Human Geography & Spatial Thinking: Pathways to Understanding Complex Systems

Sarah Bednarz

Introduction

I am a human geography with research interests in the ways people learn to think spatially using geospatial technologies. As a recovering classroom teacher, I have worked for more than 20 years to improve the quality of geography, geosciences, and environmental education in elementary, middle, and high schools, working with educators and other stakeholders to develop content standards, curriculum support materials, and research-based strategies to improve student learning. As one of the primary authors of the National Geography Standards (1994), I developed the sections on geographic skills. I have been involved with several large educational projects including *Mission Geography*, a NASA-funded project to develop curriculum materials linking the National Geography Standards with NASA's missions and results. Recently I completed a GK-12 NSF program *Advancing Geospatial Skills in Science and Social Science* which linked geospatially skilled graduate fellows with science and social science teachers, grades 6-12, in a collaborative, three year cycle to enhance teacher and student knowledge and skills in spatial thinking.

Systems in Human Geography

All of these projects and my teaching and research have caused me to grapple with how to communicate, explain, and teach about complex systems. In my *Introduction to Human Geography* course, I focus on the interconnected nature of various human and environmental systems. It is convenient to think of complex interlocking relationships as systems. I take the approach of explicitly teaching what systems are in the first unit, defining them as collections of things that influence one another and appear to form a whole. I emphasize the usefulness of this approach—conceptualizing a collection of things as a system reveals its essential elements, how the elements interact, and how the system as a whole relates to other systems, both human and physical. Systems occur at a range of geographic scales and help organize and model associations. We discuss system boundaries, driving and resisting forces, equilibrium, and threshold (what people today commonly refer to as *tipping point*), and use these concepts throughout the course to examine a range of human systems. Offering students this “tool” assists in their ability to understand complex and ill-defined problems and situations.

Spatial Thinking & Complex Systems

Spatial thinking, the focus of my recent research, comprises the knowledge, skills, and habits of mind to use concepts of space, tools of representation, and reasoning processes to structure, solve, and to express solutions to problems. Spatial thinking underlies a significant amount of geosciences learning such as the use of maps, graphs, images, diagrams, models, and visualizations. In addition, it supports the description, explanation, and discussion of the functions, structures, relationships, and operations of a wide variety of spatio-temporal processes. Thus the ability to think spatially is a prerequisite for using and understanding the geospatial technologies commonly used in the geosciences, other disciplines, and everyday life. And spatial thinking is complex.

The National Science Foundation funded *Advancing Geospatial Skills in Science and Social Science* (AGSSS) at Texas A&M University from 2005 to 2009. AGSSS was a first step to explore the utility of applying spatial-thinking research from psychology, cognitive science, and geography to improve science and geography curricula and instruction in spatial analysis and problem solving. AGSSS connected geospatially skilled graduate students, termed Fellows, with science and geography/social studies teachers, grades 6-12. Program goals focused on three questions: 1) What is the nature of spatial thinking in classroom settings? 2) What practical, classroom-based strategies can be used develop spatial thinking? and 3) What is the role of spatial thinking in the implementation of geospatial technologies?

To achieve these goals, Fellows and collaborating faculty worked directly with the teacher-partners to examine existing curricula for opportunities to feature spatial thinking; to introduce geospatial technologies, particularly GIS, remote sensing, and GPS, into classes; and to create new learning opportunities that develop students' spatial thinking, both with and without technologies.

For example, students in the middle school science classes traditionally conducted environmental science field work in a park near the school. AGSSS Fellows, working with the teachers, enhanced the data collection and observation aspects of this activity to incorporate remotely sensed images and maps as well as use GPS units which students employed to precisely locate the features they observed. After students conducted the field work, they returned to the computer lab to import their geo-tagged data into digital maps and remotely-sensed images of the park. Spatializing the field work allowed students to practice spatial-visualization skills such as transforming their perspective and visualizing the spatial arrangement of, and relationships among, the data collected revealing more about the dynamic relationship between biomes and human impacts on the environment.

Overall, more highly spatialized curricula provided the approximately 1,200 students engaged in the program with opportunities to change their attitudes, perceptions, and improve their spatial thinking skills. The impact of AGSSS on students and teachers was assessed in several ways. First, Fellows spent many hours in the classroom observing both teachers and their students. Fellows' reports indicate that as teachers began to understand the nature and importance of spatial thinking, they modified their teaching practice. For example, after teachers, Fellows, and university faculty realized that some students could not understand the tasks they were asked to perform or to express their findings because they lacked adequate spatial vocabulary, teachers increased their use of explicitly spatial language and the AGSSS team developed a vocabulary flip book to address this problem.

In addition to Fellows' observations, teachers reported on the effect of intentionally introducing spatial thinking into their curricula noticing positive impacts on their students that included, but were not limited to, greater use of appropriate terminology to describe spatial or geographical patterns, increased understanding of Earth-sun relations and seasons, better awareness of the similarities and differences among world regions, and a stronger appreciation of the importance location plays on environmental conditions. In sum, explicit instruction in spatial thinking is another strategy that can be employed to help students learn about the structure and operations of complex systems.

Modeling as a Way of Learning About Complexity of Earth Systems

Dave Bice
Professor of Geoscience
Penn State University

For the last two decades, I've been fascinated by the complexity of Earth systems and have made teaching about these systems one of the main foci of my career. I have found that my own personal understanding as well as student learning has been greatly enhanced through the use of models. To my mind, the beauty of models is multifaceted: 1) they allow for experimentation as a way of learning; 2) they force us to think about quantifying things, which necessitates paying attention to units; 3) they provide a unifying framework for discussing processes; and 4) they force us to look for and describe relationships and feedbacks. Models alone are not enough for understanding all of the complexity of Earth systems, but I think they are essential tools.

How did I get to this point? I went to graduate school at Berkeley in the mid-eighties thinking that I was going to become an all-purpose, field-based stratigrapher/structural geologist/tectonicist, like my mentor Walter Alvarez. To a certain extent, that is what I still do, but I also spend a great deal of time working with and teaching with numerical models of all kinds of Earth systems. This evolution was a natural outgrowth of my environment — Walter filled our office with computers, my classmate Lung Chang taught me how to program, and Walter had this unique way of looking at geology as the result of a vast array of processes with complex causes and effects. Before long, we began to realize the potential power of the computers to help us explore numerically the ideas we were always talking about. Thus, my slide into modeling began.

As I was about to leave graduate school for my first faculty position at Carleton College, Walter excitedly called me into his office to show me this new program that he had learned about that made numerical experimentation with systems so easy — this was my introduction to STELLA. When I got to Carleton, I bought a bunch of computers and started to find ways of including STELLA modeling into class and lab exercises in many of my classes. I found it to be an effective and stimulating vehicle for getting students to think about how earth systems work and how complex the dynamics of these systems can be. For the most part, I was tinkering with modeling these systems because I was busy with the task of teaching a crowd of wonderfully curious and fantastically talented students.

I finally got serious about developing a more comprehensive set of earth systems models during a sabbatical leave, which gave me the time to learn about the how to represent some of the key features of the climate system in the form of simple models. I created a web page presenting these materials in the hopes that they would be useful to like-minded educators (www.geosc.psu.edu/~dbice/DaveSTELLA/entrance.htm), and have been pleased to see that many people have made use of these resources. My interest in these models is now in a sort of renaissance period due to interactions with my colleagues at Penn State, many of whom are catching the STELLA bug.

I include along with this essay some examples of teaching exercises using STELLA, exploring Daisyworld and the thermohaline circulation of the north Atlantic.

Louisa Bradtmiller

I teach two introductory-level courses about complex systems: Introduction to Environmental Science, and The Earth's Climate System. As their titles suggest, one is quite broad and covers a range of topics in the natural and human world, while the other is more narrowly focused on a specific topic in Earth science, albeit one with significant links to human behavior. The courses have many similarities- they are both lecture-based, and both have required labs sections. The lab sections are used for inquiry-based activities, while lectures are a combination of lecture, discussion and occasional group activities. Aside from the content, the primary difference between the two courses is the way topics are organized (or not) and presented to students. I will use the rest of this essay to outline the two different approaches, and share some thoughts on what I see as the pros and cons of each as a strategy for teaching complex systems.

Introduction to Environmental Science is a course I 'inherited'- it fulfills a major requirement (also a college-wide science requirement), and is taught every semester. As a first-year faculty member I wasn't looking for extra work, and so left the overall structure of the course intact. The course is explicitly divided into five topics: Biodiversity, Human Population Growth, Energy, Water Availability and Pollution, and Climate Change. We spent several weeks on each topic, including related lab activities, and then switched to the next topic. The Earth's Climate System is a course I developed with colleagues before starting this job, and it follows a more organic approach. We certainly cover different topics, but they are presented to students as a continuum of ideas and concepts that build on one another. In other words, we start with what was identified as the (or at least one) basic building block of climate science- the Earth's radiation budget- and build upon that to explore other things.

These two approaches seem to have affected students' understanding of complex systems in different but not unpredictable ways. The students in Intro. to E.S. demonstrated somewhat better mastery of each individual topic- they were better prepared to answer exam questions about individual processes and specific information than their Climate peers. However, the students in the Climate course have (so far) excelled in answering questions that connect larger-scale processes and concepts together, while perhaps not doing quite as well with detailed questions about, say, Earth's radiation budget. As I stated, this is not unpredictable, but of course, student learning in the ideal course on complex systems would fall somewhere in the middle. So far, I have tried to split the difference by working with the Intro. to E.S. class to make explicit connections between topics, and by re-emphasizing specific facts and ideas several times throughout the Climate course.

This problem is familiar to anyone who has designed a course, a major, or a curriculum. How do we balance breadth and depth? In this case, breadth refers not so much to the range of knowledge covered (although this might also be applicable), but to the understanding of a complex system, and perhaps also to the breadth of ways students might be able to apply that understanding. As I continue to teach these and other courses on complex systems, I hope to find an organizational style that encourages both a complete grasp of the necessary factual information and the ability to connect ideas from different topics together in a deep understanding of the system as a whole.

Cognitive and Affective Aspects of Complexity and Emergence

Sarah Brem, Arizona State University

My work in complexity and emergence for the past several years has focused on students' and teachers' understanding of evolutionary biology and their reaction to evolutionary theory. What I have found most interesting is that many of the concerns that people have about evolution are not just about potential conflicts with their religious beliefs, but more generally with the notion that organisms evolve without purpose or direction, that a particular outcome is a result of thousands of disconnected, stochastic events. It made me curious as to whether the battles over evolution that are so familiar are really about evolution, or whether they are about an uneasiness that complexity and emergent phenomena bring about.

I had the opportunity to explore these ideas through a NSF Synthesis grant, *Evolution Challenges*, which brought together approximately 60 scholars, all of whom teach and learn about evolution, but from different perspectives. There are science educators, paleontologists, evolutionary biologists, philosophers of science, developmental psychologists, cognitive scientists, curriculum developers, educational psychologists, and scholars representing a number of other disciplines. Through this project, we identified several themes that hinder learning and teaching about evolutionary biology, and I wondered whether some of these themes could also be applied to other examples of complexity and emergence.

Working with Micki Chi and many scientists in content areas, these hunches developed into a research proposal that was recently funded by the NSF. Our goal is to test hypotheses about complexity and emergence across domains, to see whether factors that hinder learning in one domain are also present in another. The geosciences are one of the domains that we want to include as a central test bed, because of the richness of examples, and their importance to learners (even if they don't know just yet how important they are!)

Here, I will highlight just a few:

Cognitive heuristics and biases. From infancy on, human beings possess powerful "rules of thumb" that help us quickly simplify situations and make decisions on the fly. In many, if not most, cases, these rules work very well, and allow us to not only survive but to flourish. However, they tend to systematically fail us in certain situations, and cases of emergence are one sort of these situations. For example, we tend to look for single causes that exist and function in a particular way for a purpose, possibly an intentional purpose. We blame a traffic jam on one fender bender and the people who slow down to look. A stream of ants across our countertop are marching in single file because they are watching the ant in front of them, knowing that the lead is taking them to the pile of spilt sugar. To use an example from the geosciences, erosion doesn't occur because of water or wind or the type of rock and dirt, the type of flora and fauna, or the amount of time that has past—it occurs because of all of these things and more happening at the same time, at different times, in different orders, and on and on. But to grasp how all of these different processes come together, with no preset purpose or promised outcome is extraordinarily difficulty. It is easier to say, "the river washed away the rock a long time ago," or "that cliff is eroding because there are no trees with root systems on it." And we may even anthropomorphize, and talk about the river and the wind as if they were living, thinking beings.

In addition to these sorts of constraints, the experiences we have with the world from childhood on further entrench our intuitions, and create what psychologists and sociologists call naïve or folk theories about the world—we have a folk biology that tells us why we look like our parents and siblings, a folk psychology that clues us in to people's motives. We also have naïve or folk geosciences, such as Steve Semken discusses when he describes the fluid-Earth/solid-Earth beliefs of the Navajo people, or Julie Libarkin and Josepha Kurdziel capture in their work on the Proto-process level of understanding that novice students show.

Affective responses to complexity and uncertainty. In my own work with my colleagues, I found that many non-scientists who had a naïve understanding of evolution, even those who accepted evolutionary theory, worried that believing in evolution gave rise to many negative consequences. They thought that belief in evolution would make people more racist and selfish, less able to accept the spiritual, and reduce their sense of purpose and self-determination. Those who believed in evolution not only had these fears, they had them to much the same degree as those who did not accept evolution. This made us curious as to whether the random, uncontrollable nature of evolution, and other emergent processes, might cause a sense of unease, even in an area that is not so politically charged. Changes in climate and the course of rivers, not to mention earthquakes and volcanic eruptions could cause concern because they are hard to understand, hard to predict, and hard to control.

My goal for this workshop is to collect more examples of emergent phenomena in the geosciences, learn how geoscience educators teach about these phenomena and what obstacles or resistance they face, and receive feedback on how my work might help us better understand what makes emergence and complexity challenging to teach and learn.

Colleen Buzby

Essay for Complex Systems workshop

I am a project coordinator and curriculum developer in the Office of STEM Education Partnerships (OSEP) at Northwestern University. I work on the Watershed Dynamics project, an NSF-funded Earth Systems Science Project (ESSP) in partnership with the GLOBE (Global Learning and Observation to Benefit the Environment) Program Office. We have written high school curriculum materials that support student inquiry using desktop and web-based GIS software to explore data relevant to the water cycle. The project teaches students about the complexity of the water cycle and different variables that impact it. For the Water Availability unit, we built a custom web-GIS interface with the National Geographic FieldScope project to visualize and analyze geographic data. We wrote curriculum materials to help teachers and students investigate the nuances and complexities in the data, and understand that the water availability varies across the US and throughout the year.

In developing this project we worked closely with scientists to select a dataset that showed interdependent variables. We used the North American Regional Reanalysis data to show precipitation, evaporation, and surface runoff data. Students can analyze the data to find regions of high and low values, and regions where the values are not comparable. From here students are asked to identify additional inputs and outputs to the system they need to learn about.

We used the reanalysis data in an educational GIS, and made special modifications to enhance visualization and analysis. We used the FieldScope we-based GIS for easy remote access to the data. We also

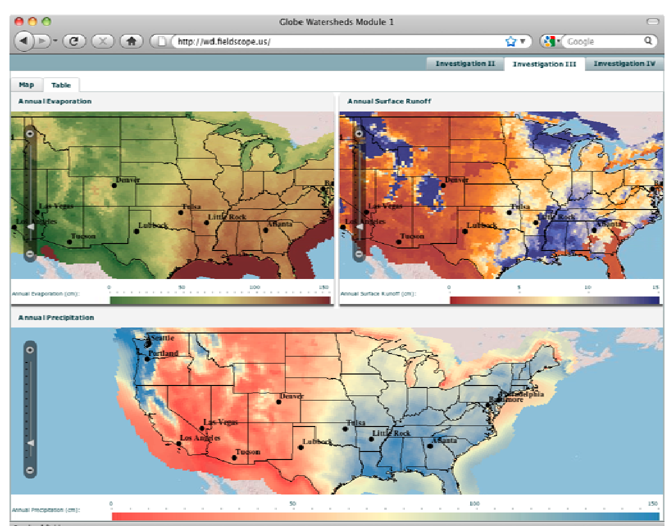

Figure 1: Watersheds GIS Map

created map tables so that students could visualize multiple datasets that would obscure one another in a typical GIS screen. A mp table displays different datasets alongside one another and is linked, so that as you move one, the others move. This linking was useful because students can collect data at a single point from each map. Giving students this ability allows them the chance to draw conclusions from the data. In particular, they learn that the values in this dataset do not represent the complete water budget and they need to get more data to understand the big picture.

Another aim of this project is to support teacher professional development. We want to support teachers so that they can use the tools and educational materials to study the Earth as a system. At workshops with high school teachers, we find they are looking for ways to connect this content to other units and draw connections. After teachers use the GIS tool, they brainstorm what other units they could incorporate these lessons into so that there is integration of the water cycle into other units. Teachers often suggest ecosystems and biomes connections, groundwater, and weather. At a teacher workshop on March 6, 2010, a teacher said, "it was nice to be able to brainstorm with other teachers about how they would use the curriculum in their classroom and bring in other concepts and ideas." Based on these observations, we believe that teachers are learning how to teach systems science and incorporate it into their classroom. Student data will need to be analyzed next.

This project is one example of the four Earth Systems Science Projects working with the GLOBE Program. Together these projects teach K-12 students about the processes of the Earth.

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References:

FieldScope: http://fieldscope.us

FieldScope Water Availability: http://wd.fieldscope.us

OSEP: http://www.osep.northwestern.edu/projects/GLOBE/

Teaching Systems Thinking in the Earth Sciences

Vincent Devlahovich, Department of Geology, College of the Canyons

I feel that Earth Sciences are one of the best possible settings to teach about complex systems. This is because at the core of the Earth Sciences are several complex systems whose connections from an incredible web of scientific complexity which is reflected in our beautiful Earth. I teach various sections of Earth Science each semester, some field based, some online, and some in the classroom setting. This allows me much creative freedom in exploring different pedagogical approaches in which to teach the course content. For the last several years I have used a significant amount of systems thinking in the course delivery, with a surprising amount of student success.

Complex systems thinking, as it relates to the Earth Sciences, involve non-linear, circular relationships in the "spheres": atmosphere, lithosphere, hydrosphere, and cryosphere, which operate independently, but affect each other in feedback and leverage mechanisms. In other words, complex and distant events in space and time are connected within a complex larger pattern. Each sphere influences the others, but in a way that is usually hidden from view. You can only understand the big "system" by contemplating the whole, not by any individual part of the systems. The connections or relationships are the most important part of the system, from the subatomic level all the way to the macro. The larger system moves together as living organism, where chaos and change operate to produce systematic order. Amazingly, the sub-systems themselves organize together to form a powerful self-organizing whole.

This type of thinking is not often taught in higher education, and I believe that it should be, because it not only applies to geosciences systems, but also applies to human relationships and business. For too long we have espoused a linear, cause and effect relationship to understanding natural phenomenon, which is unfortunately left over from the 18th century and the scientific revolution. Many concepts do not have clear lines of cause and effect, but instead operate in circular patterns involving feedback and leverage between concepts that we treat as separate, but in actuality are not separate, but connected.

There is a wholeness that can be perceived in looking at nature as a complex system. This is the way I feel that the Earth Sciences need to be taught in the 21st century.

Minerals as recorders of complex systems with coupled processes

Barb Dutrow

The intrinsic beauty and aesthetic of minerals are only outclassed by the chemical information tucked inside - minerals can be excellent recorders of complexity found in the Earth's system. While studying metamorphic rocks, it became clear that the rock's mineralogy and texture were not only products of thermally activated chemical reactions in the solid state but also influenced by fluids percolating through the intervening pore space. In these geologic settings, fluids flow in response to density gradients set up by the transfer of thermal energy. In turn, this causes changes in fluid compositions. When these rapidly evolving fluids interact with a growing mineral they cause resultant chemical changes to be recorded in the mineral. While some fluid interaction is subtle and has little compositional impact, rapidly changing chemical conditions can be manifest in spectacular chemical zoning patterns in minerals (Fig. 1).

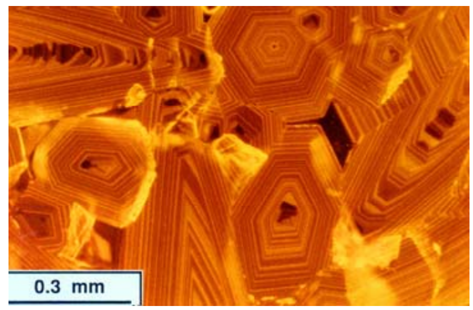

Fig.1 : Intricately zoned calcite crystals as observed in catholodoluminesce. *Photo courtesy of Prof. Ezat Heydari.*

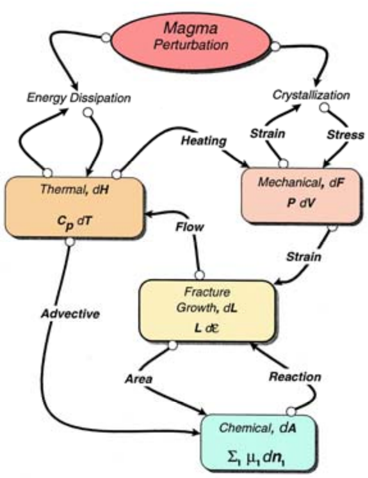

Figure 2: Schematic feedback showing the relationship of processes that occur during contact metamorphism. (Modified from Norton and Dutrow, 2001).

However, these chemical changes may reflect a more interrelated set of physical processes that occur to the rock. Environments where these coupled processes are important include metamorphic aureoles surrounding an igneous intrusions, various ore-forming environments and in other hydrothermal systems. When magma intrudes cooler host rocks, the energy is dissipated to the surrounding rocks through a series of thermal, chemical and mechanical processes. The outcome of each process affects the rates of the other processes. This coupling controls how the system evolves; an evolution typically irregular and often recorded by mineral patterns. Each of these processes affects the other processes in the system to form a series of feedbacks. This is shown schematically by a series of interrelated diagrams whose processes and their coupling can be described mathematically (Fig. 2). In the schematic, boxes indicate the level of the thermal, mechanical and chemical energy reservoirs. Their connectivity is shown by curved lines that indicate the couplings (non-linearities) amongst the processes in the system. Arrows indicate the feedback connections - as directional indicators. The rate mechanisms are described by words;

these are the mechanisms that disperse and change the level of energy each of the reservoirs.

