surface (poles) that are then represented by points on a stereonet. The distribution of structural data points will allow the experienced structuralist to interpret the orientation and geometry of deformed rocks (e.g. open, closed, isoclinal, plunging, reclined, recumbent folds) and perhaps to be able to recognize polyphase deformation. Stereonets are a convenient way to graphically represent structural data collected in the field without having to deal with complexities of topography. Spatial relations are lost, but geometric relations are
- *Crystallography;* “Equal angle” stereonets preserve the angular relations of three-dimensional structures, and are commonly used in crystallography to show the spatial relations of crystallographic axes, symmetry elements (e.g. rotation axes, mirrors, center of symmetry), poles to crystal faces (lines normal to the faces), and zone axes. For a crystal in a specific crystal system and point group, the relationships between these crystallographic elements must be internally consistent, and errors are easily detected. For example, given a point group (i.e. distinct collection of symmetry elements) and a single crystal face, it is possible to determine the number and orientation of all symmetrically equivalent crystal faces in a set of faces known as a form. Alternately, given a collection of crystal faces, it is possible to determine and locate the position of any symmetry elements.

In both cases, master geoscientists can “see” geologic structures or crystallographic forms via the abstract representations of stereonets.

Phase diagrams. Petrologists and geochemists routinely use phase diagrams to represent the physico-chemical relationships of natural and experimental systems. The behavior of geochemical systems largely depend on the composition of the system (typically multi-component), the physical and chemical state of the system (dominantly pressure and temperature, but also concerning oxidation state, pH, fugacity or partial pressure of

fluids, activities of chemical components, and the phases present (number and types of minerals, melts, fluids, gases). These relationships are predicated on the laws of thermodynamics, as typically described through Gibbs' mineralogical phase rule. Regardless of the type of phase diagram (e.g. pressure-temperature, temperature-composition, activity-activity), reaction curves are represented by projection of free energy surfaces ($\Delta G=0$) to distinguish the stability fields of different phases or assemblages.

Most phase diagrams are understood to represent systems in equilibrium, and chemical kinetics are conveniently ignored. It is often the case that complex, multi-component natural systems apply a number of simplifying assumptions and are represented by relatively simple binary or ternary systems. The following is a partial list of phase diagrams that are commonly used in petrochemistry:

Temperature-composition diagrams that illustrate a variety of petrologic processes, as well as the changing compositions of phases:

- Binary two-phase loop: displays solid solution properties of mineral systems such as olivine or plagioclase, and the changes in composition expected as a function of crystallization during changing temperature conditions.
- Binary eutectic: shows crystallization/melting relations of two phase systems such as diopside-anorthite (a simple proxy for basalt, using end-member pyroxene and plagioclase compositions), including prediction of the composition of minimum the melt phase.
- Binary solvus: shows solid-state exsolution processes in mineral systems such as alkali feldspars or calcite-dolomite; typically, the alkali feldspar solvus is shown in a series of diagrams from low to high pressure, demonstrating how the phase relations change as melt reactions intersect the solvus at increasingly higher pressures.
- Binary peritectic: shows the process of incongruent melting, where one mineral phase reacts with the melt to produce a secondary phase and additional melt (e.g. olivine + melt \leftrightarrow pyroxene).

In all these phase diagrams it is possible to calculate the relative abundances of minerals and melts using the "lever rule", which then permits more sophisticated mathematical modeling of other phenomena such as trace element behavior in the system using known distribution coefficients.

More complex phase diagrams involving three or more components include

- Ternary cotectic: shows relations of three mineral phases and melt (e.g. anorthite-diopside-forsterite), with isotherms superposed to show the effects of temperature; crystallization sequences can be followed from one phase primary crystallization (fields on the diagram), to two-phase crystallization along the reaction curves, to the final three phase crystallization at the eutectic point (minimum temperature)—the so-called "liquid line of descent".
- Basalt quadrilateral: four phase representations of basalts are often shown as perspective drawing of a quadrilateral e.g. diopside-quartz-forsterite-nepheline or

diopside-forsterite-anorthite-albite at the apices. For the former diagram, planes of silica saturation and undersaturation separate two important classes of igneous rocks, and the forsterite-albite join defines a “thermal divide” which makes it physically impossible for melts to cross this boundary as they cool.