For example, the energy dissipation and crystallization processes specific to the magma are coupled respectively through the thermal and mechanical energy levels. When magma cools and solidifies through mineral crystallization, the pluton fractures, which increases permeability to provide easier access for fluid flow which then more effectively dissipates thermal energy. Similarly, fractures can be induced in the host rock by increases in pore fluid pressure that enhance permeability, increase fluid flow that potentially increases the advective transport of chemical components. These advectively driven chemical reactions cause the consequent precipitation or dissolution of minerals lining the fractures that either decrease or increase the fluid flow pathway. In selected cases, these fracture-sealing materials reflect the feedback in the system, specifically the changing fluid compositions, and can be gorgeous (Fig. 3)!

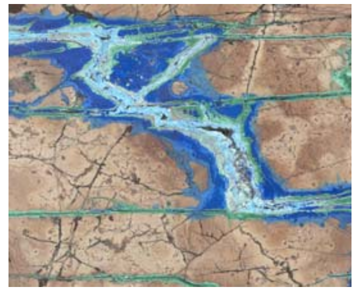

Figure 3: Fracture filled with three generations of copper-bearing minerals: azurite (blue), malachite (green), chrysocolla (light blue). These minerals record changing fluid compositions and seal the pathway for fluid migration. *Image; B. Dutrow*

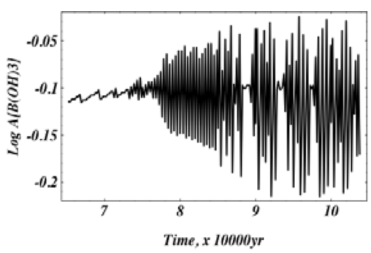

Figure 4: Log $a_{[B(OH)3]}$ vs. time in equilibrium with minerals from the Geysers systems at T,P (see Norton and Dutrow, 2001 for more details).

Patterns of feedback are not only manifest in the fracture fill but also in the individual chemical makeup of a mineral. Minerals may record near-critical conditions in hydrothermal fluids where small perturbations to the system have profound and rapid consequences (Fig. 4). An example of this situation is recorded by the mineral tourmaline that occurs in core samples from the Geysers geothermal deposit in California (Norton and Dutrow, 2001). Geologic estimates of pressure and temperature suggest that rocks likely attained supercritical state conditions in the fluid early in their history. Analysis of these tourmalines reveals that delicate zoning patterns record oscillations preserved in their chemical composition. Such oscillations provide evidence of dynamically changing conditions in the system. These dramatic features record the sensitivity of the stable mineral assemblage to the interactive thermal, mechanical and chemical processes in the system (Fig. 5).

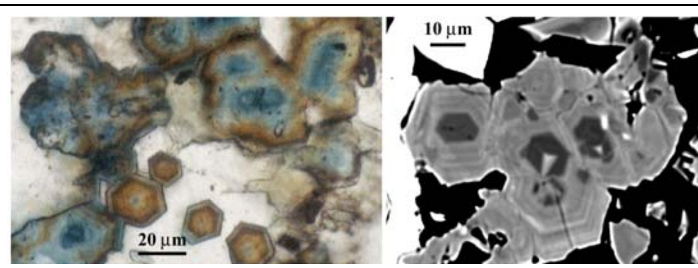

Figure 5: Plane polarized light and backscattered electron image (BEI) of tourmalines that fill veins from the carapace of the Geyser felsite. The tourmalines display oscillatory zoning that reflects chemical changes from schorl (dark gray in BSI) to foitite (light). *Image: B. Dutrow and D. Henry*

For teaching about these complex systems, fractured rocks with cross- cutting veins of distinctive and colorful minerals provide an entree into the world of coupling and feedback. This is done in two courses: a sophomore mineralogy class and a senior-level earth materials and the environment course. In mineralogy, students are given polished slabs of rocks containing copper minerals that seal a series of cross-cutting fractures. A relative geologic history can be determined in the palm of their hand. Students are asked to determine the oldest to the youngest fracture, the minerals sealing the fractures, and in the more advanced class, to determine the change in the fluid composition that cause the minerals to change. The advantage of working with these minerals is that they can be easily identified by color. The disadvantage is that ambiguity exists in determining the relative timing of events. Students then evaluate the rock with respect to the interrelated processes shown in the feedback loops.

References:

Dutrow, B., 2007. Visual Communication: Do you see what I see? Elements, v. 3, pp. 119-126.

Norton, D. and Dutrow, B., 2001. Complex behavior of magma-hydrothermal processes: Role of supercritical fluid. Geochimica et Cosmochimica Acta, v. 65, pp. 4409-4017.

Circling Complexity:

Abrupt Change in Climate & Human Networks

The climate system is an angry beast and we are poking it with sticks!
– Dr. Wally Broecker

Through teaching about complex systems in a course on abrupt climate change, I have developed learning activities driven by three guiding ideas. First, I find it useful to have students encounter complex systems in *more than one real-world context* – and it is critical that one of these contexts relates to common student experience. Second, I find that a *recursive approach* – a strategy that circles over and again through layers of real data, theory, and essential concepts related to complex system behavior – can be effective in deepening understanding. Finally, I have played with assignments that ask students to *integrate their understanding* through the use, creation, and exploration of *analogies* for complex systems across several contexts. This helps students, through a creative and fun process, to generalize behavior while exploring unique differences that depend heavily on context. I will talk a bit about each of these ideas after providing a little content for the course itself.

The course is a 200-level science-rich course for environmental studies majors. Using a data-rich and active-learning classroom approach coupled with term-long team projects, we tackle thorny questions that also baffle researchers. How fast can climate change, and why? What is the evidence and how strong or shaky is it? Is abrupt climate change in our future? How does past civilization "collapse" link to abrupt climate change? The course opens with Kolbert's *Field Notes from a Catastrophe*, anchoring students in today's issues of climate change with some captivating storytelling. We read and discuss a range literature articles on climate change, along with Alley's book, *Two-Mile Time Machine*. We also take on Gladwell's *Tipping Point* for a context related to human social networks. We engage in short cases studies on the Maya and Natufians related to abrupt climate change of different magnitudes. In addition, the course is largely driven by projects where diverse student teams, united by a common interest (water, natural resources, energy, indigenous cultures…), create a web site that tells a story at the intersection of abrupt climate change and their shared interest. Each web site is produced in connection to a partner organization chosen by students, so academic civic engagement is a key feature.

Multiple contexts. Students begin by playing the Tip-It game on the first day of class. I ask them to play the game and carefully record their observations of the systems. I argue that some "essential features" of complex systems are exemplified in the game. We make a class list of these features, and then revisit and revise it several times throughout the term. We next encounter abrupt change in climate systems, and then in human social networks. Our case studies on human civilization collapse raise yet another set of issues around abrupt change. On the team projects, students have their last deep learning experience about abrupt change. Some of their most profound learning grows from thinking about how to connect the science of abrupt climate change to their topic, and how to educate the public to move from a paradigm of gradual to abrupt change. Finally, we explicitly contrast the behavior of simple linear systems with complex ones – often on a spontaneous basis as questions arise in class.

Recursive teaching and learning. The most recursive feature of the pedagogy is the approach to using historical climate data. We begin by looking at proxies of local and global temperature in the last 100 years. Then we go back several hundred years, several thousand, 10,000, 20,000, 1 million, and 2 millions years. We also look into very deep time (several billion years) to explore earth's hothouse and icebox periods. Each time the time window opens further back in geological time, the data set also contains all prior data sets. We often have to either re-interpret the most recent data and/or revise our understanding in light of new data. In this sense, the "data game" we play all term is recursive. We also play the same game with theories at each step of the data game, exploring and refining our understanding of theories for abrupt climate change on various time scales. There is a strong interplay as well between data and theory- a huge theme in the course. Finally, as noted above, we keep revisiting our list of "essential features of complex systems". These ideas eventually get incorporated into each web site in a way that fits with the project context. Some teams decide to emphasize hysteresis or the role of noise in threshold crossing, while others focus more on feedbacks, tipping points, or emergent behavior.

Analogic and integrative assignments. This student work initially operates explicitly at the boundary between two contexts for abrupt change – at the interface between natural and human networks. While we are discussing the Alley and Gladwell books, I have students write an paper where they take concepts and terms in one kind of network, and make analogies to the other network – in an attempt to "learn something new about complex systems". A student might choose, for example, try to apply Gladwell's concept of "the connector" to thinking more carefully about the ocean's thermohaline circulation. My own scholarship in teaching and learning, through analysis of this student writing, has led to a taxonomy for integrative learning that has a developmental axis to it (ask me more this at the workshop). I find that the direct, explicit approach to comparing two system types serves to deepen understanding about both commonalities and context-specific aspects of system behavior. It helps move students from abstract concepts to multiple and concrete examples of how these ideas play out in real systems. Finally, in the team project, students are asked to make analogies for key ideas about complex system behavior. I will never forget the day in class when one team proposed that we could think of stochastic resonance in the following way: as a team of trampoline jumpers, jumping up and down mostly in unison and to large heights in a periodic fashion - disturbed by 1 more "noise" jumper who jumped randomly but to smaller heights. Once in a while, they argued, the "noise" jumper added enough in-phase amplitude to a periodic jumper to cross a threshold that flipped the periodic jumper entirely off the trampoline! "State flip induced by noise coupled to periodic processes", they cried.

Complex Systems as Evolutionary Systems

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Ask the average person, “What is the theory of evolution?” and you are likely to get answers like “natural selection”, or “survival of the fittest”, or “Darwin’s theory.” Because these ideas are systematically taught in classrooms, they may represent the only evolutionary theory people know. But, ask, “What is the theory of Earth evolution?” you will likely get a blank stare, or at best a superficial discussion of the fossil record. All systems that evolve, including mineral and rock systems, atmospheric systems, ecosystems, economic systems, social systems, etc. are complex systems in the technical sense of that term. Conversely, biological evolution is a complex system, but, until recently has not been thought of or modeled as a complex system. My work over the past decade has been to develop a coherent framework, strategy and rubrics for teaching chaos/complex systems as evolutionary systems and applying them to a wide diversity of systems.

There are impediments to incorporating chaos and complex evolutionary systems ideas into traditional scientific disciplines and into the classroom. One impediment is the dominance of linear/equilibrium thinking and training in our schools. Teaching chaos/complex systems principles requires students be familiar with mathematical principles, techniques, and properties not yet systematically taught. A second impediment is the inconsistent and ambiguous use of the terms "complex" and "system." A third impediment is the domination of biological evolutionary theory as the only systematic mechanism for evolutionary change. A fourth impediment is the absence of rubrics for introducing chaos/complex systems theories and modeling techniques in class rooms.

To say a system is complex is not the same as saying it is a complex system. A complex system, in the technical sense, is a group of "agents" (individual interacting units, like birds in a flock, sand grains in a ripple, or individual units of friction along a fault zone), existing far from equilibrium, interacting through positive and negative feedbacks, forming interdependent, dynamic, evolutionary networks, that possess universality properties common to all complex systems: bifurcations, evolution to sensitive dependent critical states, avalanches of changes following power law distributions, with fractal organization, and dynamic behavior as strange attractors that often exhibit bi-stable behavior.

Chaos/complex systems theory behaviors are explicit, with their own assumptions, approaches, cognitive tools, and models that must be taught as deliberately and systematically as the equilibrium principles normally taught to students, or the progressions from pre-algebra, to algebra, to calculus. We have developed a learning progression of concept building from basic principles of chaos theory, through a variety of complex systems, and ending with examples of how such systems work in the real world.

Complex systems are usually defined as *self-organizing* systems; Chris Lucas, for example, (http://www.calresco.org/lucas/cas.htm) states "complexity theory states that critically interacting components *self-organize* to form potentially evolving structures exhibiting a hierarchy of emergent system properties." Self-organization is, however, not the only way that complex systems evolve. We need a more comprehensive framework that can put all systems on an integrated, universal evolutionary theoretical foundation.

If we define evolutionary change as any process that leads to increases in complexity, diversity, order, and/or interconnectedness then there are at least three distinct mechanisms, or theories of evolution: elaboration, self-organization, and fractionation.

Elaborating evolution (subsuming biological evolution as a special case) begins with a seed, an ancestor, or a randomly generated population of agents, and evolves by generating, and randomly mutating, a large diversity of descendants which are evaluated by an external fitness function; those that do not measure up are selected out. The fitness function may be a real environment, an abstract environment, or another "species" of agents. What is common to all elaborating evolutionary systems is the General Evolutionary Algorithm (Beinhocker, 2007): 1) Differentiate, 2) Select, 3) Amplify. Any system that evolves by this process, regardless of the actual units that are differentiating and being selected, is an elaborating evolutionary system. For example, these algorithms are commonly used in computing to find exact or approximate solutions to optimization and search problems. In systems terminology *differentiate* equals positive feedback (an increase in the amount and diversity of information), while (natural) *selection* is negative feedback (trimming back of information).

Self-organizing evolution begins with an initial state of random agents that through the application of simple rules of interaction among the agents (e.g. an algorithm, or chemical/physical laws) evolves a system of ordered structures, patterns, and/or connections without control or guidance by an external agent or process; that is, pulls itself up by its own boot straps. A wide diversity of specific mechanisms have been identified for self organization, including: self-organized criticality, boids, cellular automata, autocatalytic networks, network theory, and oscillating chemical reactions, but they all come down to "Local Rules leads to Global Behavior."

Fractionating evolution begins with a complex parent which is physically, chemically, or biologically divided into fractions—through the addition of the right amount of energy—because of differences in the size, weight, valence, reactivity, etc. of the component particles. Fractionation as a process is pervasive in natural systems (rock and atmospheric evolution, biochemistry, etc.) and is a widespread and well understood industrial process (e.g. fractionation of petroleum, and purification of almost any thing you can imagine.) Scientists and engineers have developed analytical and sophisticated models for these systems. Fractionation is not a mystery. On the other hand, we are unaware of any computer based experimental programs that explore principles of fractionating evolution, either in the spirit of the General Evolutionary Algorithm for elaborating evolution, or comparable to the many specific self-organizing evolutionary algorithms. There are challenges, benefits, and opportunities for exploring these elaborating, self-organizing, and fractionating complex evolutionary systems. There are decades of work in every realm of the sciences to build a theoretical evolutionary foundation based on chaos/complex systems theories to our disciplines, and this should please and challenge us as scientists and teachers.

Beinhocker, E. D., 2007, Origin of Wealth: Evolution, Complexity, and the Radical Remaking of Economics. Cambridge, MA: Harvard Business School Press, 544 pages.

Systems Geobiology: $CaCO_3$-Water-Microbe Feedback Interactions in Hot Springs and Coral Reef Ecosystems

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Systems Geobiology Overview

A fundamental shift is underway in the geosciences in response to the recognition that microorganisms play a fundamental role in the co-evolution of our planet and biosphere. This realization has been shaped by the application of DNA biotechnology to a wide variety of geological marine and terrestrial environments around the world. These studies have revealed that microorganisms drive key global chemical cycles, comprise over half of all living cellular organic carbon (>10^{30} microbial cells inhabit the planet) and contain the overwhelming majority of genetic diversity. As a result, natural scientists are now probing one of the foremost theoretical and practical scientific questions of our time: *How have Microbial Life and Earth co-evolved through geological time and what will future co-evolution yield in the face of ongoing global environmental change?* Systems Geobiology is the name given to this emerging field at the intersection of the geological, chemical, physical and life sciences.

Systems Geobiology Research

The Fouke lab at Illinois has undertaken a decade of coordinated Systems Geobiology research on Yellowstone hot springs and Caribbean and Pacific coral reef ecosystems. While at first glance these seem like wildly different and unrelated environments, closer examination indicates a host of striking similarities and scientific parallels. The spring water at Mammoth Hot Springs in northern Yellowstone is derived from rain and snowmelt runoff in the Gallatin Mountains that flows down along faults into the rock subsurface. This groundwater is then heated by the Yellowstone supervolcano to ~100^{o}C (212^{o}F), chemically dissolves deeply buried ~350 million year old marine limestone, and flows back up to the surface to emerge from vents at a temperature of 73^{o}C (163^{o}F). During this hydrologic journey, the Mammoth Hot Spring water evolves a salty chemical composition remarkably similar to that of seawater. Furthermore, the limestone rock (called travertine) that precipitates to form the classic meter-scale terraced steps of Mammoth Hot Springs are composed of a form of calcium carbonate ($CaCO_3$) mineral called aragonite. This is the same mineral that corals use to precipitate and grow their skeletons. In addition, several of the microbes that we have identified in the 73 to 25^{o}C (163 – 77^{o}F) hot-spring vent drainage patterns at Yellowstone are similar, and sometimes identical, to the microbes inhabiting coral tissues, coral mucus and seawater.

As a result, our field-based controlled experiments at Yellowstone are now being used to predict how corals will respond to future global warming. Heat-loving (thermophilic) microbes living at 65 to 71^{o} C in Yellowstone are able to respond to shifts in water flow rate and temperature by changing the speed at which travertine rock (aragonite) is deposited on the floor of the drainage channels. Our biochemical analyses suggest that the microbes do this by producing different types of protein under different water temperature and flow conditions. We are now applying this mechanism derived from Yellowstone to form new interpretations of how density banding in the aragonitic skeleton of scleractinian corals (similar to tree rings) reflects coral response to changing sea surface temperature. Accurate interpretation of coral skeleton density banding is critically important for predicting future changes in sea surface temperature and thus plays a central role in shaping long-term policy strategies on global warming.

Systems Geobiology Teaching

I teach a variety of courses at Illinois that emphasize the role of microbes in key earth system process. The students in these courses are from many different disciplines, including geology, microbiology, physics, chemistry, engineering, and animal sciences. These courses, have a significant lab component and a field trip, include GEOL 143 History of Life (162 students every Fall), GEOL Sedimentology and Stratigraphy (30 students every Spring), GEOL 415/515 Modern-Ancient Coral Reef Geobiology (SCUBA-based with 30 students every other Spring), and CHP 392 Yellowstone Biocomplexity (30 students every other Fall). I am now including a genomic/metagenomic component in all of these courses, each illustrating the quantitative and qualitative linkages of microbial molecular ecology (and resulting knowledge of community composition and metabolic activity) with understanding of the physical, chemical and biological structure of a natural environment across multidimensional scales of time and space.

Multidimensional Teaching About Climate Change:
A Complexity Perspective

Catherine Gautier

I have been teaching about The Earth as complex system for almost 20 years now and over timeexplored various ways ofteaching it.My learner-centered approach builds uponconstructivist theory principles and fosters teaching practices that recognize the active roles students must play in their learning. Below is a short summary of my experiences adapted in part, from an editorial paper I wrote about Earth System Science Education a few years ago (Gautier, 2006).

Several characteristics encapsulate how learning is conceptualized from this learner-centered perspective. They include students' involvement in the material to be learned, students' acting on the information at a deep level, students' relating the new material to what they already know (proximal learning), students' continually checking and updating their understandings based on new experiences, and students' becoming autonomous and long-life learners aware of the learning process. The nature of the knowledge and research environment that characterizes Earth system science naturally lends itself to the facilitation of student construction of knowledge according to those characteristics. By providing an active learning experience to students, we effectively offer them both opportunity and motivation to understand this complex area of scientific inquiry and to experience deep, enduring and enjoyable learning.

Over time I have developed a number of courses that aim to achieve this learner-centered instruction. My way to address the human sides of Earth System Science is through a**Mock Environmental Summit**course**,** which I offer nearly every summer. This course uses role-playing, argumentation and discussion to heighten epistemological awareness and motivation and thereby facilitate conceptual change.My graduate students and I have documented the significant learning achieved through this approach (Gautier and Rebich, 2005 and Rebich and Gautier, 2005) by developing new evaluation tools based on the analysis of concept maps to evaluate the conceptual learning that occurs (Rebich, 2006, Master's Thesis). One our main findings had to do with misconceptions and their evolution throughout the learning process (Gautier et al., 2007) when provoking cognitive conflict for the student.

Through teaching courses that address either the science of climate change or the policy associated with climate change, I have observed my students clearly and effectively constructingtheir knowledge by gathering and synthesizing information from lectures, books, articles, andfrom internet research. Two main challenges arose: 1) to guide students through integration ofthis complex and extensive information and, 2) to coach students through the assessment ofinformation quality when obtained from the internet. The interdisciplinarity of ESS compounds thedifficulties of the integration as it often requires input from many different fields. The assessment of information quality represents a tough challenge and made even more difficult recently with available sources presenting "skeptical" views of the science. Iaddress it in a variety of ways loosely followinga cognitive apprenticeship approach that involves both providinggeneral guidelines (e.g., try to assess the author's reputation, look for the presence and quality ofthe references), and analyzing in class with students some material that can be challenging for them. For instance, in one of my freshman classes (**Living with Global Warming**) after a distraught student came tome asking me to help her reconcile what she had learned in class with what was presented in a newly released Youtube movie "The Great Global Warming Swindle", we spent the last course lecture critically analyzing the validity of the arguments presented in parts of that movie and discussing how the authors artfully present their material and how that can be convincing to a student (or a broader audience for that matter) whose knowledge is fresh and incomplete.

As integration of information and making connections are central to looking at the issues from a system's perspective, I always ensure that they are performed within the context of critical thinking about contemporary issues and that mystudents investigate issues from different perspectives (political, geopolitical or intergenerationalviews) to broaden their understanding. For instance in my **Oil and Water**class, I help students develop their knowledge base using a book I especially wrote to support this course ("Oil, water and Climate: An Introduction, 2008, Cambridge University Press). I emphasize the development of critical thinkingabilities regarding the interconnectedness of the issues through in-class and homework activities. This is especially valuable as it helps students develop aknowledge framework that they can later use as a basis for evaluating scientific evidence fordecision-making.