Metamorphic processes are driven by chemical reactions involving solid phases and fluids, and these are typically represented by

- Chemographic diagrams: binary or ternary diagrams that represent the possible reactions among minerals in two- or three-component systems, based on the law of mass action. In a ternary system, reactions involve four phase (univariant reactions, with one degree of freedom) and possible reactions are recognized as “tie line flips” ($A+B=C+D$) or decomposition reactions (e.g. $A = B+C+D$). By knowing the compositional relations of mineral assemblages, it is possible to predict possible reactions without having to know the full stoichiometry of the reactions
- ACF diagrams: the classical representation of metamorphic facies is through diagrams that show assemblages of minerals for metabasites at different physical conditions. These diagrams are projected from quartz as an excess phase, H_2O is recognized as being present in the system, and numerous assumptions are imposed (e.g. assigning FeO-MgO-MnO as a single component, and “perfectly immobile components” such as Ti and trace elements are ignored) to represent complex basaltic compositions as three essential components.
- AFM diagrams: J.B. Thompson’s classical approach to representing metamorphism of pelitic rocks. Projections from K-excess phases (muscovite or potassium feldspar) are used to represent mineral compositions, which further demonstrate changes in composition of solid solution minerals (e.g. Fe-Mg exchange in garnet, biotite, etc) and the nature of continuous (divariant) and discontinuous (univariant) reactions.
- Petrogenetic grids: Pressure-temperature diagrams that show the distribution of reaction curves as projections of free energy surfaces. The location of the curves is determined from experimental or theoretical studies. Reaction curves typically represent end-member compositions, but these curves can be displaced as a result of compositional variations determined from analysis of the reacting phases. In a qualitative manner, the sequence of reaction curves around an invariant point may be determined using the method of Schreinemakers, and the orientation of the curves may be approximated using first principles of thermochemistry (e.g. the slope of the curves, $\Delta P / \Delta T = \Delta S / \Delta V$ of the reaction according to the Clapeyron equation).
- P-T-t paths: Diagrams that use the petrogenetic grid as a reference to physico-chemical conditions, coupled with geochronologic data, are used to show the evolution of metamorphic systems as rock units traverse through the Earth’s crust throughout their histories.
- Isograds: Representation on geologic maps of the first or last occurrence of metamorphic minerals or assemblages (e.g. biotite-in; talc-out, “first” and “second” sillimanite isograds). Isograds are recognized at the surface (in the field) and in suites of samples (typically through petrography) by observation of mineral assemblages. Isograds represent the intersection of free energy surfaces that separate different stable mineral assemblages with the surface of the Earth. They represent on maps the same types of reactions illustrated in phase diagrams.

- T-X_{fluid} diagrams: Show reaction curves that define mineral-fluid reactions, that can demonstrate reaction pathways that may buffer fluid composition in the system by consumption or creation of metamorphic minerals.
- Composition space: Representation of complex mineral compositions by a number of exchange vectors. For example, starting with the simple formula for the amphibole tremolite, the complex mineral hornblende can be represented as the additive sum of the composition vectors Fe-Mg, NaAl-□Si (edenite), and MgSi-AlAl (tschermakite) substitutions. To the extent that vectors can be presented in 3-d visualizations, the net vector of the hornblende composition can be graphically portrayed. Obviously, more than three components (dimensions) are difficult to portray in graphical form, but even complex formulae may be represented three components at a time if all other components are held constant.
- Reaction space: in the same way, minerals may be represented as vectors in n-space, where n is the number of components, and rocks may be represented as matrices that are a collection of mineral vectors that are composed of the n-components. Univariant reactions involve n+1 phases, so it is possible to efficiently balance complex reactions by solving for the n x n determinant for each successive phase absent to determine the stoichiometric coefficient for that phase. Reaction space provides complementary quantitative solutions to the relative graphical representations provided by chemographic projections.

Thoughts for Further Work:

There is an emerging awareness next generation of research is needed to inform scientists and educators about how we learn about complex Earth systems. There is a coupled need, in the general case, to understand how to effectively use complex datasets in geoscience education. Given the widespread use of projection diagrams in the geosciences, it is important to characterize how expert geoscientists construct, use, and interpret data and their relations that are presented in this manner. An understanding of how experts use projections in their professional work should then inform educators how to better construct instructional materials and activities that introduce these approaches, and to better support student learning in the classroom (including mentoring, monitoring, and assessment). Although projected diagrams seek to simplify complex natural systems, they are inherently complex in how they are constructed and used. For instructional purposes, it is probably fair to ask of each projected diagram:

- What content knowledge is needed to interpret the diagram?
- What conceptual knowledge is needed?
- What assumptions have been applied to construct the diagram?
- Has the purpose of the diagram been clearly articulated?
- What are the reasonable interpretations of the diagram, what are the limitations?
- Have the diagrams been effectively integrated with other instructional methods?
- Have the diagrams been effectively grounded in other scientific contexts—e.g. related to field, petrographic, experimental studies?
- Is it possible for students to construct their own versions of the diagram, or in some (most) cases, must the standard diagrams simply be accepted?