Inquiry-based problem solving approaches are central to my teaching as they facilitate students'involvement in their learning. My students use models to address quantitative questions such aswhat is the influence of greenhouse gases or aerosols on climate or perform internet research toinvestigate what potential greenhouse emission limitation can be proposed for a developingcountry in the context of anafter Kyoto Protocol. Whether studies of the sensitivity of climate tovarious external forcing or what if scenarios, targeted inquiries guide my students' learning.
All this is achieved through a collaborative, cooperative and supportive learning environment, where I learn with my students. My teaching is designed toensure that students understand and extend themselves because it is at these edgesthat the learning takes place. For example, in my **Earth System Science** class I use the cognitive apprenticeship method to promote conceptual learning in climate science by encouraging student inquiry, which literature shows to be conducive to learning a multi-faceted topic. In this course students conduct their own research using an up-to-date user-friendly climate (1-D radiative transfer) model. They perform their own experiments around five topics addressed in this class: Earth Radiation Budget and Clouds, Greenhouse Effect, Ozone, Aerosols and Surface Processes. Assigned readings serve as the basis for formulating initial individual questions, while lectures and discussions help to define and refine group research questions and associated projects whose results are then presented in class. Our analysis of students' questions shows improvement in students' ability to formulate questions and that conceptual learning has taken place (Gautier and Solomon, 2006).

In the smaller classes, the evaluation of my students' learning takes place continuously as the learning occurs and isdone in partial collaboration with them using a variety of instruments (e.g., discussions,presentations, short web submissions). Under this evaluation paradigm, there is no longer a cleardistinction between teaching and assessment. They have become intertwined with the role ofassessment ending up being that of promoting and diagnosing learning and no longer limited tograding. In larger classes, multiple assignments are designed to address a variety of learning styles (e.g., verbal, visual) and evaluation is more grade oriented because feedback is harder to give. The continuous evaluation forces me to exercise flexibility and adjust my teaching to the pace at which the overall class learning proceeds. What is covered in class varies each time depending on the make up of the class. To me, this is an acceptable solution as, in a broad and rapidly evolving field as ESS, it is impossible for students to learn everything about it in a classroom setting. So, I believe that instruction must provide students with the tools and motivation to study by themselves and become life-long learners who can actively construct their own knowledge during and after class and continue learning long after their schooling has ended.

Two other aspects permeate all my classes: the development of high-level scientific questions and the ability to use graphics, in terms of both their interpretation and their use in students' own work to support their arguments. To prepare for every classes, students are expected to generate a high-level question around their reading and analyze one graphic relatingto the lecture to come. Although in large classes I do not have time to provide students feedback on their pre-class submissions these important aspects of science are discussed and reinforced in lectures.

More recently I have become even more interested by teaching about complexity and emergenceas they pertain to climate change in particular. I offered a graduate seminar entitled **Emergence and Complexity** a couple years ago as an introduction to these issues and have over the last years integrated more and more explicitly the ingredients of complexity into my courses.

References

Gautier C. , 2006: A personal Experience of Designing Earth System Science Instruction based on Learner-Centered Environment Paradigm, Editorial in **J. Geosc. Ed., 54**, 54-58.

Gautier C., K. Deutsch and S. Rebich, 2006: Misconceptions about the greenhouse effect, **J. Geosc. Ed., 54**, 1, 386-399.

Gautier C. and R. Solomon, 2005: A Preliminary Study of Students' Asking Quantitative Scientific Questions for Inquiry-Based Climate Model Experiments, J. Geosc. Ed., 53, 4, p. 432-443.

Rebich S. and C. Gautier, 2005: Concept Mapping to Reveal Prior Knowledge and Conceptual Change in a Mock Summit Course on Global Climate Change, J. Geosc. Ed., 53, 4, p. 444-457.

Gautier C. and S. Rebich, 2005: The use of a Mock Summit to Support Learning about Global Climate Change, J. Geosc. Ed., 53, 1, 1-15.

TEACHING STUDENTS TO WORK WITHIN THE ENVIRONMENTAL ANALYSIS LITERATURE

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I teach a course entitled "Environmental Analysis" (CHEM/ENVS 328) which requires any 200-level chemistry course as a prerequisite. Beyond that, anything is possible. In the course, we use the primary literature as our textbook in an exploration of the types of quantitative analyses that researchers are carrying out in the real environment. In the course, we hope to directly address many aspects of each paper including the environmental context, the measurement principles used, relevant regulations with particular emphasis on any regulated measurement methods, and the basic scientific background. This not only requires students to learn a variety of complex material about complex environmental and analytical systems, it requires them to assemble it into a coherent framework through which to assess the paper under discussion. Because the environmental system is so broad, in that the papers we discuss could range from the analysis of mercury in tuna to an assessment of air toxics in Beijing to determination of anthropogenic CO_2 in the ocean, there is no possibility that students will have enough specific knowledge to assist them in understanding all of the work we discuss. Additionally, the class as a whole is responsible for choosing the papers that will be addressed throughout the term, so there is no lead-time for me to prepare class discussions in detail. Thus, I find that my goal as the course instructor is more that of a facilitator, and I will describe here how I have been doing this in the various offerings of this course.

The most useful strategy that I have adopted for helping students *decide what they need to learn* to fully understand a paper about an environmental analysis topic is simply to break down the topics in a reproducible way. Because of the various goals of my course, we emphasize the following three areas:

1) the scientific context of the paper (e.g. toxic properties of mercury, where it comes from, and how it gets into the tuna);
2) the experimental techniques used and their benchmarks (e.g. how the mercury in the tuna is sampled and measured, the details of the measurement principle and limits of detection, as well as any standard methods used for analysis of mercury in tuna); and
3) how this compound/class of compounds is regulated, if it is, and what the motivations and issues are for these regulations (e.g. who cares and why).

Students sign up in pairs to lead discussions (to be the "local expert") on these three topics for the various papers, and I enforce that each student leads a discussion in each of the three topics for at least one paper during the course. The discussion of each topic for each paper tends to take approximately one class period. This strategy serves to create students who have specific and relevant knowledge about various aspects of the paper, to give them a venue to teach the rest of the class what they have learned, and then to participate in the group effort of putting it all together. The students who don't lead a discussion on a given paper have the assignment of bringing written questions to the discussions.

The strengths of this approach are that the students are given a narrow slice of a complex topic to tackle with a peer and then to share with their classmates. This is, presumably, more manageable for the students than asking them to tackle all of the parts of a given paper and to help their peers understand the complexities of it. I have found that the defined roles for each local expert, and the fact that they have to take on each role at least once, also allows them to generate good questions to ask each other in the various discussions that they don’t lead, because they are aware of the types of questions that might be asked in that area from other examples. This approach also means that it is the class that does the overall evaluation of the paper and grapples with the whole package of information in all of its complexity, rather than the individuals, and I can assist in managing the discussion.

As alluded to above, one of the challenges of this approach is the role that the instructor takes in the discussions. I find that my role has settled into the following: I am prepared to facilitate the discussion on each topic on each day, but I hope not to do so. I typically don’t know all of the specific details that the student experts bring to the discussion, but I make sure I am conversant in the big picture, and that I have a list of discussion-questions that I can pose to the students to get them thinking about aspects of the topic that the student experts may not think about. The students tend to find it challenging to sort out their jobs as local experts in both directions. They are wary of bringing too much detailed information about their sub-topic because they feel that too much information in any one area might skew the conversation about the paper as a whole. They are similarly wary of bringing too much of the context and big-picture evaluation of their topic because they fear they won’t be detailed enough, and also because they haven’t always developed the perspective to know what the context actually is. A transformation typically occurs during the course, with students getting better and better at navigating what seems initially like a conflict. My role as a faculty member in this process is to help them assess for themselves what the right balance is in any given situation.

Complex Systems, the required essay.
Vicki Hansen

Complex systems thrill me; ultimately I think that is what brought me into geology from chemistry. Many years ago at SMU, I began teaching Physical Geology course as an Earth Systems course. After the first experimental time, I could not go back. Earth Systems science was not the new idea many of us thought it was in the 1990's; A 1975 textbook written by Lee McAlester, SMU Dept. Chair at the time, took an Earth Systems approach. According to Lee the book's approach was inspired by 'The Blue Marble' the first Earth from space, taken by Apollo 17 astronauts on December 7, 1972. The image, which we all know, clearly shows Earth as a gorgeous, wonderfully complex system.

The joy of complex systems is key to several courses that I am lucky enough to 'teach'. Structural geology embodies rheology. Rheology is the key to basically everything, and almost everything affects rheology in one way or another— and those effects come at potentially at a wide range of spatial and temporal scales, to say nothing of the evolution of a material rheology as dependent on its unique history.

I start each year in structural geology with an exercise I call 'play with your food'. Students divide into groups of 4-5; each groups is given the same assortment of food goodies—pretty much what catches my eye [or is on sale] in the grocery store that morning: spaghetti noodles or other pasta, canned frosting, peanut butter, jelly, marshmallows, stick pretzels, saltine crackers, fruit roll ups… you get the idea. The assignment: Build a structure using some of all of the different materials, with the goal of building the highest and strongest structure. During the building consider what is meant by strength, and what makes something strong—we'll work on a definition later. After a limited time we evaluate each structure—deciding the highest is easy, but strength is trickier, and requires defining terms, and 'designing' evaluative tests. The students have great fun, lots of learning occurs too—during building, discussions, evaluation, and throughout the rest of the semester as we refer back to specific topics.

In graduate courses on Early Earth and Advance Structure, consideration of complex systems play a huge role. Early Earth challenges us all to think about the proto- and nascent Earth in ways that open our minds, challenge dearly held beliefs, and, if we are to be successful, to be honest with assumptions and be open to tossing each of those assumptions. In Advance Structure, rheology reins again, but now with even more complexity. We know a bit more, so we are all that more aware of what we don't know and the true pitfalls in our simplified view of the wonderfully complex systems embodied in attempting to understand stress, strain, rheology. Again, in iterative fashion we try to quantify the complexity, always keeping foremost in our minds, that the systems' complexity will (always) trump our understanding—always!

I teach a sophomore-senior level major/minors/teachers course title "Earth's Dynamic Interior'. The goal is to study Earth as a planet, from core to crust—well OK, we also need to include the atmosphere, hydrosphere and biosphere, and we consider the Earth through time—and we compare and contrast the Earth with other terrestrial planets, or terrestrial-planet-like bodies. The other major course goal is help student to be able to begin to think about the Earth quantitatively. The course includes homework problems aimed at teaching students how to quantify: isostacy in various ways, seafloor spreading, uplift-erosion rates, etc. the idea is to help them to understand basic simplifying assumptions, and when we can make these assumptions, and when we cannot. Isostacy is simple, right? Yes, right, but also, absolutely wrong! (Or frightfully naive, at best). Consider a region's topography (through time) as a function of all the players… from the atmosphere above (generating weather and climate), to the components of different density from crust, to mantle, to core-mantle boundary… and yes, perhaps even into the core. Now think about how those different density components came to be. Is their density related to composition? To temperature? To fluids? To history? By the end of the semester we have a class discussion on the complexity of region's elevation (and its elevation through time). We bring in concepts that the students used in their completion of different homework exercise with differ 'views' of isostacy, and first-order concepts and 'facts', that we touch-on, and learn about, during the fair bit of time and effort learning about the Earth's interior. It seems effective to take a simply concept, like the elevation of a region that students can all picture, and to discuss as a whole group—in what becomes a non-linear and open discussion with nearly everyone taking part—all the different factors that come into play, and the scale (in space, density, and time) in which these different factors play a role. We do a similar discussion about the water cycle. All students did a water cycle project in elementary or middle school, but we consider the water cycle involving the mantle, the transition zones, mantle melt formation, ocean floor hydration, subduction—bringing in as many different avenues, side-trips and cycles as the class brings up.

To me, learning about complex systems is very much an interactive exercise, and it starts with this type of thinking. Figuring out the various 'players' or variables, and then seeing how a few variables interact with one another, and then continuing to add complexity and feedback loops—using equations, or modeling programs, or to start with, thought experiments. Many students find it very challenging to accept, or to wrestle with, the concept that they might be able to understand (or begin to understand) complex systems, rather than to just toss up their hands to the complexity. Clearly the reaction to complex systems differs by student. Some students are truly thrilled to learn about complexity, whereas other students seem to be immediately defeated when they catch a glimpse of a systems' complexity.

Working toward an understanding of, and working toward ways to teach about, help others to learn to embrace complex systems, is a life long journey. As in life, I have so much to learn, but I sure find the journey enjoyable.

Student Learning of Complex Earth Systems

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Understanding near-surface earth systems is central to the development of solutions to important environmental issues arising from the growth of human populations and economic activities (Herbert, 2006). A recent report from the National Research Council (2000), *Grand Challenges in Environmental Sciences,* highlighted the need for new models of science education and training that focuses on developing expertise in problem-orientated science. In particular, the need for expertise that can address interdisciplinary problems through the efforts of collaborative groups that integrate the natural sciences, social sciences and engineering around common research problems was cited by the report.

Most environmental issues involve complex earth systems, which are defined as near-surface earth systems that exhibit complex spatial characteristics and dynamics. There are three fundamental cognitive challenges in understanding complex earth systems. The first challenge is the conceptualization of natural earth environments as systems with accurate definition of boundaries and the nature of interactions between the elements of the system. Descriptions of the processes that transfer and manipulate matter and energy within the systems and across system boundaries as well as relations between one system and other systems should also be included in an accurate conceptualization. The second challenge is the characterization and explanation of the complex nature of earth systems through a description of the system's state over space and time, self-organization, or emergence of structure or patterns. A system's state encompasses a description of the all the important variables of the system and how they change under both steady state and non-equilibrium conditions. The third major challenge is the application of conceptual and scientific models of earth systems to support problem solving and the development of effective environmental policy.

Students, experts, policy managers, and stakeholders have been found to commit cognitive errors when reasoning about environmental issues. The behavior and dynamics of earth systems are often complex enough to make prediction of future behavior difficult. Differences in the conceptualizations of systems by stakeholders have contributed to conflict concerning ecosystem and water resources management, through differences in assumed cause and effect mechanisms and average characteristics of the systems. People's conceptualizations of earth systems, when applied to risk perception, are also often ill-structured leading to incorrect perceptions of risk due to global warming, radon, and electric fields.

Environmental decision-making can present policy managers and stakeholders with serious behavioral, cognitive or technical demands. As a result, innovative decision making processes have directly incorporated learning and adaptive management within the processes to identify and minimize cognitive errors. Adaptive management techniques utilize cycles of implementation, evaluation, and improvement to develop more effective environmental management strategies. I propose that a better understanding of the cognitive and epistemological issues students have in understanding and reasoning about complex earth systems, along with teaching methods that directly address these learning issues, are needed to support reform in both earth science education and the management of major environmental issues facing human society.

My research group has focused on the development of student's conceptual models about specific earth systems (McNeal et al., 2008; Miller et al., 2010; Sell et al., 2006). Students, like all people, organize knowledge and reason about environmental issues through manipulation of conceptual models. A conceptual model is a relatively enduring and accessible, but limited cognitive representation of an external natural phenomenon. The nature of near-surface earth systems may present major cognitive difficulties to students in their development of authentic, accurate conceptual models of earth systems. Recently, I have become interested in the potential role of analogous reasoning concerning surficial earth systems using large geospatial datasets to scaffold student development of richer, more accurate models of earth systems. Scientific research of complex systems generally focuses on combing the results of three types of studies: modeling, field work and mechanistic-focused experimental studies. Research has shown the benefits of using simulations constructed with Netlogo or Stella. Focusing on scaffolding analogous reasoning in students as they manipulate geospatial datasets may be an important strategy to support student learning about important earth systems that exhibit complexity.

References

Herbert, B.E., 2006, Student understanding of complex Earth systems, *in* (Eds.), C.A.M.a.D.W.M., ed., Special Paper 413: Earth and Mind: How Geologists Think and Learn about the Earth: Boulder, CO, Geological Society of America, p. 95-104.

McNeal, K.S., Miller, H.R., and Herbert, B.E., 2008, The effect of using inquiry and multiple representations on introductory geology students' conceptual model development of coastal eutrophication.: J. Geosci. Ed., v. 56, p. 201-211.

Miller, H.R., McNeal, K.S., and Herbert, B.E., 2010, Student's conceptual model development of coastal sand-sediment transport during authentic science inquiry in an introductory physical geology course.: J. Geographic Ed. , v. *Accepted*.

Sell, K., Herbert, B.E., Stussey, C.L., and Schielack, J., 2006, Use of physical models and information technology to address undergraduate student mental model development of complex environmental systems: J. Geol. Ed., v. 54, p. 396-407.

Challenges in Learning about Complex Systems

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My research on complex systems began as part of the learning-by-design project (Hmelo, Holton, & Kolodner, 2000). In this work, I initially focused on human biological systems and our research group was investigating how to use design to help support science learning in middle school science. I observed that the children tended to think about structures, with little understanding of functions and behavior. The idea of structure-behavior-function (SBF) as a conceptual representation for thinking about systems originated in work in artificial intelligence that demonstrated that such a representation could be used to effectively reason about designed systems (Goel et al, 1996). To investigate whether this SBF representation might account for expert understanding of complex systems, I studied experts and novices in two domains: human biology and aquarium ecosystems. The results of this study demonstrated that experts thought about complex systems in terms of SBF whereas novices represented these systems largely in terms of structures, occasionally in terms of functions and only rarely in terms of behavior (Hmelo-Silver, Marathe, & Liu, 2007). Novices tended to have simple mental models that revolved around a single structure (e.g, lungs, fish). Experts tended to think about these systems either hierarchically if they were scientists or pragmatically, depending on their goals. For example, the hobbyist experts in the aquarium domain considered what it would take to maintain a healthy aquarium in terms of keeping the fish healthy, breeding, etc. The scientists experts considered how the entire system was driven by energy. One conjecture is that the hobbyist model might form a bridge to a hierarchical scientist model. Another conjecture is that organizing instruction around SBF might help learners push beyond just considering structures.

The first proof of concept study compared structure-oriented hypermedia with function-oriented hypermedia (Liu & Hmelo-Silver 2009). The results demonstrated that the function-oriented hypermedia helped learners develop a deeper understanding of phenomena that were occurring at a microlevel. These were phenomena that novices never considered in the Hmelo-Silver et al, 2007 study. The results suggest that organizing text in terms of a conceptual representation can be a powerful tool for making the invisible visible. However, behaviors were still not well represented, This made sense as the hypermedia was a static medium. Helping learners understand system behaviors was a challenge that required the use of dynamic models.

To address the challenges of helping learners understand the behavioral and functional dynamics in ecosystems, we used the aquarium as a model system. We made behaviors and functions visible through the use of NetLogo simulations (Wilensky & Reisman, 2006) that allowed us to focus on the emergent behaviors and functions at both macro and micro level (Hmelo-Silver, Liu, Gray, & Jordan, 2010). The macro level simulation modeled fish reproduction and carrying capacity. Water quality was a black box in this simulation. This created a problem of understanding that motivated the use of the microlevel simulation. The microelevel simulation modeled nitrification in the aquarium and opened up the black box, allowing learners to explore the relationships between fish population, bacterial populations, and nitrification. A continuing challenge is to encourage learners to make connections between the virtual world and the real world of the aquarium and to take the lessons learned from a model system out into the world. One approach we are currently exploring is using a sequence of curricular units that move from the closed aquarium system to increasingly open ecosystems such as ponds and estuaries. The use of a new tool, the Aquarium Construction Toolkit (Vattam et al., 2009), helps make the SBF conceptual representation explicit. A variety of other challenges remain such as the tension between inquiry and content and teacher's understanding of both inquiry and content.

References

Goel, A. K., Gomez de Silva Garza, A., Grué, N., Murdock, J. W., Recker, M. M., & Govinderaj, T. (1996). Towards designing learning environments -I: Exploring how devices work. In C. Fraisson, G. Gauthier & A. Lesgold (Eds.), *Intelligent Tutoring Systems: Lecture notes in computer science*. NY: Springer.

Hmelo-Silver, C. E.. Liu, L., Gray, S., & Jordan, R. (2010). Using Representational Tools to Learn About Complex Systems: A Tale of Two Classrooms. Manuscript submitted for publication.

Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *Journal of the Learning Sciences, 16*, 307-331.

Liu, L., & Hmelo-Silver, C. E. (2009). Promoting complex systems learning through the use of conceptual representations in hypermedia. *Journal of Research in Science Teaching, 46*, 1023-1040.

Vattam, S., Goel, A. K., Rugaber, S., Hmelo-Silver, C. E., & Jordan, R. (2009). *From conceptual models to agent-based simulations: Why and how* Paper presented at the Fourteenth International Conference on AI in Education, Brighton UK.

Wilensky, U., & Reisman, K. (2006). Thinking like a wolf, sheep, or firefly: Learning biology through constructing and testing computational theories-- an embodied modeling approach. *Cognition and Instruction*, 171-210.

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The two major problems in teaching complex systems as I define them are 1.) student expectations of simple "cause and effect" relationships are eliminated for the most part, and 2.) the systems are not amenable to analysis by looking at small parts and then reassembling the system. The first is a problem because complex systems have feedbacks which typically obscure or remove the cause and effect ideology that students have built up through years of science education. Feedback in many systems removes the ability to say what caused what - the chicken and egg problem. So getting students to understand feedback is a primary task at the beginning of the semester. I work at this through analogies with everyday examples and use the STELLA modeling program in which feedback is visible to the student within the model.

Working with students to understand feedback is an ongoing process that typically takes the whole semester. Starting with simple feedback systems such as bank accounts, we work up through environmental models of CO2 cycles adding more feedbacks as the models become more realistic. Eventually, we study a socio-economic model of the world, the World 3 model, that has 2 major driving positive feedbacks and numerous negative feedbacks. In many complex systems, delays are intrinsically related to feedback and so it is important to look at models that contain both explicit and implicit delays. Implicit delays are not obvious from the how the models look or the underlying equations but are found in the characteristic time that is takes for a process to run. Such delays are often indicated in terms such as half-life, residence time, equilibrium time, mixing time, compounding and others.

The second major challenge to teaching about complex systems is that they are non-linear, they are more than the sum of the parts. So the typical Cartesian method of breaking down a system into small parts, solving each separately and reassembling into a whole does not generally work. This method works so well that even the modeling program STELLA that solves the non-linear differential equations uses it by breaking the equations into very small linear steps that approximate the non-linear solution. In fact, we have no general way of solving non-linear problems. For many, or even most non-linear systems, approximations are acceptable and we can often come very close to the "real" solution. Using the visual STELLA modeling program allows me to put off discussion of the problems of non-linearity until later in the course. The modeling program successfully hides the problems in the simpler models that the students work with at first.

The non-linear aspects of complex systems often first come up for discussion when students start validating and calibrating their models. They note that changes in a variable do not result in consistent or equivalent changes in the results. This leads naturally into working with error analysis and randomness. Randomness is a pervasive part of natural systems and must be built in to most environmental and economic models. Again, the World 3 model is a good complicated model that demonstrates the synergistic effects found in non-linear systems. Students work on analyzing sensitivity of the model to changes in various parameters and typically find that changing any one parameter results in practically no changes in the result. Only by changing multiple parameters and enjoying the multiplying effects of their synergy does the result show changes.

Using a visual systems modeling program such as STELLA and Vensim seems to aid in teaching complex systems analysis to students for many reasons. It reduces the learning curve in discussion of feedbacks because the feedbacks are explicit and visually displayed in the models. The programs allow me to skip discussion of many aspects of non-linearity until later in the course when students have absorbed earlier lessons. Discussions of the "holy trinity" of complex systems; feedback, delay and randomness is what ultimately brings most students to the realizations of non-Cartesian behavior and the fuzziness of the idea of cause and effect. Finally, by building models all through the course, students are able to build their own models of complex systems that they run across during their education and work.

What ideas from physics education research can be useful in teaching complex systems?

Andy Johnson

I have not been working on teaching complex systems - instead I have been studying physics teaching, which focuses on simple systems, yet still offers plenty of learning challenges for students. I want to learn about teaching complex systems, because very few members of our society seem prepared to think in terms of how complex biogeophysical, economic, and cultural systems function, or to act accordingly. This essay will highlight some of the learning challenges that are becoming well known in physics (and in science in general) and ask how these things play out in the teaching and learning of complex systems.

Students walk into our courses with feelings that they already understand things. They have constructed explanations that have worked for them up to that point, and while they may expect to learn something new, they will interpret everything they encounter in terms of their current understandings. The consequence is that learners often construct very different understandings of what was taught than what the teacher intended. And you have to listen carefully to hear the differences.

This happens because learning is not simply the acquisition of information. Learners instead have to form mental images, models and stories that use information, connect to existing knowledge, and provide meaning. It is not enough to just get facts - learning requires developing understanding which is something the learner must create. You can't do this step for your students no matter how hard you try. Instead, the students have to do it themselves. The challenge of teaching, then, is then to put learners in situations in which they need to make sense of something and then to provide appropriately crafted opportunities for this sense-making to get done. The task of the teacher and curriculum developer is one of arousing interest, focusing attention on particular issues, and providing appropriate structures that support sense-making and elaboration. This is what a well-organized inquiry classroom accomplishes.

In any classroom, including inquiry-driven ones, students interpret their experiences in light of what they already know. Part of the time they just "add new knowledge", a process Piaget called "accretion". However, sometimes students need to reconsider something they thought they already knew. They may need to substantially change their thinking in some way to accomodate something new. This is called "restructuring" (Carey, 1988, Posner et. al. 1982) or "conceptual change". Restructuring involves significant changes in one's existing knowledge and belief structures. For example, when studying motion and force, most students have to make major changes in their views of reality to understand Newton's laws because they typically use a "naive physics" that they developed in childhood with limited experience. They have to think in new ways about the causes and effects of motions. To use an analogy, restructuring is more wrenching than just rearranging the furniture in your living room - it may require deciding to use the TV as a countertop, turning the couch on its end, and bringing in a new set of bar stools. You might have to tear out a wall. As you can imagine, restructuring one's thinking is difficult and scary. Students don't generally make substantial conceptual changes like this without a lot of support, effort, and courage so in many cases they will learn to "talk the talk" without actually changing how they think. Thus, they probably don't understand but it's hard to tell because they sound so "correct" part of the time. You can't tell until you really dig into what they are saying and find the right questions to ask.

A restructuring event happened in my own classroom during an inquiry sequence on electric circuits. As students started constructing explanations about what was flowing in circuits, they talked about "electricity" flowing. Many of them used a general idea about one thing flowing that had some of the properties of current and some of the properties of energy. Only when the students made distinctly different measurements of electrical current vs. electrical energy and were explicitly asked to consider the differences did they start thinking that current and energy might in fact be two separate things that both flow in circuits. This was a type of conceptual change that Dykstra (1992) calls "differentiation". The students had to decide that the one thing they were talking about - electricity - was actually two different things - current and energy - with distinctly different behaviors and properties.

Another type of restructuring - class extension - requires students to see two things they previously thought of as different as manifestations of one thing. A third type, which Dykstra calls "reconceptualization", involves changing one's concepts of how things relate to each other and what are the relevant relationships. For example, students must abandon the common belief "force implies motion" in order to understand Newtonian dynamics, and they must construct a new idea - "force implies acceleration", and then use it reliably.

Physics education research has made some progress in identifying the conceptual changes that need to be made to understand various topics in physics, and some teaching schemes have been developed that support needed changes. What has been found in the teaching of complex systems? Are there known troubles that students encounter? What conceptual changes are required? Are there known ways to help students move into new ways of thinking?

There is some overlap between learning math, physics and complex systems. Researchers have found that students seem to have trouble distinguishing between rates and accumulated amounts. The notion of a "rate of change" requires, for many people, thinking in new and unfamiliar ways (Thompson, 1996). This begs the question, what other components of complex systems may cause trouble? Students at lower levels (and maybe some at higher levels) have trouble deciding whether to use additive reasoning or multiplicative reasoning. This would be a key issue in understanding relationships in systems. Also, do students have difficulty thinking about relationships rather than about objects? Models of complex systems include time delays and variable rates of change. How do students make sense of these things as causes, and of their effects? Notably, the feedback loop is a fundamental structure in models of systems. How do students understand the behaviors of feedback loops? What is required to make sense of their implications? Al Bartlett has said that "mankind's greatest shortcoming is our inability to understand the exponential function".

Another huge issue in science education is the role of context in reasoning. People tend to reason from concrete contexts. When students seem to understand some particular topic, a seemingly slight change in context can significantly influence how students think (Bao, 2002). What kinds of contexts are involved in thinking about complex systems? How do students negotiate different contexts in the study of systems, and in particular how much experience do they need before they can they distill or apply general principles or properties of systems in varied situations?

I hope to learn something about these and other issues at this conference, and I hope that ideas from physics education research can be useful in teaching about complex systems.

References:

Bao, L., K. Hogg, et al. (2002). "Model analysis of fine structures of student models: An example with Newton’s third law." American Journal of Physics **70**(7): 766-779.

Carey, S. (1988). Reorganization of Knowledge in the Course of Acquisition. *Ontogeny, Phylogeny, and Historical Development*. S. Strauss**:** 1 - 27.

Dykstra, D. (1992). Studying conceptual change: Constructing new understandings. *Research in Physics Learning: Theoretical Issues and Empirical Studies Proceedings of an International Workshop at University of Bremen*. R. Duit, F. Goldberg and H. Niedderer. Kiel, Germany, IPN**:** 40-58.

Posner, G. J., K. A. Strike, et al. (1982). "Accommodation of a Scientific Conception: Toward a Theory of Conceptual Change." *Science Education* **66**(2): 211-227.

Thompson, P. and A. Thompson (1996). "Talking about rates conceptually, Part II: Mathematical Knowledge for teaching." Journal for Research in Mathematics Education **27**(1): 2-24.

Using Logic Diagrams to Organize One's Knowledge and Pinpoint One's Ignorance concerning Complex Earth Systems

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Essay for Workshop on
"Developing Student Understanding of Complex Systems in the Geosciences"
April 6, 2010

Introduction

One of the hardest aspects of learning about complex Earth Systems is organizing fragments of knowledge into some kind of coherent framework. I teach students who want to be science journalists or environmental journalists. These students are looking towards a career in which they will have to jump right into the deep end and come quickly up to speed frequently on complicated new ideas. I am always on the lookout for techniques that will help them construct understandings quickly and accurately, techniques that will continue to work for them when they no longer have me and their other professors to scaffold their learning, techniques that will help them to become effective self-directed learners.

One of the most powerful techniques that I have come up with is a type of concept map I call logic diagrams[1]. A concept map is a diagram showing the relationship among concepts. Concept map relationships can take various forms, but the subspecies of concept map that I am advocating includes only one kind of relationship: causality relationships. Such links in the concept map can be read as "causes" or "influences" or "gives rise to" or "leads to" or "enables." I use logic diagrams in three contexts: to build explanations in class, to support student research projects, and to critique student writing.

Using logic diagrams to build understanding in class:

Figure 1 is the first logic diagram I ever constructed for my Case Studies in Earth & Environmental Science Journalism class. The case was about the Dead Zone in the Gulf of Mexico, and as I read in preparation for developing the case, I felt overwhelmed by how many different things were going on. (Another challenge in teaching journalism students is that I am continually teaching about topics I don't know much about; if they were sufficiently well established that I already knew the full story, they wouldn't be newsworthy.) As I read and puzzled, I gradually sketched out a crude version of the diagram below, adding onto it as I read more papers and assembled more fragments of the big picture.

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[1] The name, "logic diagram," is inspired by the so-called "logic models" used in educational evaluation, which spell out the logic or reasoning by which specified inputs are intended to enable specified activities which in turn are supposed to lead through various intermediate steps to specified outcomes. Another possible name would be "influence flowcharts."

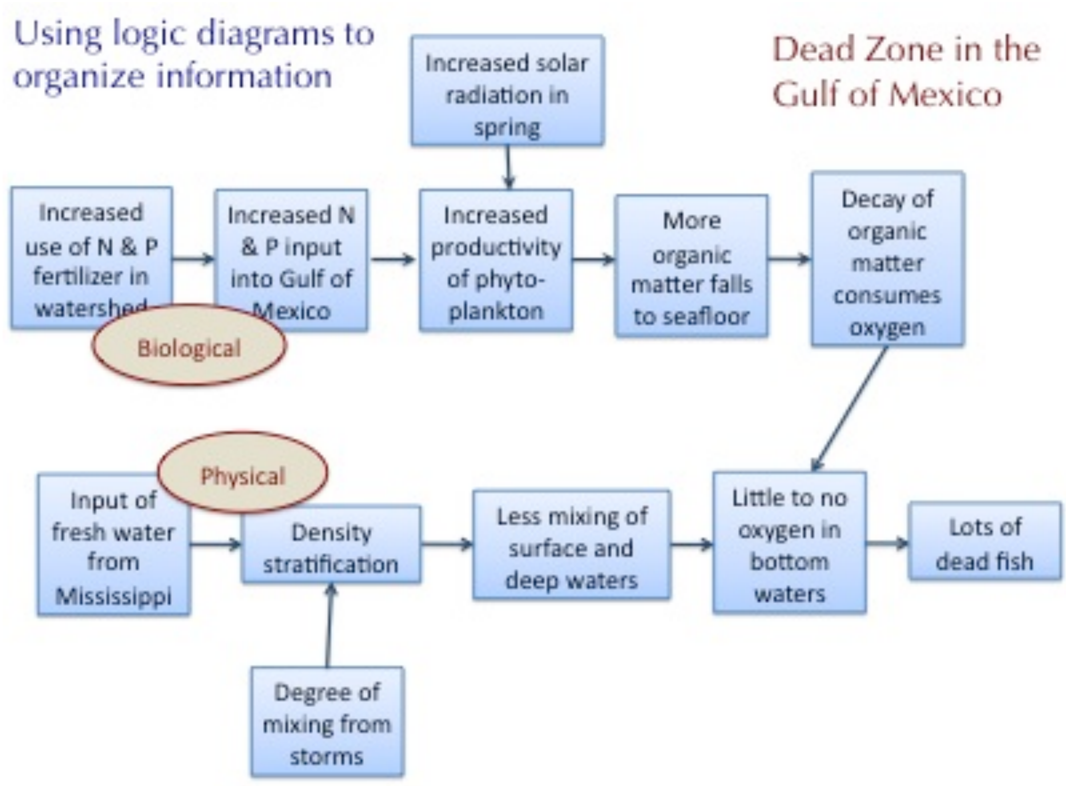

Figure 1: Logic diagram shows that both biological processes and physical processes contribute to causing a zone of anoxic bottom water and dead organisms offshore of the mouth of the Mississippi River each spring and summer.

In class, I construct logic diagrams on the black board interactively, collecting student suggestions, fielding student questions, and adding new boxes and arrows to the diagram as the various bits of insight emerge from students. Based on the assigned readings, the group of students brainstorming collectively are usually able to come up with the important elements of the system under discussion, but the ideas tend to be fragmentary and disconnected. As students articulate fragments of how the system works, I probe for pieces of understanding of what causes or influences what, and ask students to direct my chalk as I to where to fit each snippet of causal logic into the diagram. When contributions stall, I add in a few boxes and arrows myself, and then return to collecting student ideas. (I don't try to make up logic diagrams in real time in front of the class; I always have a pencil sketch ahead of time. These things are hard to make.)

When the basic framework of the logic diagram is in place, my students and I can then use that framework to provide attachment points to incorporate new insights, new datasets, into our understanding of the system. Here are two examples from the Dead Zone case study. A key paper seems to be obsessed with silica in sediments. Why, I ask, are these authors going on and on about silica, when the Dead Zone story is supposed to be about carbon, nitrogen, and phosphorous? Eventually, we are able to attach this line of reasoning to an existing portion of our logic diagram (figure 2, lavender boxes), revealing that silica in the sediments preserves a record of a key element in the dead zone puzzle--how much phytoplankton productivity is going on in the sunlit surface waters.

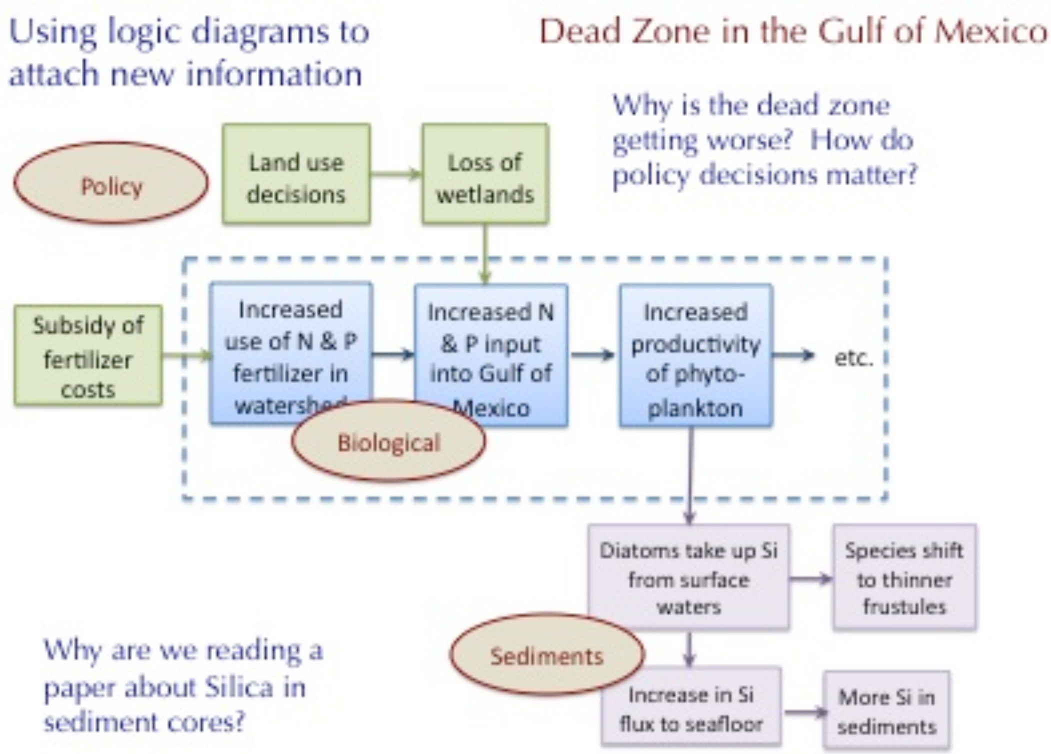

Figure 2: Once the basic logic diagram is in place, we can use it as a framework onto which to attach new information. The blue boxes and arrows are carried over from the basic Dead Zone logic diagram of figure 1. The purple boxes add on new information from a paper about silica concentrations in sediment cores. The green boxes add on new information about policy decisions.

The dead zone in the Gulf of Mexico seems to be getting worse, and some of our readings blame this on bad policy decisions or lack of good policy decisions. If a paper or an interviewee claims that a policy decision, either past or future, impacts or will impact the extent of the dead zone, then we should be able to put our finger on a point in the logic diagram where the policy influences some component of the system (figure 2, green boxes). If we can't do so, then either we don't fully understand the system, we don't fully understand the policy, or the policy will not make any difference.

Asking good questions is one of the most important tools of the journalists' trade. Learning by asking questions and seeking answers is the essence of inquiry, either in science or in journalism. Logic diagrams help my students and me to pinpoint our areas of ignorance, and thus to ask fruitful questions. For each arrow in the logic diagram we can ask: What is the evidence that A causes or influences B? Do I understand the evidence? Is there actually any empirical evidence for this step in the logic chain, or is this a place where more observations would be useful? What is the mechanism by which A causes or influences B? Do *I* understand the mechanism? Does *anyone* understand the mechanism, or is this a piece of the frontier between the known and unknown?

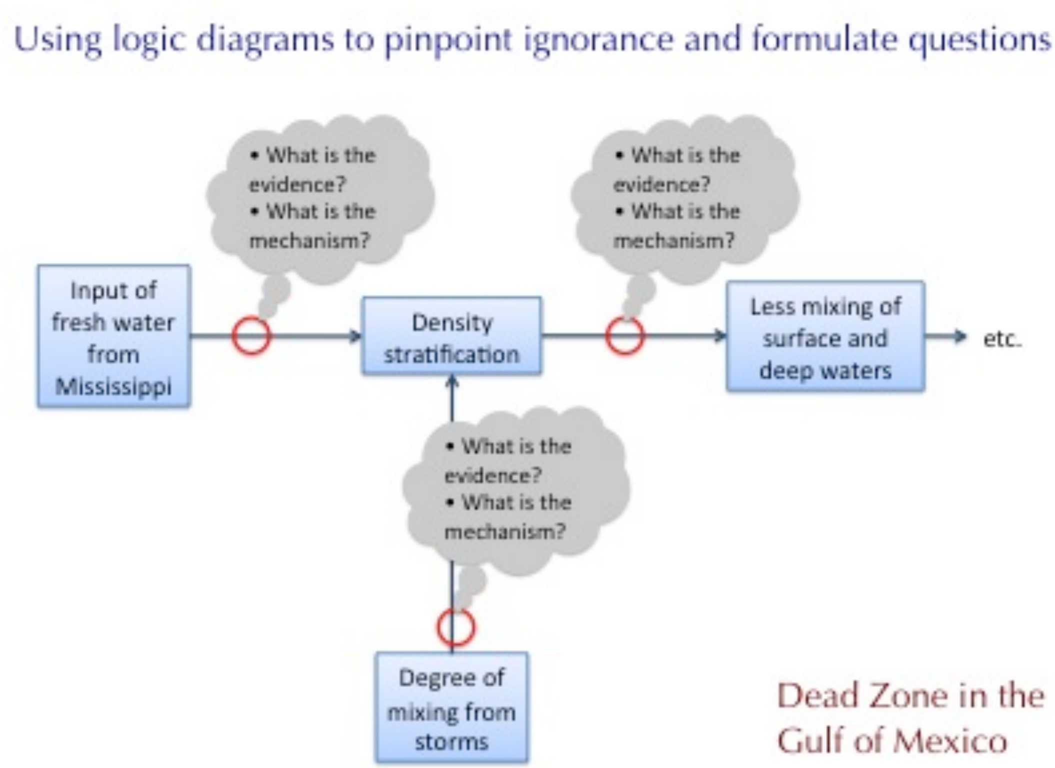

Figure 3: Each arrow in the logic diagram asserts a claim that A (in the upstream box) causes or influences B (in the downstream box). For each arrow, we can ask: "What is the evidence that A causes or influences B?" and "What is the mechanism proposed by which A could cause or influence B?" Trying to answer these questions reveals gaps in one's own personal knowledge, where more learning is needed, and gaps in humanity's collective knowledge, where more research is needed.

Using logic diagrams to support student research projects:

When my journalism students are formulating and implementing their science masters research projects, I encourage them to construct their own logic diagrams for portions of the Earth System they are trying to understand or elucidate. They typically find this hard, but deeply illuminating.

Figure 3 is a logic diagram constructed by Earth & Environmental Science Journalism student Diya Chacko. Her research project used stable isotopes of boron in corals to investigate variations in paleo-pH levels in the tropical Pacific. The boron pH proxy is so new that it doesn't yet show up in textbooks, and the handful of published papers in the specialized research literature using this proxy make some pretty ambitious assumptions about how much the reader understands about stable isotope systematics. Diya struggled mightily to understand this complex system. Again and again she thought she had it figured out, but her inability to construct a chain of coherent, logical steps running from the pH of seawater to the stable isotopes of boron telegraphed to me and to her that her understanding was still incomplete. She returned again and again to the seminal papers and to her geochemist research advisor with newly refined questions, each time further organizing her understanding and pinpointing her ignorance, until finally she constructed an internally consistent line of reasoning, captured in the logic diagram of figure 3.