- Do computer programs that create projections (e.g. stereonet programs) enhance or diminish learning? (i.e. Can students construct diagrams with computer-assisted exercises without having to fully understand the process)?
- Are there situations where static diagrams could be replaced by animations? (e.g. Frank Spear's animations of prograde metamorphism shown on AFM diagrams).
- How can we better assess student learning? At some levels, students can usually replicate rote operations (e.g. plotting points on a stereonet, using the lever rule)—but can we also demonstrate deeper levels of understanding?

Practical 3-D Visualization for Understanding Maps
Basil Tikoff
University of Wisconsin – Madison

Visualizations are extremely important tools for most aspects of earth sciences, particularly for investigating the solid earth. Although I have been involved in a variety of types of visualizations, I have always been somewhat concerned about what students learn from them. In particular, computer graphics are great tools, but sometimes are not as effective at communicating results as they could (should?) be. Our experience with advanced technology to demonstrate visualizations, students tend to fall into one of three groups: 1) Students who do not need the technology to grasp the basic concepts; 2) Students who are much more interested in the technology, and therefore often miss the point of the visualization; and 3) Students who do not understand the basic concept, but who often do not choose to use the technology. Although this may seem to portray a negative image of visualization, it merely intends to point out that technology is not going to solve all the problems. Students have other interests besides academics and the major problem is often just getting their attention (the why-you-should-care factor).

I have started to take an Achem's razor approach to visualization. I worry first about resolving the conceptual difficulties that students are having with spatial data. The poster shows a very simple type of technology – called an anaglyph – that appears to work because it is so simple. It renders a standard USGS topographic map in three dimensions. The use of this technology combined with more tactile experiences – making one's own topographic map and clay models – seems to work quite well, and also addresses the different types of learning styles. I am increasingly convinced of the effectiveness of multiple methods of teaching the same material, although it often seems redundant.

The poster also presents some preliminary results from an ongoing classroom assessment designed to address students' visualization difficulties. The assessment consists of frequent, anonymous, ungraded one minute quizzes, each designed to gauge the students' understanding of the most relevant material. The goal is that these quizzes will improve.

Jeff P. Crabaugh
Dept. of Geology and Geophysics, University of Wyoming and
SERC Visiting Fellow, Carleton College

I am the SERC visiting fellow working to develop the on-line resource collection for the *Teaching with Visualizations* website project. As we move into the workshop days and the following weeks, one means of pursuing that goal will be to help you in contributing your visualizations or visualization research for inclusion in the workshop website. I'm here at SERC for a three month period this winter with additional visits planned for this spring. In my 'other life,' I am a postdoctoral research associate at the University of Wyoming investigating the interplay between changes in sedimentation, climate, and tectonism. My teaching takes place in both the classroom and the field. As both a researcher and a teacher, I jumped at the opportunity to involve myself in this project and immerse myself in the world of visualizations and visualization research for several months. It has been, and continues to be, an eye-opening experience. The number of impressive, stimulating visualizations available in digital form is increasing at a rapid rate. This new generation of visualizations excite me with their visual richness, but my personal impression is that there is huge variability among visualizations and their ability to clearly communicate central ideas. What are the elements common to all truly useful visualizations? How do we actually understand what we are seeing? As teachers, what do we need to know about the differences in how an introductory geology student sees an image and the way we as experienced geoscientists see an image? Seeking answers to these questions is the major motivating factor for my involvement in this project. And to give a nod to the obvious, this is an incredible amount of fun!

Another development that excites me about the world of visualizations and their potential in teaching is the increase in their availability and the breadth in types of visualizations made available through the internet. For years I've thought, "Wouldn't it be great if the geoscience classes I taught could be like an interactive version of an episode of some David Attenborough nature documentary or *This Old House*?" The thought was intoxicating. I imagined a lecture peppered with simple animated visuals, but specifically animations that I or the students could manipulate to discuss key points or address questions. In my mind's eye I could see a class that moved seamlessly back-and-forth between live lecture and video clips of small parts of lecture in the field or teacher and students working through key parts of experiments or field observations. I imagined lecturing with an almost limitless number of high quality photos from around the world. I saw the classroom as an exciting springboard into lab where interactive video of physical experiments were integrated with hands-on physical experiments; where interactive animation and computer mapping and modeling packages allowed students to work with models, changing parameters, and then seeing the results. I used to dream about those things. But now all this is possible. At this point it seems to me that the limiting factors are: (1) finding the time to track down all the material, (2) learning how to use them, and (3) finding or creating materials that are actually well-suited to the task and that communicate clearly. My hope is that the *Teaching with Visualizations* workshop and website will serve as a large step forward toward addressing these limiting factors and become a major resource for all of us.