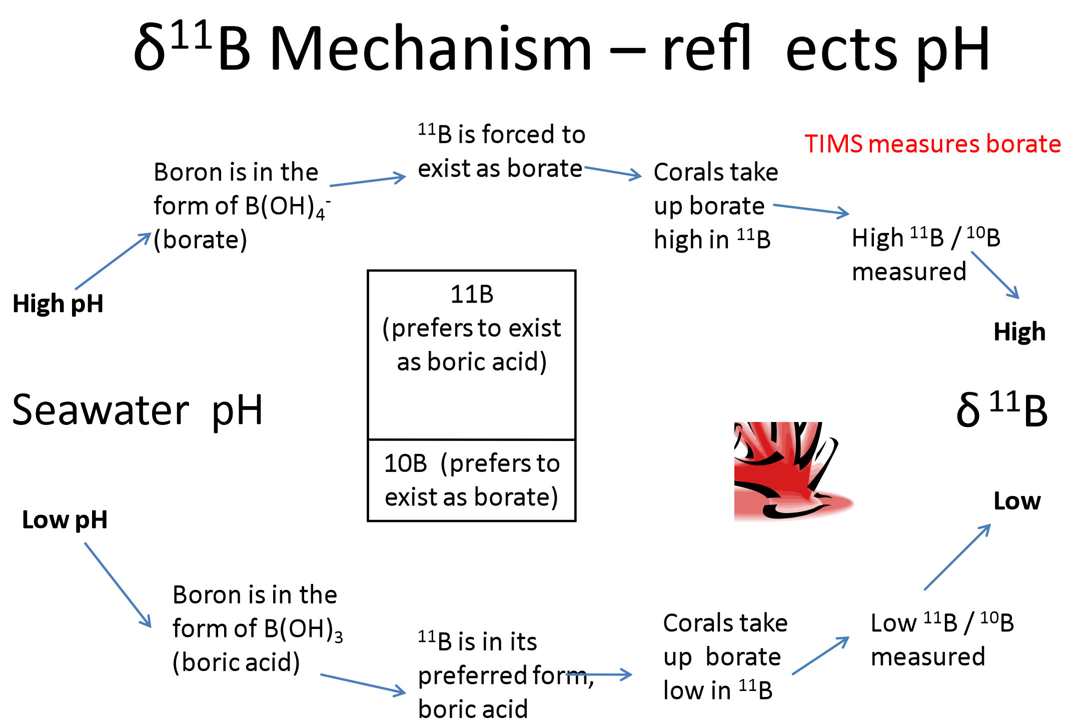

Figure 3: From Chacko (2009), used with permission. Logic diagram shows how seawater pH (on the left) influences the ratio of stable isotopes of boron in corals that grew in that water (on the right). The line of reasoning underlying the boron paleo-pH proxy is not spelled out in the literature in a form easily accessible to a beginning graduate student, and Diya had to construct this understand through repeated trials interspersed with targeted questioning of experts.

Using logic diagrams to critique student writing:

One final use I make of logic diagrams is to critique student writing about complex systems. In a story pitch, a student wrote:

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As the planet continues to warm, glaciers within the
Cascade Mountains are steadily decreasing.  These
glaciers feed many rivers including the Columbia
River and as the glaciers shrink the water flow in
these rivers is also decreasing.  The Columbia River
has a total of 14 hydropower dams on it, and these
dams provide cheap electricity for the region … As
glacier melt and river flows decrease due to climate
change, these dams become less productive.  The
result is that residents of the area can expect to
pay more for power.  In addition...residents can
expect to pay more for water.
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This paragraph attempts a compact description of the ramifications of a change in the earth system, encompassing both the causes of the change and its implications for human society. In a story pitch, the writer has only a few words with which to capture the attention of a busy reader, in this case the editor of a newspaper in the Pacific Northwest. The urgency of the implications come through, but the nature of the threat may not make sense to a non-geoscientist reader. If we turn this paragraph into a logic diagram, we come up with:

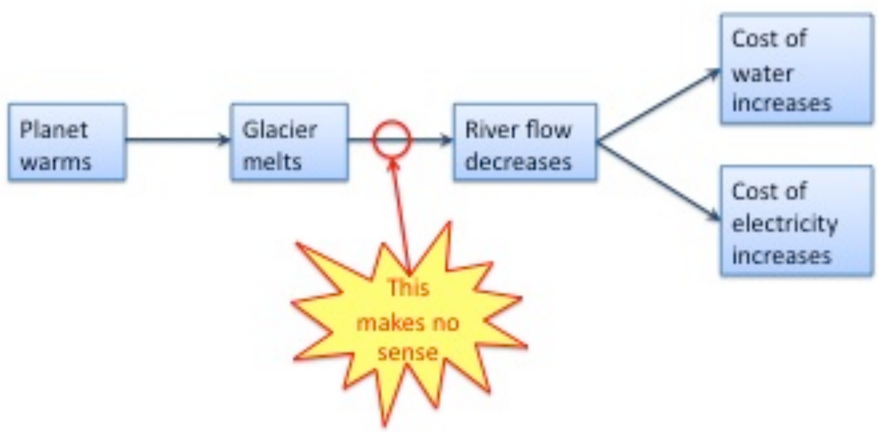

Figure 4a: Logic diagram reflecting student's paragraph includes a step that appears to make no sense on the face of it; it would seem that glacial meltwater should augment rather than decrease the stream flow in a glacier-fed a river.

When spelled out stepwise in a logic diagram, a missed step in this line of reasoning becomes glaringly obvious. It is not logical, on the face of it, to say "…as glaciers melt and river flows decrease…." If a glacier feeds a river, then as the glacier melts, more water--not less water--should flow into the river. Something must be either wrong or missing in the logic spelled out in the student's paragraph. Further scrutiny reveals that a step is missing: the complete line of reasoning requires the extra step that global warming leads to decreased snowfall which leads to shrinkage of the glacier mass, which in turn leads to decreased available stream flow in the summer months when water and electricity are most in demand.

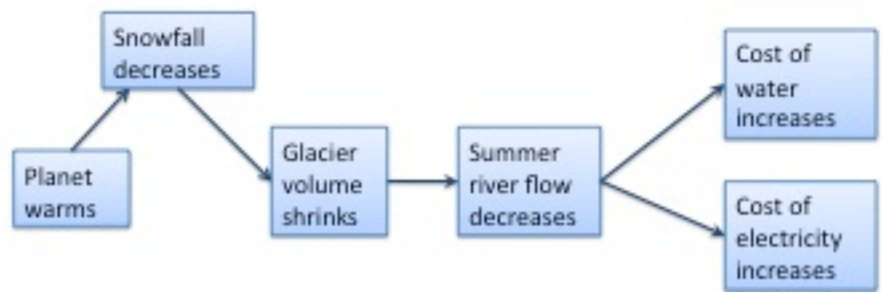

Figure 4b: Only when an extra step (snowfall decreases) is added into the logic diagram does the line of reasoning make sense.

A newspaper editor reading through this pitch letter might not be able to pinpoint the missing step in the chain of reasoning, but might very well come away with the overall sense that "this doesn't make sense to me; I don't want this story."

Concluding comments:

School-based science experiments tend to deal with short and simple causality chains. Students come to us with experience conducting science inquiries in which they have been rewarded for successfully isolating one "manipulated variable" and holding constant one "controlled variable." To understand complex Earth Systems, they need to stretch their view of science to include causality chains that are many steps long, and may include multiple converging or diverging pathways. Logic diagrams can help.

Sketching a logic diagram helps my students and me construct a framework to organize our fragments of information into a coherent systemic overview. Logic diagrams provide an attachment point for newly-arrived bits of knowledge, increasing the chances that those knowledge snippets will become lasting learning.

It turns out that journalists and scientists both learn through the process of asking questions and seeking answers. Logic diagrams help us to pinpoint our areas of ignorance and generate well-focused questions, as we ask of each arrow: What is the evidence that A causes or influences B? What is the mechanism by which A causes or influences B?

Reference:

Chacko, D., 2009, Corals as recorders of ocean acidity: Seasonal and long-term variation from the Industrial Revolution to the present, unpublished masters research project, Department of Earth & Environmental Sciences, Columbia University, abstract online at:
http://www.ldeo.columbia.edu/edu/eesj/projects/Chacko.html

Where do complex systems fit in the undergraduate curriculum?
Peter Lea

One of the main issues that I would like to discuss in this workshop concerns where and how student understanding of complex systems fits with in a geoscience department's overall undergraduate curriculum. With the addition of an oceanographer and a biogeochemist in the current academic year, we are transforming our curriculum to emphasize earth systems, but have yet to pin down the exact approach for our still-small (5 FTE) department.

One question is the extent to which systems thinking should be presented in sub-disciplinary context ("course by course approach") as opposed to a theoretical underpinning for many or all courses. The latter approach would seem to offer a greater likelihood that students could transfer their knowledge to analyze new situations, but perhaps entails greater "cognitive and affective overhead" and requires substantial coordination among different courses within the major if it is to be offered early rather than late in student's careers. Introductory courses are a particular concern. We already offer successful introductory courses that emphasize authentic research for potential majors and non-majors, commonly in a service-learning context. Although projects within these courses deal with components of complex systems, there is currently little in the way of systems abstraction and overview—would such additions help or hurt student learning at this level?

Additionally, a complex-systems approach naturally lends itself to modeling, and a current junior-level course explicitly treats uses and limitations to modeling. Among the issues addressed are the use of models for explanation vs. policy-relevant prediction, the impossibility of model verification (Oreskes et al., 1994, *Science* **263,** 641-6), equifinality (Beven, 2006, *Journal of Hydrology* **320,** 18-36), and appropriate levels of complexity and parameterization (Murray, 2007, *Geomorphology* **90,** 178-191). I would be interested in learning about—or developing—materials that allow students to undertake hands-on exploration of these concepts without getting bogged down in the commonly steep learning curves of many off-the-shelf numerical modeling packages.

I teach two integrated geo-science programs that I developed around the two sets of curricula that my students have to master to be successful on college placement exams. I teach 11th and 12th grades in the International Baccalaureate diploma program and in the Advanced Placement program at Bellaire High School in the Houston School District. Currently, we are the only school in the district that runs these programs together. The courses became integrated studies as a result of the need to blend the curriculum demands of both programs into one course. I designed an advanced IB/AP Geography program 15 years ago and the IB/AP Environmental Science course 4 years ago. Both courses are integrated within and between each other. Almost half of the curriculum of both courses overlaps in content areas but the approach is either from the human response to the physical environment and spatial perspectives or from the environmental action and response and anthropogenic perspective. The students who take the classes concurrently or consecutively seem to have the best understanding of the intricate nature of complex systems and are quicker to draw upon those knowledge bases in either course. Both of my courses are survey courses that have significant depth within each of the topics of study. However, it is the complexity of the interrelationships between these topic areas that is ultimately the greatest challenge, as it requires application skills and analytical assessment and not just simple memorization.

At the high school level the challenges to teaching or even student understanding of complex systems has multiple influences that range from the state school board personal agendas, limitations on text publishers to insufficient teacher preparations. Fortunately, both of my courses receive little attention since neither has an approved state textbook and the curriculum that guides them are driven by national programs. The challenges that I see in my students are two-fold. First, they do not come to me with a basic content understanding of earth science or geography topics that should have been covered in earlier grade levels as required by state objectives. Secondly, students fail to apply the learned content that they may have had to real-world situations. As events occur in the lithosphere, atmosphere, or hydrosphere they fail to see the implications or connections of those incidences to the human world or the biosphere in general. In particular, the relationship to global economics and the impact on sustainable resource practices is frequently misunderstood due to the influence of development levels. The inability to apply the content to real-world analysis creates a greater challenge to understanding the intricate networks of complex systems. However, recent events have provided excellent opportunities to illustrate the linkages between geologic systems, human development and response systems.

Approaching these dynamic challenges requires a variety of methods. I utilize models to illustrate the feedback loops inherent to the disruption or success of a complex system, (e.g. regional climatic patterns, coastal processes, population controls). Addressing the "what if" mode of inquiry stimulates application thinking as well as overly creative responses, however the students are evaluating changes to a particular system and what potentially happens once the threshold is reached. I use simulated labs where the answers can only be obtained through actually carrying out the experiment. In these experiments, the initial inquiry as to what the students think will happen and the post evaluation confirming or denying what did happen is crucial to understanding the concept and how it impacts a system at a different level of scale. Ultimately, I have found that fieldwork in the natural environment is one of the best ways to understand the operation and interrelated nature of complex systems. My geography and environmental science students conduct three major field investigations during the course of the year, which cover multiple systems in a cause and effect relationship. To understand the relationship between historical geology, geomorphology, climatic change, and biology, I lead them through an intensive multi-systems study in the Yellowstone region. In this area we conduct water quality analysis in multiple areas, measure conditions for the survival of thermophiles, investigate rock types, processes and formations, observe the impact of glacial periods on the landscape and evaluate the ecological niches of predator animals. To better understand coastal systems and the role of humans in the coastal environment we have been collecting data from shoreline changes for the past 15 years on Galveston Island. This data is compared to *Lidar* measurement changes conducted by government agencies. The student's look at change over time to evaluate reasons from natural occurrences to human induced for possible answers. Lastly, fieldwork in the urban area leads to investigation of economic induced changes on the cultural landscape. All of these are attempts to develop an understanding of the many components of a functioning system and their relationships to other systems in a real-world setting.

The challenge of teaching a systems approach in an integrated geo-science course requires a pedagogical change to effectively evaluate the operational causes, potential threshold influences and functionality of the system.

Tammy Long

Undergraduate introductory biology courses traditionally focus on memorization of linear sequences of facts and concepts. Chapters in texts imply discrete boundaries between one topic and the next and provide useful endpoints for assessing learning. Multiple-choice tests prevail as a means for assessing learning, particularly where resources are scarce but students are not. The image we conjure is not a flattering one. Not only does it promote a view that fragments the discipline into small bits of knowledge, it does not reflect the way in which biologists work. Biology is, in fact, the study of complex living *systems*, characterized by emergent properties, multiple hierarchical levels of organization, networks of interactions and feedback loops. Increasingly, biological questions are intersecting with other disciplines and biologists are incorporating the language and tools of modeling, computation and engineering to communicate their science.

Our work with complex systems begins in the classroom. As introductory biology instructors, we depart from the linear model of instruction and investigate ways to engage students in learning that will help them develop the skills required to manage biological complexity. To demonstrate understanding of biological systems, students must be able to identify system components and the interconnections among them, predict sources and consequences of feedbacks, and resolve apparent discrepancies between emergent properties of whole systems versus properties of constituent parts. Instructional models that focus exclusively on content and rely on students' capacity for recall will not advance our goals of helping students manage complexity, nor facilitate their understanding of how scientific knowledge is constructed and applied.

We are exploring the extent to which an introductory biology curriculum infused with tools and practices that reflect disciplinary epistemology can improve students' ability to manage complexity in biology. We are specifically interested in the potential of using student-constructed conceptual models and structured arguments to reveal student thinking and promote metacognitive skills.

Models and arguments are foundational tools in biology. Creating and evaluating models of biological systems engage higher-level thinking skills, such as identifying relevant concepts and proposing meaningful connections among them, interpreting relationships within models, discerning a model's purpose, evaluating completeness and accuracy of information represented, and predicting consequences of model perturbations. Structuring a scientific argument requires using data, or evidence, as the basis for constructing a concise and coherent claim supported by appropriate reasoning. Deep understanding of both principles of biology and the nature of scientific evidence are necessary in order to make informed judgments about the quality and appropriateness of evidence-based claims.

We developed and implemented an instructional model for introductory majors' biology that uses scientific models and arguments as both instruction and assessment. The course focuses on genetics, evolution, and ecology, and is the subject of a longitudinal study that examines the impacts of instructional reform on long-term student learning (NSF DUE 0736928). An overarching learning goal for the course was that students would build connections among biological concepts, rather than view the progression of content as a series of discrete and unrelated subjects. Our incorporation of concept modeling was an explicit strategy to force this way of thinking.

Early in the course, we provided instruction on concept modeling, including a guided discussion in which students derived the elements common to all scientific models – structures, behaviors and functions. *Structures* represent model components, *behaviors* indicate relationships between pairs of model structures, and *functions* describe the role or purpose of the model holistically (Goel and Chandrasekaran 1989; Hmelo-Silver et al 2000). In subsequent assessments – both formative and summative – we used SBF language to scaffold modeling activities and provide feedback about student work.

Throughout the course, we used a variety of cases and activities to provide students multiple opportunities to practice model construction and revise their models following feedback. As students constructed models, they wrestled with their understanding to determine which concepts were connected in meaningful ways and with how to explain the relevant processes that accounted for relationships. Early in the semester, students' models focused on building relationships among key genetics concepts (e.g., DNA, gene, allele, chromosome, phenotype). As the course progressed, students had to incorporate into their models increasingly complex principles of evolution (e.g., phenotypic variation, fitness, selection). It is important to note that students did not build a model that explained genetics concepts, then a new one to explain evolution. Instead, they progressively revised a "core" model that *incorporated* biological concepts *as they learned them*. Students adapted their models to explain how the same foundational principles applied to multiple cases, thus transferring "general" principles to "context-specific" cases.

It is a substantial cognitive challenge to build a conceptual model that accurately communicates how micro-scale molecular and sub-cellular genetic processes can lead to variation, expressed at the organismal level, which can be acted on by macro-scale processes in the environment to produce evolutionary changes in a population! It proved at least as challenging as asking students to construct a claim based on evidence and defend it using the principles in a scientific model (theirs or another). Indeed, student feedback at the midterm indicated a less than enthusiastic view for this approach to teaching and learning. However, by the end of the term, many students indicated recognition that this approach did, in fact, help them see that "every concept we learned in class [was] connected to the next concept after it" and "how all the topics were related - I could really see the connection between things that I thought were previously unrelated!"

References:

Goel A, Chandrasekaran B. 1989. Functional Representation of Designs and Redesign Problem Solving. In Proceedings of the Eleventh Internation Conference on Articial Intelligence (pp. 1388-1394). Los Altos, CA: Morgan Kaufmann.

Hmelo CE, Holton DL and Kolodner JL. 2000. Designing to learn about complex systems. *Journal of the Learning Sciences* 9: 247-298.

Perspective on Complex Systems
By Bob MacKay

This essay begins with a brief description of my background in teaching, followed by my view of the important building blocks required for student understanding of complex systems. The essay ends with a brief description of some teaching methods that, based on my experience, promote student learning and understanding of complex processes. The ideas presented here are biased towards the idea that computer modeling is a very effective tool for learning about complex systems. Other highly effective teaching methods are not discussed here.

I began my teaching career in 1982, teaching introductory college physics. Soon after my first year I attended a meeting in which Arthur Beiser from UC Santa Barbara presented his ideas for using microcomputers in physics to introduce students to nonlinear dynamics. His idea was that students with little or no calculus background could use computer simulations to explore the behavior of complex systems without being overwhelmed by mathematics. My colleague and I at Clark Community College began creating learning activities on the Apple IIe microcomputer to explore such topics as air resistance, viscous drag, charged particles in magnetic fields, and damped harmonic motion.

Inspired by my graduate work in climate change science (Atmospheric Physics) I began teaching introductory meteorology to students with very little mathematical background. Over the past 20+ years I have developed, used, and modified modeling activities to help students understand aspects of topics such as the carbon cycle, air pollution, and Earth's climate system. My interests expanded into the broader field of environmental systems after being requested by my dean to teach an environmental modeling course for Environmental Science majors. My work load typically includes a variety of physics courses and introductory meteorology at the community college, and a course in environmental modeling at Washington State University. While on sabbatical over the past six months my focus has been the development of learning modules for my environmental modeling course.

There are several fundamental ideas common to all systems. These include:

- The concept of equilibrium.
- Time delays.
- Stocks and flows, total atmospheric carbon and carbon emissions are respective examples.
- Positive and negative feedback processes.
- The idea of interconnectedness; the whole is something unique from the sum of the individual parts.

Although the above list is surely not exhaustive, it does provide a base to work from when trying to develop course content appropriate to learning about complex systems.

A crucial tool used for student understanding is some sort of graphical representation or visualization. It is easy to overlook the fact that, although most students have been exposed to graphs and graphical analysis in the past, many, including our best students, need a supportive review of key ideas related to graphical analysis. The diverse mathematical background of students in any course also offers unique challenges in that we want our students to be both intellectually stimulated and successful in a course with college level content.

For students with limited mathematical ability, online JAVA or Flash type computer simulation environments offer an easy way to actively engage students with activities aimed at understanding system dynamics from a black box perspective. Equations and background information about model structure may be added as introductory material to an assignment to make the model dynamics more transparent. These environments are good for guided inquiry based learning and can also be useful as introductory exercises for more advanced students. A clear advantage of these environments is their portability. As an example, the game at http://cs.clark.edu/~mac/Geol390/physlets/GEBM/EBMGame.htm is designed to introduce introductory meteorology students to the basic concepts of atmospheric radiative transfer.

Spreadsheet programs like Microsoft Excel, Graphical modeling tools such as Vensim (http://www.vensim.com/) or Stella II (http://www.iseesystems.com/), or more comprehensive mathematical packages like MatLab (http://www.mathworks.com/) or Mathematica (http://www.wolfram.com/) can all be used to help students begin to learn how to build their own models. An advantage of these environments is that the model structure is completely transparent. Existing models in any of these environments can be used in much the same way that the online JAVA or Flash models are used. Assignments requiring students to follow instructions to enter the code themselves can help students learn the basics of each environment to prepare them to either modify existing models or do their own projects. One disadvantage of these environments is that all require some course time devoted specifically to learning about the environment. Spreadsheet programs are fairly easy to learn and most students already have some familiarity with this environment. Graphical modeling tools and more advanced mathematical packages have correspondingly steeper learner curves.

The above strong bias towards a modeling approach for learning about complex systems is driven from the author's background and expertise, and is not intended to imply that this is the only appropriate teaching method for learning about a complex system. Role playing games, writing assignments, critical thinking questions, and group activities are several examples of methods that can also be used to help students learn about complex systems. My experience compels me to use a variety of teaching approaches in my courses in an attempt to make the course more fun and to accommodate different learning styles. One motivation for me to participate in this workshop is to possibly gain insights into alternative methods for successfully teaching complex systems.

Exploring Complex Systems in the Social Sciences

Greg Marfleet

Since 2004, I have regularly taught a course titled the Complexity of Politics. I introduce students--who are mostly political science and economics majors--to the application of agent-based, computational modeling techniques in the social sciences. The course explores some of the important concepts of complexity as they relate to social and political phenomenon including emergence, adaptive agents, co-evolution, positive and negative feedback systems, non-linear processes self-organized criticality and tipping points, and perpetual novelty. We look, for example, at the co-evolution of strategies among political parties in electoral competition, the emergence of alliances and power-balances in international relations and how feedback can push civil unrest past a tipping point into civil war. We explore these models and others through readings and a workshop-driven, hands-on, model-building experience using NetLogo programming software.

The primary challenges I have encountered teaching this class arise from the fact that Complexity-oriented modes of inquiry are very new to the social sciences. This problem manifests itself in several ways including lack of teaching resources, limited prerequisite skills among students and even accessibility of intellectual and conceptual foundations among students.

First, what is available in the way of teaching resources has generally been oriented toward economists and geared toward graduate-level instruction. Few undergraduate programs offer any training in this area almost none in political science. Consequently finding texts books or even topically-relevant research papers accessible to students has been a challenge. Fortunately this has become easier over the last five years as more research has been presented. However, there is still no complexity text book for undergraduate political scientists. The closest item I have found to a political science oreiented introduction is Axelrods "Complexity of Cooperation" (1997). Over the years I have used Schelling's "Micromotives and Macrobehavior" (1978) and currently use Miller and Page's "Complex Adaptive Systems: An Introduction to Computational Models of Social Life" (2007).

A second hurdle I have had to overcome is a common lack of student familiarity with computer programming. It may seem incongruous that our highly internet-savvy and 'wired' cohorts of students that we have in our classes may be less exposed to the basics of programming than we were in our high-school days. Most of our students have a sufficient background in mathematics and statistics to feel immediately comfortable in their mainstream methods training; remarkably few have any background in computer programming in any language. Since I was determined to incorporate a direct experience in model building into the complexity course, I have had to include many of the elements of an introductory computer science course into the first few workshop assignments. Topics that I address in the first three weeks including algorithmic thinking and the basics of variables and flow control using loops and conditional statements.

The third and most central challenge to teaching this course relates to the way social scientists, particularly political scientists, approach social explanation. For most social scientists, methodological training focuses on statistical techniques for causal inference. Our undergraduates begin their methods education with Gaussian, linear, statistical approaches to hypothesis testing. A key feature of these techniques is data aggregation. When we look at large-sample survey data, for example, it is virtually always through descriptive summary statistics or bivariate and multivariate correlation or regression models. One consequence of this training is our tendency to be more attentive social outcomes than to social processes and to focus on the median indicators.

Political science, in particular among social sciences, has tended to engage in 'top down' (macro) level explanation more than 'bottom up' (micro) theorizing. Institutions, structures and elites draw our attention. Typical explanations for election outcomes, for example, arise from factors like elite campaign behavior, voter registration laws, mode of districting or balloting systems. I have found that economics students, who have been exposed micro-economics and/or game-theory, have an intuitively stronger grasp of bottom-up processes through their ubiquitous market metaphor. A key goal of the early workshops for the class is to encourage political science students to begin thinking about exploring social processes and to conceptualize macro-level outcomes as the result of a series micro-level interactions situated in time and space.

One of the early workshop assignments that I use to do this is the "Standing Ovation Problem". This problem was suggested by Scott Page in a lecture that was provided in a class in complexity and modeling that he taught at the University of Michigan's ICPSR workshops. Based on this lecture I developed a NetLogo assignment that walks students through some basic code and suggests possible expansions. Subsequently, Miller and Page have written a short paper exploring the SOP problem as a teaching tool which I have students read after they have tried to write the program. I have uploaded both the ourse syllabus and the SOP assignment.

Citations:

Axelrod, Robert. 1997. *The Complexity of Cooperation.* Princeton University Press: Princeton NJ.

Miller , John H. and Scott E. Page . 2007. *Complex Adaptive Systems: An Introduction to Computational Models of Social Life.* Princeton University Press: Princeton, NJ.

Schelling, Thomas C. 1978, *Micromotives and Macrobehavior.* Norton, New York.

Wilensky, U. (1999). NetLogo. http://ccl.northwestern.edu/netlogo. Center for Connected Learning and Computer-Based Modeling. Northwestern University, Evanston, IL.

Teaching and Learning about Complex Biogeochemical Processes in the Earth System

Karen S. McNeal, Dept. of Geosciences, Mississippi State University

As a result of the complex behavior of Earth systems (e.g., bifurcations, self-organization, chaotic responses, positive and negative feedbacks, etc.), there are three major challenges associated with understanding and learning about complex Earth systems. These include (i) identifying the interactions between system components, (ii) conceptualizing the changes in the system's state over space and time, and (iii) applying models to predict self-organization and feedback behaviors (Colucci-Gray et al., 2006; Herbert, 2006; Sell et al., 2006). Further challenges may include using interdisciplinary knowledge to understand the relationships between system components and identifying the importance of scale and its influence on a particular system (Sell et al., 2006). Inquiry based approaches combined with multiple representations (e.g., technology and physical models) can be used as teaching strategies to assist students learning and enhance their conceptual model development about complex Earth systems.

In my research I have employed the use authentic inquiry and multiple representations as the classroom pedagogy to enrich undergraduate student learning of complex Earth systems, and specifically in my teaching of the process of coastal eutrophication. I have found that simulated research activities (e.g., laboratory methods and/or physical models) provide an opportunity for students to participate in authentic inquiry activities and when these activities are coupled with multiple representations in upper and lower division undergraduate geology classrooms the learning results, especially in regard to student conceptual model development, are encouraging. In summary, the results of my previous research have shown that expressed conceptual models are significant ($\rho < 0.05$) predictors of inquiry performance of high prior knowledge students (Sell et al., 2006). Also, through comparing experimental and control groups, results evidence that the use of the coupled inquiry and multiple representations pedagogical strategy provides significant ($\rho < 0.05$) learning gains in students exposed to the intervention, specifically in regard to the development of critical thinking skills, the use of scientific literature and references, and the understanding of system behavior. Moreover, students in experimental groups have significant ($\rho < 0.05$) pre-post gains in both their conceptual model development and content knowledge (McNeal et al., 2008; Miller et al., 2010).

Furthermore, during my training of in-service teachers in Earth system science, the use of technology and inquiry based learning strategies are at the forefront of the designed professional development activities. As a result of these practices, teachers' attitudes about technology and Earth system science have improved (McNeal et al., 2009). These teaching strategies have also proved effective while teaching 5th and 6th grade science students in at-risk school districts (McNeal et al., 2007; Radencic and McNeal, 2008). In my teaching at the graduate level, I have integrated these same ideas into the biogeochemistry classroom where my students conduct inquiry based experiments and simultaneously employ appropriate biogeochemical laboratory research methods during their analyses. I also affirm best practices in my teaching of complex Earth systems (and in my teaching in general) which includes highlighting the learner-, assessment-, community-, and knowledge-centered lenses described in the *How People Learn: Brain, Mind, Experience, and School* (Bransford et al., 1999) framework and the backwards design approach in assessment and lesson design described in *Understanding by Design* (Wiggens and McTighe, 2005) whenever possible in order to properly support and facilitate my students' learning.

References:

Bransford, J.D., Brown, A., Cocking, R.R., 1999. *How People Learn: Brain, Mind, Experience, and School*. National Academy Press, Washington, DC.

Colucci-Gray, L., Camino, E., Barbiero, G., Gray, D., 2006. From scientific literacy to sustainability literacy: an ecological framework for education. *Sci. Educ.* 90, 227-252.

Herbert, B.E. 2006. Student understanding of complex Earth systems. In Manduca, C.A., & Mogk, D.W. (Eds.) Special Paper 413: *Geologists Think and Learn about the Earth* (pp. 95-103). Boulder, CO, Geological Society of America.

McNeal, K.S., Buell, R., Eiland, L. 2009. Training Teachers to Use Technology and Inquiry-based Learning Practices in the Geosciences through an Industry University Partnership Paper Number. In 2009 American Geophysical Union Fall Meeting, Section ED44A, San Francisco, December 14-18, *Eos Trans. AGU, 90(52)*, Fall Meet. Suppl., Abstract ED44A-04.

McNeal K.S., Miller H.R., and Herbert B.E. 2008. The effect of using inquiry and multiple representations on introductory geology students' conceptual model development of coastal eutrophication. *Journal of Geoscience Education* 56: 201-211.

McNeal, K.S., Vasquez, Y., Alvandano, C., Moreno, C., Besnaiz, J. 2007. At-Risk and Bilingual Fifth-Grade Students' On-Task Behavior and Conceptual Understanding in Earth Science-Related Topics during Inquiry-, Technology-, and Game-Based Activities. In 2007 American Geophysical Union Fall Meeting, Section ED23B, San Francisco, December 10-14, *Eos Trans. AGU, 87*(53), Fall Meet. Suppl., Abstract ED23B-1293.

Miller, H.R., McNeal, K.S., and Herbert, B.E. 2010. Inquiry in the physical geology classroom: supporting students' conceptual model development. J*ournal of Geography in Higher Education*: in revision.

Radencic, S. and McNeal, K.S. 2008. The Use of Internet-Based GIS Resources to Increase Conceptual Understanding of Hydrologic Systems In Low-Income, Middle School Students. In 2008 Joint Meeting of The Geological Society of America, Soil Science Society of America, American Society of Agronomy, Crop Science Society of America, Gulf Coast Association of Geological Societies with the Gulf Coast Section of SEPM, Section T175, Houston, Oct. 5-9, *Conference abstracts with programs, pp.192.*

Sell K.S., Herbert B.E., Stuessy C. and Schielack J. 2006. Supporting student conceptual model development of complex earth systems through the use of multiple representations and inquiry. *Journal of Geoscience Education 54:* 396-407.

Wiggens, G. and McTighe, J. 2005. *Understanding by Design* (2^{nd} edition). Association fro Supervision and Curriculum Development, Alexandria, VA.

Kirsten Menking

The class in which my students acquire the most hands-on experience with complex systems is my senior seminar on numerical modeling, entitled Modeling the Earth. This course introduces students to finite difference modeling through a series of geological and environmental science problems. Each week students read articles that form the basis for the week's project. They then construct models using the STELLA software and run a number of experiments. The projects include:

• the global phosphorus cycle

• the U-Pb Concordia/Discordia dating method

• flow of ice in glaciers

• impact of changes in runoff and evaporation on the volume of water contained within a chain of lakes in eastern California

• heat flow in permafrost

• scarp retreat

• Earth's energy balance with the sun and resulting temperature

• impact of biological organisms with different albedos and temperature-dependent growth functions on planetary temperature under conditions of increasing solar luminosity (Daisyworld)

I have chosen these topics to expose students to a variety of system behaviors (e.g. steady state, linear growth or decay, exponential growth or decay, oscillatory) and types (open vs. closed) as well as to introduce positive and negative feedback loops, boundary conditions, initial conditions, and response and residence times. I find that the act of creating models and experimenting with them is a powerful way of learning about and understanding complex systems. Model construction requires students to identify the different components of a system and how they are related to one another physically and mathematically. Modeling also engages students' critical thinking skills as they compare their outputs to empirical data and try to explain system behavior.

The STELLA software is well suited for introducing undergraduates to model construction. It is icon-based and represents reservoirs as boxes and flows between reservoirs as arrows. Additional tools include circles that hold values of constants or equations and linking arrows that are used to show dependencies between variables. A drop down menu specifies run time parameters and model time step from which the software automatically constructs the do loop architecture necessary to execute each iteration. Double clicking on reservoirs and flow arrows allows the specification of initial and boundary conditions, and a graphing window shows the values of variables over time. The visual nature of the software allows students to quickly develop working models without having to learn a programming language such as Fortran or C++, and is therefore less intimidating for math phobic students. That being said, the STELLA software includes a menu item that allows students to see the first order differential equations the software is solving.

Response of students to the course has been highly positive. Many have commented on the value of using models to understand complex systems composed of numerous interacting parts. Many have said that they felt empowered by learning a new skill and that they enjoyed the ability to develop hypotheses, run experiments, and receive confirmation or negation of those hypotheses in real time. Students also remarked that the exercises gave them newfound appreciation for mathematics. One of their favorite aspects of the course was the end of semester project, in which they worked on a problem of personal interest. These projects have been quite diverse in reflection of students' majors or minors and have included eutrophication of lakes, the flow of traffic on city streets, the wage-fund doctrine economic model, groundwater flow, and the production of tidal power.

Though the course has been successful and well received by students, it has also had some challenges. First, most of the times I've taught the course, there has been a student who has found the process of modeling to be highly frustrating. This student typically has difficulty sustaining the patience required to find the one misplaced parenthesis or exponent that is making his or her model behave incorrectly. This student often stews in silence while his or her classmates are asking each other or me for help and then storms out of the classroom in tears or a fit of anger. In recent years I have addressed this problem at the beginning of the semester by telling students that they should expect to be frustrated, angry, and in tears at times, and that they need to take a deep breath and ask for help before they get so frustrated that they are no longer capable of carrying out the assignment.

Another challenge of this course is that students occasionally forget to use their intuition and critical thinking skills, or show that they have never fully developed these skills. When presented with odd model behavior that is caused by a misplaced parenthesis or exponent, students may try to explain away the behavior by invoking variables that aren't included in the model. For example, they may attribute odd behavior in a lake model that incorporates runoff, overflow, and lake surface evaporation to changes in temperature over time, even though temperature appears nowhere in the model. These students seem to have difficulty understanding the old "garbage in, garbage out" mantra and think that because their model runs, it must be behaving correctly. This is the same sort of student who makes conversion errors and seems incapable of spotting those errors even when their results are clearly ridiculous. They might, for example, calculate a discharge of 1 million m^3/s for a campus stream that flows at 0.1 m^3/s, having incorrectly converted from centimeters to meters. I have not yet found a way to assist these students to my satisfaction and hope to learn strategies from my colleagues at the Complex Systems workshop.

A final challenge of teaching a course such as this is the fact that modeling can be difficult, small errors are hard to find, and there is only one of me to help debug the models of a class of 8-10 students. As a result, students spend a lot of time waiting for my assistance. Unfortunately, we teach this course on an alternating year schedule, primarily to juniors and seniors, so it's impossible to have a student who has already taken the course act as a teaching assistant. Having a TA would be very helpful in a course such as this.

Work Done On, By, and To the Earth: Complex Physical, Chemical, Biological and Anthropogenic Interactions in the Earth System

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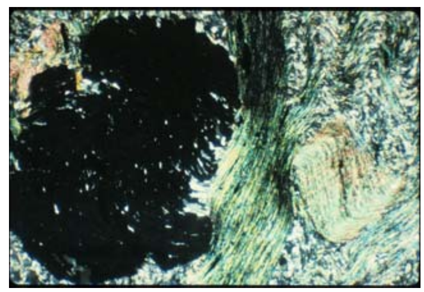
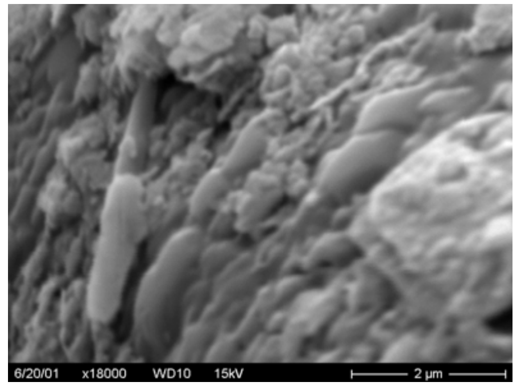
I have advocated using an Earth system approach to teaching undergraduate geoscience since we convened the *Shaping the Future of Undergraduate Earth Science Education: Innovation and Change Using an Earth System Approach* workshop (see Ireton, Manduca and Mogk, 1997). I have been particularly interested in the topics of pathways and reservoirs of energy and mass in the Earth system, across spatial scales from microns to mountains, and including temporal concepts such as rates, fluxes and evolution (see the On the Cutting Edge workshop on *Teaching about the Early Earth: Evolution of Tectonics, Life, and the Early Atmosphere*). As energy and mass are transferred in the Earth system, I think of Earth processes in terms of the **work that is done on the system, by the system, or to the system.** With this perspective, it is important to identify the agents at work, how they interact, and what the consequences are.

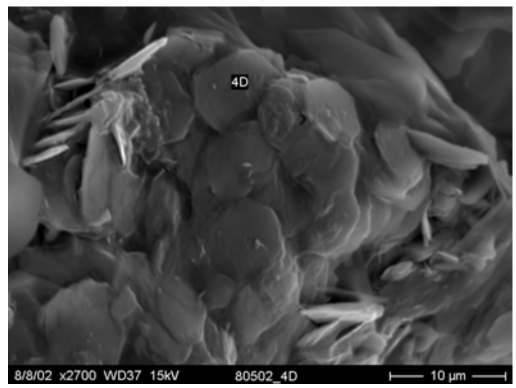


My early geoscience training was in the field of metamorphic petrology. The long-term heritage of this discipline is to use the approaches of classical thermodynamics and heterogeneous phase equilibria. Metamorphic petrology is also concerned with the deformational history of rocks (mostly in the ductile regime) and the role of deformation in orogenesis (mountain building). Thus, there are two components of work that are readily identified: Gibbs' Free Energy is the chemical work done by the system, and deformation represents the mechanical work—these may operate independently, but more often, chemical and mechanical work are contemporaneous and result in positive feedback mechanisms. This is how I teach my metamorphic petrology course: first, a review of the principles of chemical equilibria (mass balance, types of reactions, influence of solid solution, influence of mixed volatile or melt reactions), followed by a an overview of deformation mechanisms and products (folds, faults, ductile shear zones, and their relationship to crystal growth as revealed through textural analysis of rocks in thin section). These two work functions are then integrated by an in-depth study of the evolution of selected orogens of the world: the Archean Limpopo Belt, Proterozoic Grenville Orogeney, and Cretaceous-Eocene North Cascades system.

An example of the positive feedback between chemical and mechanical work can be found in the relationship between migmatization (partial melting processes) and ductile deformation (Mogk, 1992). Once a body of rock has exceeded the minimum conditions required to induce melting (initially in the presence of a water-rich fluid), these small amounts of melt greatly influence the structural integrity of the rock body, and this initiates localization of deformation in the form of ductile shear zones. In turn, the ductile shear zones serve as a conduit to locally concentrate the flow of water which leads to melting, and the migration of these melts into zones of relatively low pressure. This decompression causes the melt to crystallize, thus locally liberating water that then results in another cycle of melting, deformation, decompression and crystallization. These cycles of melting and deformation continue until the entire system either cools or decompresses below the minimum melt conditions. There are two important implications of these observations: 1) only a small amount of free water is needed in the lower crust to produce these melt reactions if it is efficiently recycled in the volume of rock, and 2) even though the entire volume of rock has been deformed and melted, textural evidence on outcrop and thin section (based on cross-cutting relations) show that only a small fraction of the system was either melted or deformed at any one time. Thus, the fabric that we see today shows a single effect that is the result of multiple causes.

The concept of work done by the system extends to the biological world, as seen in our work on microbe-mineral interfaces in hot spring deposits in Yellowstone National Park (see the Mogk, 2003 in the *Teaching Biocomplexity in the Geosciences Workshop*). The extremophile bacterium, *sulfolobus*, oxidizes sulfur to produce sulfate as a metabolic by-product. Chemical equilibria precipitate gypsum, thus buffering the sulfate content of the hot spring waters at concentrations low enough to sustain *sulfolobus* as a viable life form (even at 80^{o}C and pH= 2-3!). In a sense, microbes are metamorphic agents that are capable of contributing to the chemical work of the system. Mechanical mixing of natural waters in hot springs (meteoric v. magmatic) provides yet another possible work function in these systems. (Images at the right: top, *sulfolobus* attached to mineral substrate; bottom, gypsum crystals precipitated in acid-sulfate hot springs).





Work done by humanity on Earth (climate change, modifying landscapes, any large engineering system) is yet another topic I explore in my Environmental Geology course. In all these cases, the challenge (for me) is to present the Earth system in such a way that we can readily identify the work that is being done by chemical, mechanical, biological, or anthropologic agents, and then show how these agents work together in processes that shape the Earth system around us.

References

Ireton, F., Manduca, C., and Mogk, D., 1997, Shaping the Future of Undergraduate Earth Science Education: Innovation and Change Using an Earth System Approach http://web.archive.org/web/20080204030228/www.agu.org/sci_soc/spheres/intro.htm

Mogk, D., 1992, Ductile shearing and migmatization at mid-crustal levels in an Archean high-grade gneiss belt, northern Gallatin Range, Montana, USA, Jour. Metamorphic Geology, v. 10 no. 3, 427-438.

Mogk, D. W., 2003, Mineralogical and Geochemical Characterization of Two Sulfolobus Harboring Hot Spring Systems: Rabbit Creek and Ragged Hills, Yellowstone National Park, WY, USA (Summarized from Braden Hanna's Thesis) http://serc.carleton.edu/files/NAGTWorkshops/biocomplexity03/Mogkgeochemistry.doc

Teaching Biocomplexity in the Earth Sciences (2003) http://serc.carleton.edu/NAGTWorkshops/biocomplexity03/index.html

Teaching about the Early Earth: Evolution of Tectonics, Life, and the Early Atmosphere (2007) http://serc.carleton.edu/NAGTWorkshops/earlyearth/workshop07/index.html)

TACKLING THE GRAND CHALLENGES: THE ROLE OF COMPLEXITY IS STUDENT PREPARATION

INTRODUCTION

Current estimates of the world's human population places it at 6,681,111,786 (U.S. Census Bureau, 2010). At a minimum, each of these individuals must be fed, clothed and sheltered. However, many live beyond the minimum and require extensive resources to support every aspect of their lives. Supplying humankind with the resources it needs (i.e., food, water, shelter, energy) has dramatically altered the planet, including its many diverse ecosystems and global climate. This alteration has become so pervasive and extensive that some have suggested we have entered a new geologic epoch, i.e. the Anthropocene (Crutzen, 2002; Clark et al., 2004), as humans have become a dominant geologic force on the planet. Concurrent with supplying our needs through natural resource exploitation, humans have arguably had irreversible effects on other forms of life on the planet. Of particular note is the evolutionary arms race we now find ourselves engaged in centered on antibacterial resistance. Decades of use of antibacterial agents aimed at controlling and eliminating pathogenic microbes has led to the proliferation of "superbugs" through evolutionary processes. As our population continues to grow and as many people in third world countries strive for a higher standard of living, a significant number of global challenges lie ahead (e.g., food production, fresh water supply, energy needs, climate change, antibacterial resistance, invasive species, etc.). So encompassing are these challenges that they are often referred to as *grand challenges*.

Although a precise, universal definition is lacking, grand challenges share some common characteristics including: 1) social relevance; 2) significant economic impact; 3) solvability; 4) the need for multidisciplinary approaches; and 5) investment of significant of resources. In the last two decades, the concept of grand challenges has permeated the scientific, engineering, technological, medical and social science communities. A partial list of disciplines or research areas in which grand challenges have been identified include: environmental sciences (NRC, 2001), disaster mitigation (NRC, 2005a), engineering (NAE, 2008), the chemical industry (NRC, 2005b), Earth and environmental sciences (Zoback, 2001), Earth system science (Schellnhuber and Sahagian, 2002; Steffen et al., 2004) and global health (Varmus et al., 2003). In his presidential address to the AAAS, Omenn (2006) identified a series of grand challenges in science and engineering, multidisciplinary research and public understanding and decision-making. Many of the grand challenges cite energy, water, climate change, environmental impact, land use modification and resource utilization and depletion as particularly pressing issues facing humanity.

To deal with grand challenges effectively and equitably, our nation, as well as the entire global community, will need scientists/engineers, policy makers and citizens capable of viewing the grand challenges from multiple perspectives. Scientists/engineers will need to work collaboratively across disciples, both within and outside of science (e.g., economics, politics, social sciences). Policy makers must also be cognizant of the scientific and technological dimensions of the grand challenges as they craft national and international responses. Finally, successfully addressing grand challenges will not be possible without a scientifically literate global citizenry. They must be familiar with both natural and human systems and how they interact. These three constituencies (scientists/engineers, policy makers and the general public) represent the human capital needed to effectively explore and solve the grand challenges facing humankind and it is our task, as educators, to prepare them for this challenge.

By their very nature, grand challenges represent the intersection of natural and human systems, which are characterized by varying degrees of complexity. Preparing our students to address the grand challenges, whatever their future role may be, requires introducing them to a variety of systems and the complexity that characterizes these systems. They must understand the basic concepts of natural systems, e.g. energy cycle, carbon cycle, the atmosphere, soil systems, water cycle, etc. At the same time, they need to be able to work with the complexities inherent in human systems. Thus, they need to know the external costs of using fossil fuels and how governmental policy and economic models may be crafted to offset these impacts. The problem is to introduce enough complexity so that students become adapt at working with uncertainty, ambiguity and randomness, but do not become discouraged by the magnitude of the issues we face.

ENERGY: A GRAND CHALLENGE EXAMPLE

Energy is arguably one of the most pressing of the grand challenges facing humankind. It is tied to: water (both for energy production and water as a resource itself); mineral resource utilization (mining is an especially energy intensive activity); climate change; and social and human development. The associated concerns and challenges are many, complex and multifaceted. They vary spatially (local to region to national to international) as well as temporally (short-term measured in days to weeks through long-term). These issues are further complicated in that they are not isolated by are closely interrelated.

Given the complex nature of the energy grand challenge, any solution must be multifaceted as well. Historically, energy issues have been “solved” by considering energy science (Where should we explore for oil?), technology (What can/cannot be done with current engineering systems?) and economics (Excluding externalities, is it cost effective?) [Fig. 1]. Unfortunately, countless historical examples show that “solutions” based on these perspectives have not always been the most just and equitable. Increasingly, we have come to realize that more sustainable, equitable and effective energy systems must be designed and constructed with input from many additional perspectives, e.g. energy context, environment, social institutions, culture, politics, etc., as well as different constituencies, i.e. multiple stakeholders, NGOs, citizens, companies, etc.

The economics, energy context, environmental, social and other perspectives of energy solutions are determined by social context, i.e. the setting or location of the energy issue (Fig. 1). Clearly, where an energy resource is found has significant impact on the human systems that will be necessary to produced, process and distribute the resource as well as the existing human institutions. These, in turn, will have different implications for environmental or social impacts. To illustrate, consider the case of oil and gas production in Norway and Nigeria. In Norway, the discovery of the North Sea oil and gas fields has been an economic boon. Part of the resultant wealth has been used to guard the natural environment and reinforce and grow social and political institutions. It has been widely shared throughout the population and a portion has even been set aside for future generations. Few would argue against the overall benefit of hydrocarbon production in this nation. Conversely, Nigeria’s hydrocarbon reserves have had a much less positive impact. They have resulted in widespread corruption, an uneven distribution of wealth, enhanced conflict between regions and ethnic and religious groups as well as severe environmental damage – often on a massive scale (Hammer, 1996).

The multifaceted nature of the energy grand challenge can be illustrated symbolically using a simple functional relationship:

$$\begin{matrix}\text{solutions}\\ \text{to energy}\\ \text{issues}\end{matrix} = f\left(\underbrace{\begin{matrix}\text{energy}\\ \text{science}\end{matrix}, \begin{matrix}\text{tech-}\\ \text{nology}\end{matrix}, \text{economics}}_{\text{historical approach}}, \overbrace{\pm\begin{matrix}\text{energy}\\ \text{context}\end{matrix}, \pm\text{environment}, \pm\text{social}, \pm\ldots\ldots\ldots}^{\text{social context}}\right)$$

Fig. 1: Graphical representation of the energy grand challenge solution function.

By displaying the energy grand challenge symbolically, it is easier to demonstrate the complex nature of the topic, the many dimensions that must be addressed and the interconnectedness of these dimensions. Similar functions can be written for virtually any of the important global grand challenges.

These grand challenge solution functions visually demonstrate the formidable task an educator faces when preparing his/her students for the grand challenges they will face during their lifetimes. Given the repeated and varied intersections of human and natural systems the grand challenges entail, it is clear that complexity (in its many forms) is something students must be able to deal with effectively if just, equitable and sustainable solutions are to be found and, even more important, implemented in a timely manner. Historically, there are many examples of scientifically-grounded societal issues that have been adversely affected by the general public's inability to effectively deal with complex issues. Health concerns about silicone breast implants, the purported connection between vaccines and autism and the health impacts of EM (electromagnetic fields) fields are examples of scientifically-grounded issues that an uninformed public has been influenced counterproductively by activitist interest groups. The latter example cost the United States an estimated $25 billion before the issue was finally put to rest (Pollack, 2003). Likewise the debilitating debate about an issue that employs the public's lack of understanding of science and how science operates, e.g. climate change, can delay actions for solving a grand challenge thereby making subsequent solutions more difficult and often more expensive. For example, in 2004 Pacala and Scolow (2004) estimated that seven carbon wedges would be required to limit doubling of atmospheric CO_2 by 2050. Yet, the U.S. public's reluctance to accept proposed climate change legislation means that just six years later an additional wedge will be necessary to prevent a doubling of pre-industrial carbon dioxide levels. Clearly, educators must do a better job of preparing our students to handle the real and complex issues and systems that populate the real world. Toward that end, I have introduced two fundamental changes to my teaching strategies. They are: 1) the development and implementation of a new course design paradigm ($L(SC)^2$); and 2) the creation of a new type of case study that emphasizes investigating real world issues from multiple perspectives (Myers and Massey, 2006, 2008).

RESTRUCTURING THE SCIENCE COURSE: THE $L(SC)^2$ PARADIGM

Clearly, preparing our students for the challenges of the grand challenges, whether as scientist/engineer, policy maker or citizen, requires a different pedagogical model than what is used for most traditional science courses. Not only must this model address student mis/pre/naive conceptions, it must also teach a skill set that is often poorly addressed in the traditional lecture-based course. This skill set must include: mastery of scientific literacy; ability to think critically and solve complex, ill-defined, and open-ended problems;

proficiency with a specialized set of expertise (fundamental, technical and citizenship literacies); capacity to appreciate multiple and often competing perspectives; and ability to handle effectively complexity, uncertainty and ambiguity, i.e. important attributes of all human and natural systems. Only with such a skill set will students be able to make sense of the complex natural and human systems that will be encountered when dealing with a grand challenge.

Literacies and Scientific Content in Social Context, $L(SC)^2$ offers an alternative approach to science education by linking the physical sciences to the social sciences and humanities. The course format is expressly designed to address two implicit, but erroneous, assumptions common among gen ed science instructors: 1) students are proficient enough in literacies (skills) to handle effectively the quantitative aspects of science courses; and 2) students can readily apply the scientific knowledge they learn to societal issues outside the classroom (Myers and Massey, 2006). $L(SC)^2$ addresses scientific literacy while promoting mastery of fundamental qualitative and quantitative skills, as well as the habits of mind necessary for active civic engagement. In putting science in social context, the $L(SC)^2$ paradigm redefines and expands the concept of the interdisciplinary course (Bennett, Lubben and Hogarth 2007). These courses also use a variety of educational tools (active problem-based learning, collaborative work, peer instruction, oral and written presentations, role playing, and conflict resolution strategies) to create an effective learning environment (Schneider and Shiffrin 1985; Anderson 1982; Lesgold et al. 1988).

In $L(SC)^2$ courses, science, technology, engineering and mathematics (STEM) students learn that although there may be a technically or scientifically optimal solution to a problem, it must be responsive to a society's institutional, cultural and normative parameters before it can be implemented responsibly. Conversely, students majoring in the social sciences or humanities learn how solutions to societal problems must be scientifically valid and technologically feasible to be successful. Without scientific understanding, their proposals may lack legitimacy and may be discounted as unrealistic and ineffectual. Business majors discover that their economic models are limited by scientific and technological constraints and must take into account many difficult-to-quantify social and political costs, i.e. externalities. At the same time, interaction of STEM and non-STEM students in $L(SC)^2$ courses encourage discussion among students across disciplinary boundaries and prepares them for professional and civic settings where they will work with experts outside their own area of specialization.

Though instructors expect students to integrate into other courses the scientific content they learn in their introductory science courses, we have found that most students rarely make connections between courses, even within the same discipline. We often assume that an enthusiastic and socially engaged instructor will inspire students, as citizens, to recognize the importance of applying integrated scientific knowledge to their own lives as well as a variety of issues of social importance. Again, our assumption is usually wrong. Students need to learn the skills of engagement and practice these in a context that makes clear the relevance of natural and social science understandings. Thus, L(SC)2 courses explicitly teach the citizenship literacies, a set of skills necessary to apply scientific understanding and knowledge to a variety of complex societal problems. Specifically, the citizenship literacies consist of three classes: critical thinking; understanding social context and informed engagement. The addition of citizenship literacies produces a complete toolbox that an informed citizen can use to apply scientific fundamentals to energy and resource issues in a systematic, logical and informed manner. It allows the individual to create a defensible position and to present that position to others in an effective manner. Simultaneously, the citizen toolbox allows one to understand the positions of other on an issue. In this manner, it will hopefully facilitate achieving common ground on contentious issues.

PREPARING UW STUDENTS FOR THE GRAND CHALLENGES: CASES

Dealing with the grand challenges will require the highest levels of problem solving and critical thinking, i.e. comprehension, application, analysis, synthesis and evaluation. A proven way of developing higher-order thinking skills, while providing practice with messy, real-life problems is through case studies (Herreid, 1994, 1997a, b). Case studies (or cases) are real or simulated stories or situations in which a central character faces a complex, ill-defined problem or dilemma. Based on the story, students must devise a solution(s) to the problem and identify the consequences of their solution(s). In this manner, cases build student confidence in dealing with the ill-formed and difficult problems of life as well as critical thinking and problem-solving skills.

Because of their pedagogical benefits, case studies are the centerpiece of the laboratory in my classes where they have replaced traditional paper and pencil exercises (Myers and Massey, 2006, 2008). Unlike most case studies (Herreid, 1994; 1997a; 1998), these cases place students in a variety of professional roles in organizations dealing with resource issues; e.g. an international oil company, an environmental NGO, a multinational mining company, or a miner's labor union. Students are assigned tasks these organizations routinely perform: e.g. evaluating a hydrocarbon reservoir's economic potential; prospecting for gold deposits; or establishing a labor union's negotiating position. To provide each case with relevancy and immediacy, they are set in social contexts (local, regional, national or international), which the student should recognize from the media, e.g. oil production in Nigeria, copper mining in Peru, burning coal in China, etc. (Myers and Massey, 2006, 2008).

Each case study consists of three components focused on a different perspective. These include geology, economics and social impact. The case studies have proven useful in introducing students to the complexity, uncertainty and ambiguity typically associated with these issues. A list of the energy cases and their components is provided in the table below.

<table>
<tr><th>grand challenge</th><th>topic/ resource</th><th>country</th><th colspan="2">component</th></tr>
<tr><td rowspan="14">energy</td><td rowspan="12">petroleum</td><td rowspan="4">Saudi Arabia</td><td colspan="2">Petroleum: Saudi Arabia, OPEC & Global Oil</td></tr>
<tr><td>I.</td><td>Tapping the World's Largest Oil Fields</td></tr>
<tr><td>II.</td><td>OPEC & The Economics of Oil</td></tr>
<tr><td>III.</td><td>Energy Dependency: Exporters vs. Importers</td></tr>
<tr><td rowspan="4">Nigeria</td><td colspan="2">Petroleum: Oil, Wealth & Conflict in Nigeria</td></tr>
<tr><td>I.</td><td>Using Geology to Find Petroleum</td></tr>
<tr><td>II.</td><td>Is There Enough Crude to Produce?</td></tr>
<tr><td>III.</td><td>Wealth vs. Social Impact</td></tr>
<tr><td rowspan="4">United States</td><td colspan="2">Petroleum: USA, Oil and ANWR</td></tr>
<tr><td>I.</td><td>Understanding ANWR's Geology</td></tr>
<tr><td>II.</td><td>Getting ANWR's Oil to the Lower 48</td></tr>
<tr><td>III.</td><td>Is ANWR the Path to U.S. Energy Independence?</td></tr>
<tr><td rowspan="2">nuclear energy</td><td rowspan="2">Iran</td><td colspan="2">Power, Weapons & Iran</td></tr>
<tr><td>I.</td><td>Designing a Uranium Mine</td></tr>
</table>

			II.	Choosing a Reactor Design & Fuel Cycle
			III.	Iran, the West and Nuclear Non-proliferation
	biofuels	Brazil	Brazil – The Future of Global Energy?	
			I.	The Production of Biofuels
			II.	Economic Reality: Biofuels vs. Petroleum
			III.	Food vs. Fuel: The Global Implications

SUMMARY

Throughout the 21st century, humankind will be faced with a multitude of grand challenges. These challenges all involve the intersection of many natural and human systems and are characterized by varying levels of complexity. Unfortunately, many surveys suggest the U.S. public is ill-prepared to deal effectively with the complexities and subtleties of these issues and systems. Progress on justly, equitably and sustainably solving the grand challenges requires better preparing our students to deal with the complexities of both human and natural systems. In addition, we must encourage our students to value to need for multiple, competing perspectives in achieving consensus.

REFERENCES:

Bennett, J., F. Lubben and S. Hogarth, 2007, Bringing science to life: a synthesis of research evidence on the effects of context-based and STS approaches to science teaching: Science Education, vol. 91, pp. 347-370.

Clark, W.C., P.J. Crutzen and H.J. Schellnhuber, 2004. Science for Global Sustainability: *in* Schellnhuber, H.J., P.J. Crutzen, W.C. Clark, M. Claussen and H. Held (eds.), 2004. *Earth Systems Analysis for Sustainability*: Dahlem Workshop Reports, MIT Press, Cambridge, MA, pp. 1-28.

Crutzen, P.J., 2002. The Anthropocene: Geology of mankind: *Nature*, vol. 415, pp. 23.

Hammer, J., 1996, Nigeria Crude – A Hanged Man and an Oil-fouled landscape: Harper's Magazine, June, pp. 58-70.

Herreid, C.F., 1994, Case studies in science – A novel method of science education: Journal of College Science Teaching, vol. 23, no. 4, pp. 221-229.

Herreid, C.F., 1997a, What is a case?: Journal of College Science Teaching, vol. 27, no. 2, pp. 92-94.

Herreid, C.F., 1997b, What makes a good case?: Journal of College Science Teaching, vol. 27, no. 3, pp. 163-165.

Myers, J.D., and G. Massey, 2006, Teaching Global Citizenship Using Case Studies: A New Interdisciplinary and Integrated Template: Geol. Soc. Am. Abstracts with Programs, vol. 38, no. 7, p. 495.

Myers, J.D., and G. Massey, 2008, Earth Resources: What's Sociology Got to Do with It?: *in* Hartman, H. (ed.), *Integrating the Sciences and Society: Challenges, Practices, and Potentials*, Research in Social Problems and Public Policy, vol. 16, pp. 76-98.

National Academy of Engineering, 2008. *Grand Challenges for Engineering*, 56 pp., http://www.engineeringchallenges.org/?ID=11574, (September, 2009)

National Research Council, 2001. *Grand Challenges in Environmental Sciences*: National Academy of Sciences, Washington, D.C., 106 pp., http://www.nap.edu/books/0309072549/html/index.html, (September, 2009)

National Research Council, 2005a. *Creating a Disaster Resilient America: Grand Challenges in Science and Technology*: National Academy of Sciences, Washington, D.C., 19 pp., http://www.nap.edu/catalog.php?record_id=11274 .

National Research Council, 2005b. *Sustainability in the Chemical Industry: Grand Challenges and Research Needs*: National Academy of Sciences, Washington, D.C., 206 pp. http://www.nap.edu/catalog.php?record_id=11437, (September, 2009)

Myers, J.D., and G. Massey, 2006, Teaching Global Citizenship Using Case Studies: A New Interdisciplinary and Integrated Template: Geol. Soc. Am. Abstracts with Programs, vol. 38, no. 7, p. 495.

Myers, J.D., and G. Massey, 2008, Earth Resources: What's Sociology Got to Do with It?: *in* Hartman, H. (ed.), *Integrating the Sciences and Society: Challenges, Practices, and Potentials*, Research in Social Problems and Public Policy, vol. 16, pp. 76-98.

Omenn, G.S., 2006, Grand challenges and great opportunities in science, technology, and public policy: Scinece, vol. 314, pp. 1696-1704.

Pacala, S., and R. Scolow, 2004, Stabilization Wedges: Solving the climate problem for the next 50 years with current techonologies: Science, vol. 305, pp. 968-972.

Pollack, H.N., 2003, *Uncertain Science...Uncertain World*: Cambridge University Press, New York, NY, 243 pp.

Schellnhuber, H.J. , and D. Sahagian, 2002. The twenty-three GAIM questions: Global Change Newsl., vol. 29, 20-21.

Steffen, W., A. Sanderson, P.D. Tyson et al. (eds.), 2004. *Global Change and the Earth System: A Planet Under Pressure*: The IGBP Book Series, Springer, Berlin.

Varmus, H., R. Klausner, E.Zerhouni, T. Acharya, A. S. Daar, and P. A. Singer, 2003. Grand Challenges in Global Health: *Science* 302: 398.

Zoback, M.L., 2001. Grand Challenges in Earth and environmental sciences: Science, stewardship, and service for the twenty-first century: GSA Today, December, pp. 41-47.

Cailin Orr

Currently I am teaching in the School of Earth and Environmental Sciences and most of my students are Environmental Science majors, both graduate students and undergraduates. My students have chosen this major most often because they have an interest in conservation or management of natural resources or a vague notion that they want to do something for the environment when they finish school. My goal for teaching is to give them tools to do that effectively, without discouraging this inclination. But the environmental problems that are timely right now are complex and will require creative interdisciplinary approaches to solve. Many of these issues are also confounded by uncertainty and/or lack of data.

For example: Central Washington is an area of arid land farming where water is held in reservoirs following snow-melt and used, along with groundwater, to irrigate through the summer months. Climate forcing is changing the amount and timing of available water. Downstream water users, for example hydropower dam operators and cold water fish, are impacted by both climate variability and upstream users' choices. In turn, upstream producers are responding to changes in global commodity prices, fuel prices, their own preferences and their need to meet water use requirements to maintain their water rights, as well as future uncertainty. Predicting something that might seem simple at the start, like about how much water there might be in the Snake River during fall salmon spawning runs in 2030, quickly becomes very complex. Another example is the conceptual diagram for the WSU IGERT NSPIRE program shown below.

Teaching students to understand this complexity and then be able to start teasing it apart without throwing up their hands can be difficult. I want my students to be able to figure out the level of complexity they need to work with to address the question (science or management) they are interested in. I would also like them to be able to be able to understand and embrace uncertainty and move forward without perfect information. And finally, I would like to be able to teach about both natural heterogeneity within a system (such as periodic flooding in a river) and non-linear behavior (tipping points or alternate stable states) in a way that students can apply these concepts appropriately.

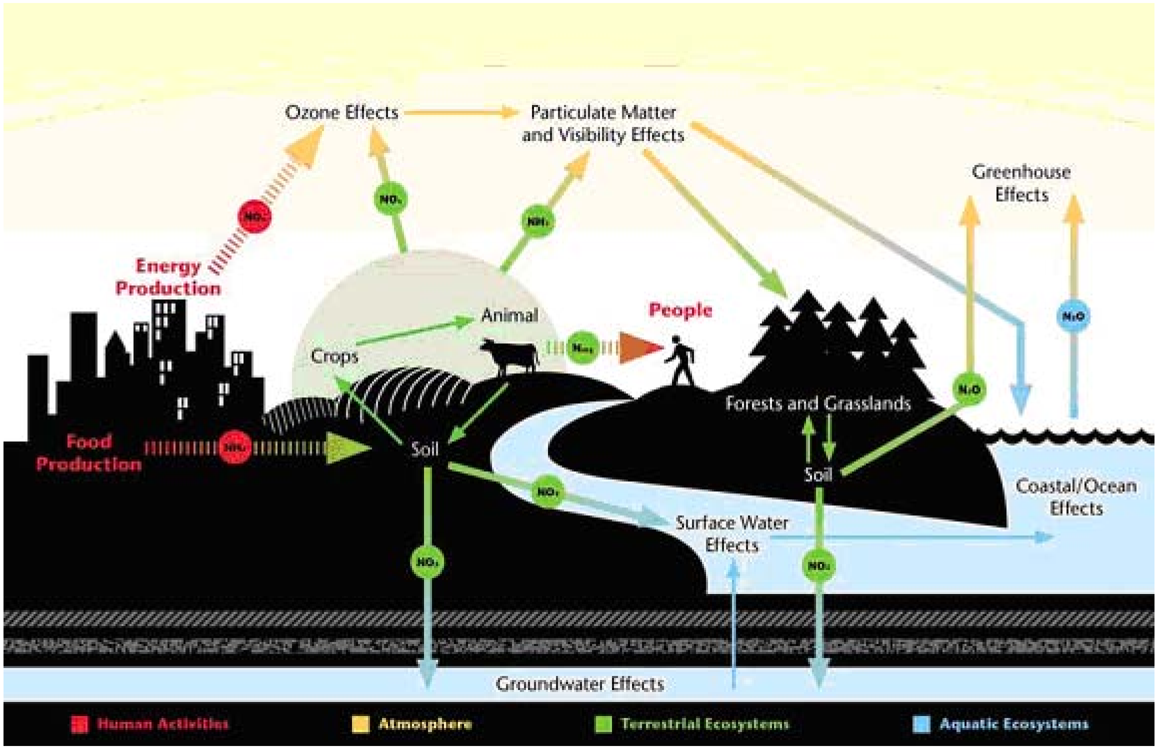


Figure from: WSU Nitrogen Systems: Policy-oriented integrated research and Education (NSPIRE).

Eric Pyle, James Madison University

When I contemplate the nature of complex Earth systems, I am immediately drawn to both the philosophical aspects of their descriptions as well as the instructional opportunities that they represent. When I was a high school science teacher in the late 1980s and early 1990s, I recount being profoundly dissatisfied with both the curriculum for Earth science my instruction was expected to adhere to as well as lack of utility provided by the available instructional materials that were purportedly intended to support learning by the students. Materials were either at too low or too high a level, but in both cases were characterized by discrete chunks or knowledge, with the main difference being the grain-size of those chunks. Having had rich learning opportunities in the geosciences myself, this type of curriculum simply could not convey the richness of Earth systems in a manner that students could appreciate. When the textbook discussed “global warming,” for example, the text only mentioned generalities that left students with the impression that things would simply be warmer by 2-3 degrees. Trying to describe how increased warming would make global climates increasingly unstable by adding more energy to the atmospheric system, I was rewarded by blank stares. Retrospectively, I believe more could have been done if I had only had the right tools for supporting student learning, or had a more organized framework for constructing them myself.

In my first faculty position, at West Virginia University, I was almost immediately engaged in an environment that had embraced, in large part, an interdisciplinary approach to science curricula, particularly at the crucial middle school juncture, when so many students are turned-off to mathematics and science. An NSF-funded Teacher Enhancement project, Coordinated and Thematic Science (Project CATS), had driven the reorganization the curriculum in grades 6-10 and provided the necessary professional development to teachers in those grades to provide instruction that was rich, longitudinally coordinated, and promoted the interaction of science concepts to broader situations. In the funding life span of this project, approximately seven years, positive changes in student performance in science were being realized, closing the gap between West Virginia students and their peers in other states. Sadly, many portions of what had become a successful program were dismantled when the funding expired, driven by teachers in upper grades who wished to return to a disciplinary focus, since their prior training and materials were oriented in this manner.

When I started teaching at James Madison University in 2005, I found there in several of the faculty not only the well-thought out framework that I sought to organize my own thinking, but also a suite of learning experiences that could be adapted to a broader student audience, at least in the Earth sciences. Drs. Lynn Fichter and Steve Baedke had already organized coursework for geology majors and non-majors alike. Interacting with them and other faculty members, it became clear to me that this was the feedstock for the reorganizing of Earth science curriculum and instructional materials. Organized into a relatively simple framework, these elements include (a) small changes in systems are cumulative and drive a system from equilibrium; (b) patterns in the behavior of Earth systems are describable with a greater degree of satisfaction than any deterministic outcome; (c) these patterns are repeated at a range of scales; (d) the frequency of input from forces that drive changes in system patterns areinversely exponentially related to the energy input, and (e) patterns in Earth systems often represent one equilibrium condition or another, and that change form one pattern to another is often rapid and dramatic.

Philosophically, these factors captured much of my thinking, but there remained the dilemma of their instructional significance in pre-college science settings. A paper in the *Journal of Research in Science Teaching* in 2005, by Assaraf and Orion, spoke directly to this problem. Outlining eight separate "stages" of student thinking on Earth systems, they not only documented something of a learning progression for students, but they also identified prerequisites and barriers to Earth systems thinking that needed to be addressed. The factors they identified were:

1. The ability to identify the components of a system and processes within the system;
2. The ability to identify relationships among the system's components;
3. The ability to organize the systems' components and processes within a framework of relationships;
4. The ability to make generalizations;
5. The ability to identify dynamic relationships within the system;
6. Understanding the hidden dimensions of the system;
7. The ability to understand the cyclic nature of systems; and
8. Thinking temporally: retrospection and prediction.

Through their research with middle school students, they determined that students are often lacking in their understandings of each of these components. In tracking students' learning towards these components, they found a strong hierarchical component, such that 70% of students could identify system components and processes, while only about half could identify dynamic relationships between system components. Less than a third of students could identify networks of relationships, make generalizations, or suggest predictions of the system. Until such time as students were able to understand each of these elements, significant barriers to students understanding of Earth systems would remain.

Another important aspect of Earth systems appealed to me, and that was the way in which systems have and do evolve over time. It was clear, however, that the prevailing definition of evolution focused on biology was not adequate to the task. Biological evolution is an *elaborating* process, but understanding the evolution of Earth systems over time also requires an understanding of the evolution of *self-organizing* systems as well as evolution that *fractionates* Earth materials. Indeed, this expanded definition of evolution allows for a richer discussion of everything from the development of stream channels and rocks to the geologic history of other planets. In both a philosophical as well as an instructional sense, concepts are summarized in two articles that have been recently accepted by the *Journal of Geoscience Education*: (a) *Expanding Evolutionary Theory Beyond Darwinism with Elaborating, Self-Organizing, and Fractionating Complex Evolutionary Systems*; and (b) *Strategies and Rubrics for Teaching Chaos and Complex Systems Theories as Elaborating, Self-Organizing, and Fractionating Evolutionary Systems.* (Steve Whitmeyer from JMU serves as the third author on both of these manuscripts.

Working within a mental framework of complex Earth systems has been an instructional playground, allowing me to develop and disseminated, or recognize the application of, a wide range of instructional materials. For example, an examination of prevailing wind patterns on an overhead transparency led to a layering of transparencies containing the different elements that drive these winds as well as the impact that these winds have on currents and weather. Different system elements can be added or subtracted, and allow students to access the hidden elements of the global climate system in a simple manner. Discussions on igneous rock fractionation first led to a colored-bead model of partial melting, in which a basaltic parent collection of beads is left enriched in mafic elements by the extraction of a string of beads enriched in more felsic minerals. This next led to the development of an activity where students "construct" analogical igneous rocks by fusing crushed hard candy of various colors, in specific proportions. Taken to a larger scale, fractionation of Earth materials, combined with the evolution of continents in the Wilson cycle led to the development of a classroom poster of the Wilson cycle, with an accompanying teacher's guide that describes the process of fractionation in the context of place and time and is inclusive of all three major rock types. It is a graphical representation of a plate tectonics rock cycle. Two of the activities and the poster/teacher's guide are currently being produced and marketed by a major supplier of educational materials, where they enjoy steady sales.

In a classroom setting, students are well exposed to different cycles of matter and energy through systems. Indeed, this is mandated in the current language of the National Science Education Standards. Yet despite having had a parade of cycles throughout school, starting with the water cycle in elementary schools, relatively little of this knowledge either retained or capitalized on by students, as was shown by Assaraf & Orion's research. In an effort to impact this difficulty, I've used a simple activity with classes that not only demonstrates the interactions between cycles but also allows for a demonstration of the dynamic nature of these interactions. Called the "Web-o-Cycles," groups of students are each assigned a different matter cycle to become deeply familiar with not only the internal components and interactions, but also possible connections to other cycles. For example, volcanic activity in the rock cycle also discharges sulfur into the atmosphere, which turn interacts with the water cycle in cloud formation. Connections such as these are made between posters of the cycles using colored yard, hooked on the appropriate nodes on each cycle and labelled by the nature of the interaction. In a short period of time, the classroom is a web of yarn, connecting each cycle to the others.

The next element of this activity attempts to capture elements of complex Earth systems, especially the concepts of equilibrium, hysteresis, power law relationships, and sensitive dependence. All lines connecting the cycles are held taut, representing an equilibrium condition. Small shifts in one cycle are compensated for by consequent shifts in other cycles. Selecting one of the interconnecting strands, tension is in introduced, first in small pulls which accumulate to imbalance and shift the cycles slightly. A single large pull in one strand, to the point of breaking the yarn, causes some lines to slacken, perhaps to the point that they cannot be easily restored to tautness without dramatic shifts in the connected cycles. Re-tightening the connections causes a shift in the cycles, which takes place quickly and assumes a slightly different but at least familiar pattern. Having students then share their observations of the process of pattern description-imbalances-shifts-new equilibrium allows them to recognize the dynamic nature of Earth systems interactions as well as to seek deeper understanding of hidden elements within the Earth system.

What remains for future challenges to teaching about complex Earth systems is already being addressed, at least in part. The *Earth Science Literacy Initiative* of 2009 directly focuses on the curricular aspect, such that one cannot fully appreciate how the Earth works until one grasps complex interactions that define the flow of matter and energy in the Earth system, and how this system is subject to change from a variety of sources and has evolved over time. The *ESLI* framework one of the documents being reviewed as revisions to the National Science Education Standards are being conceptualized. Once revisions are in place, instructional materials will consequently change. What has not been addressed fully, though, is once curriculum changes, assessment will also have to change. It is preferable from a resource and coherence standpoint that assessment be considered contemporaneously with curriculum. Past history, however, indicates that assessment lags far behind curriculum in development. When assessment becomes high-stakes, there is a risk of the assessment driving the curriculum and consequently instruction. Such a condition is not conducive to deep understanding by students, who are "taught to the test."

With respect to participation in this Cutting Edge workshop, I wish to accomplish four things: (a) deepen my understanding of the elements of complex Earth systems as described above, to better incorporate them into instruction, (b) share the instructional materials development that I have engaged in with other faculty who seek these materials; (c) discuss the best approaches to ensure that complex Earth systems are incorporated into pre-college science education standards, curricula, and teacher preparation and professional development; and (d) integrate information from previous Cutting Edge workshops on Teacher Preparation and Assessment to ensure that the curriculum-instruction-assessment chain is reinforced at all educational levels.

Federica Raia
Causality in Complex Systems the Role of Pattern Recognition

Processes of self-organization, adaptation, emergence, characteristics of complex systems, are regulated by causal principles and causal couplings that are not describable by a linear chain of causes and effects and not defined in the deterministic framework. For example simultaneity of causal interactions -where causes are at the same time effects- is of fundamental importance to understand negative and positive feedbacks processes and continually changing boundary conditions.

Results from research I am conducting on student understanding of complexity indicate that students utilize simple linear model of causality (LMC) and establish a one-to-one correspondence between cause and effect which impede a conceptual understanding of complex causal relations. A very interesting and important result was found in the relation between this approach -with the explicit use of only mechanistic causality (a force for example) - and the absence of description of patterns in student discourse. In both my research and classroom experience I saw that students, given a pattern and asked how it has emerged rush to identify "the cause" to justify the observed phenomena while never describing the pattern as an essential part and condition to proceed in their explanation of a shape formation (as for example crystals, convection cells etc) or maintenance/ modification. Similar attitudes have been also reported in physics and chemistry students' reasoning (Rozier and Viennot, 1991; Viennot, 1998; Nicoll 2001; Taber, 2001).

Based on my on-going research I am seeing that it is of fundamental importance to help students recognize time and space distribution of variables as causal determinant of system behavior (formal causality –Raia 2008). Distribution of variables as a form of causality is unknown to students but, it is amply utilized in science. Unfortunately it seems that it is not made explicit to students For example in the teaching of natural systems, initial and boundary conditions are most often provided to students as a given and the students are very rarely asked to identify and describe them or considering how the same boundary conditions can change and modify systems' behavior. Students are also rarely asked to describe patterns and variables distributions in space and time as important controls on the system behavior. These represent, as discussed in previous study (Raia 2008), types of causality necessary to integrate in the description and analysis of natural complex phenomena. Of particular importance in complexity is the understanding that from variations of distribution of variable amplification (positive feedback) or a dampening (negative feedback) of a phenomena or systems characteristic can emerge.

In my research I observed that the recognition and utilization of specifically formal causality helps students develop and utilize richer and more adequate repertoire of causal models for the analysis of natural complex phenomena. Based on the above, in my classroom I teach students to describe pattern, distribution of data, their change in space time and, build from their observations possible lines of explanations and investigation.

Paul Riley

I am coming into this conference from a slightly different angle than most of the participants: I am still a graduate student who has not yet taught a course on nonlinear, dynamic systems. My research centers around how fractures self-organize into recognizable patterns, with an emphasis on developing methodologies to quantify said organization. I greatly enjoy not only my research, but also the fundamental theory behind my research (i.e., what exactly is a self-organizing system). I am admittedly biased from my research, but I believe that a greater understanding of how patterns exist in the natural world can be done through a course on nonlinear dynamics in the geosciences. Although I have taken mathematics courses on nonlinear systems, I have not had the chance to see how the topic is approached in geoscience classes. My involvement in this conference is based on the premise that I hope to teach such a course in the near future.

Nonlinear dynamics includes the fields of fractal analysis, chaos theory, and self-organization (Baas, 2002). Largely, applications in the geosciences have been in the field of hydrology (see Sivakumar (2000) for a complete review) and geomorphology (e.g. Sapozhnikov et al., 1998; Baas, 2002), but also include stylolite spacing/agate banding (Wang and Merino, 1990; Merino, 1992), stick-slip fault behavior (Feder and Feder, 1991), plate organization (Anderson, 1999), and biogeochemistry. My research suggests an applicability to fracture organization, as well. Thus, nonlinear dynamics covers a diverse suite of topics within the geosciences. Consequently, teaching this subject should require a knowledge about the range in nonlinear dynamical geoscience systems. A problem arises when we, as researchers, center too much on topics of our own interest, and ignore the range of topics that may be of interest to a diverse student body. I am interested in learning how others have approached teaching topics in nonlinear dynamics that are outside their realm of expertise.

Despite the range of nonlinear dynamical systems that exist in the geosciences, understanding the fundamental theory of self-organizing and chaotic systems should be a unifying theme of courses teaching these topics. Whether this is through cellular automata models, observing changes in a predator-prey model, or through hands-on construction of a fractal pattern, I believe there should be some basic knowledge that students should possess upon completion of any nonlinear dynamics course. I am interested to see what teaching methods instructors have used to address the fundamentals of nonlinear dynamical systems.

Noelle E. Selin
Understanding Interactions of Human and Natural Systems

My main interest in researching, teaching and learning about complex systems is in the interactions of human and natural systems. I am interested in how to analyze and model complex human-natural interactions in ways that are useful for decision-making and promote sustainability.

My area of expertise is in atmospheric chemistry modeling. In particular, I look at human-caused air pollution, and use complex models to identify sources and chemical mechanisms that are relevant to air pollution decision-making.

An example of my research in this area is on the transport and fate of mercury in the environment (Selin, 2009). Mercury is a global environmental pollutant, and in the form of the neurotoxin methylmercury, it accumulates in fish and poses a risk to human health, particularly to the offspring of pregnant women who are exposed. Human activities have increased the amount of mercury depositing to the Earth's surface by a factor of three to five. Understanding the pathways by which mercury from natural sources (e.g. volcanic activity), anthropogenic sources (e.g. coal-fired power plants), and the continuing circulation of mercury from both these sources, travels through the environment and reaches humans through exposure is necessary for those who want to minimize or manage these risks.

One policy-relevant question that demands understanding of this complex system is deciding what regulations are appropriate for mercury on what level of political scale (local, national, international). Mercury released in elemental form circulates globally, while that released in oxidized or particulate form tends to deposit on a regional scale. Through global atmospheric chemistry modeling (Selin et al., 2007, 2008), we were able to show that different areas of the U.S. are influenced by different source regions: the Midwest receives up to 60% of its deposition from U.S. sources, but the Southeast (which has the highest measured wet deposition in the U.S.) receives only a small fraction from domestic sources and most from the global background (Selin and Jacob, 2008). This means that addressing the mercury problem will require action at both domestic and international scales (Selin and Selin, 2006). In addition, human systems combine with natural systems through fish consumption patterns to influence exposure. Combining atmospheric models with ecosystem modeling and exposure assessment shows that while domestic action can have a substantial influence on exposure levels for certain U.S. populations (for example, Native American fish consumers in the Northeast/Midwest), the lag times in the biogeochemical cycle of mercury suggest dramatic, global action would be necessary to change the trajectory of exposure from marine fish consumption (Selin et al., 2010).

One of the challenges that I am particularly interested in, both in communicating my research with policy-makers and teaching students interested in applied environmental issues, is how quantitative information and modeling is used (or not used) for decision-making. Understanding the complexities of the natural system is only the first step: a more complicated question is how this natural system interacts with human factors as well as human decision-making. My background is interdisciplinary, and I have previously conducted research on trying to understand how scientific information influences international negotiations (Selin, 2005; Selin, 2006). A particular challenge I have encountered is conveying to students the complexities of using scientific information in political contexts. Students (and scientists in general who become involved in policy) can be overly optimistic about the influence of information; overly pessimistic about providing information (why bother?); or seek a clear, scientific answer to these complex social challenges. I feel that understanding the human-natural interactions, including decision-making under uncertainty, are research questions which require interdisciplinary techniques to address, and I hope to encourage students to pursue these challenges.

References:

N.E. Selin, E. M. Sunderland, C. D. Knightes, and R. P. Mason. 2010. "Sources of mercury exposure for U.S. seafood consumers: Implications for policy." E*nvironmental Health Perspectives,* 118(1):137-143, doi:10.1289/ehp.090081122.

N.E. Selin, "Global Biogeochemical Cycling of Mercury: A Review." 2009. *Annual Review of Environment and Resources*, 34:43-63, doi:10.1146/annurev.environ.051308.084314*.*

N.E. Selin and D.J. Jacob. 2008. "Seasonal and spatial patterns of mercury wet deposition in the United States: Constraints on the contribution from North American anthropogenic sources" *Atmospheric Environment*, 42, 5193-5204, doi:10.1016/j.atmosenv.2008.02.069.

N.E. Selin, D.J. Jacob, R.M. Yantosca, S. Strode, L. Jaeglé, and E.M. Sunderland. 2008. "Global 3-D land-ocean-atmosphere model for mercury: present-day versus pre-industrial cycles and anthropogenic enrichment factors for deposition," *Global Biogeochemical Cycles,* 22, GB2011, doi:10.1029/2007GB003040.

N.E. Selin, D.J. Jacob, R.J. Park, R.M. Yantosca, S. Strode, L. Jaeglé and D. Jaffe, 2007. "Chemical cycling and deposition of atmospheric mercury: Global constraints from observations." *Journal of Geophysical Research-Atmopsheres*, 112, D02308, doi:10.1029/2006JD007450.

N.E. Selin and H. Selin. 2006. "Global Politics of Mercury Pollution: The Need for a Multi-Scale Approach." *Review of European Community and International Environmental Law* 15(3):258-269

N.E. Selin. 2006. "From Regional to Global Information: Assessment of Persistent Organic Pollutants (POPs)." Book chapter in: Ronald B. Mitchell, William C. Clark, David W. Cash, and Frank Alcock, eds. *Global Environmental Assessments: Information, Institutions, and Influence.* Cambridge, MA: MIT Press.

N.E. Selin. 2005. "Applying Assessment Lessons to New Challenges: Sulfur and POPs." Book chapter in: Alex Farrell and Jill Jäger, eds. *Assessments of Regional and Global Environmental Risks: Designing Processes for the Effective Use of Science in Decisionmaking.* Washington, DC: Resources for the Future.

C. Shellito, University of Northern Colorado

Introducing students to the complexities of the atmosphere and climate system

As a meteorologist and paleoclimate modeler, nearly every course I have taught in the past five years has required students to delve into the complexities of the atmosphere and climate system, and consider both short and long-term temporal changes and feedbacks between system components. In introductory meteorology courses, I introduce students to the 3-dimensional fluid nature of the atmosphere; in Climatology and Paleoclimatology courses, I introduce students to the complex interactions between and among the Earth system that affect global climate on varied temporal and spatial scales; in Mesoscale Meteorology, a senior-level course, we focus on the complex dynamics of 'mesoscale' atmospheric phenomena such as low-level jets, thunderstorms and tornadoes. I have taught no class the same twice, as I find that each year I have a better grasp of the extent to which students have difficulty understanding concepts in my courses.

The primary challenges of teaching students about complex topics in meteorology and climate system dynamics are generally similar between introductory and more advanced courses. I see the following as the primary challenges:

- Overcoming simplified preconceptions. Students often enter my courses with their own ideas about how the atmosphere and climate system work. (For examples: students think that the ozone hole is causing global warming, or that wind causes weather). Additionally, if they are presented with new material too quickly, they will often seem to oversimplify new concepts as a way of trying to remember them.
- Promoting understanding of feedbacks. Students are often looking for very clear connections – they want to be able to state very explicit outcomes. Feedbacks muddy the process and throw into question their preconceptions about the linear nature of cause-effect relationships.
- Conveying the 4-dimentional nature of climate system interactions or of atmospheric motion. Truly understanding the nature of the atmosphere requires developing mental images of 3-dimensional structures in the atmosphere and then being able to move these structures in time. This is a challenging task that requires a significant amount of spatial ability when using something concrete (evolving landforms, for example), but it requires an added amount of imagination when trying to build these structures out of thin air!

Among the strategies I've adopted in my courses and scholarly pursuits to meet the challenges outlined above:

- Coach students in *how* to learn material on complex topics. Often students try to learn lots of new material by making index flash cards for memorizing definitions. Students who do this, often don't see the connections between concepts. Providing students with some instruction in how to use concept maps to supplement their studying encourages them to consider how various concepts are linked together. I also walk them through my own cognitive process in drawing, reading, and interpreting weather maps or maps of climate data. I start with the simplest possible map, then have them draw and interpret maps of increasing complexity. Next we add maps or visualizations that depict the atmosphere in motion.

- Assess students' preconceptions. What ideas do they have when they walk into my classroom? What ideas do I need to build on? In my introductory courses, I require my students to complete a short questionnaire during the first week of the semester asking them about their ideas concerning the structure of the atmosphere and climate change.

- Break complex systems down into components and focus on one component or process at a time. For example, in studying the climate system, we may focus on the atmosphere first, and then the ocean. After discussing the individual components, it's critical to link them together. In discussing the climate system, I do this by incorporating a discussion of the hydrologic and carbon cycles.

- Use current research data, online, or from journal articles, to make activities more relevant.

- Incorporate maps, models or simulations and visualizations. I find that numerical models of varying complexity can be useful tools for promoting understanding particularly of global-scale processes and feedbacks. I use a range of numerical models, beginning from a very simple energy-balance model, and progressing to more complex models in advanced courses. Or, I will provide exercises where students need to interpret/extrapolate data presented in visualizations. I find, however, that introducing students to models or model output is a very tricky thing. Not all students (particularly at the introductory level) are comfortable looking at maps and visualizations. It's important to give them sufficient background to understand how to read and interpret maps or visualizations. Introducing too much too soon – particularly animated visualizations – can be overwhelming.

Jim Slotta, Ontario Institute for Studies in Education, University of Toronto

After an undergraduate, and some graduate training in physics, I moved to graduate studies in cognitive psychology at The University of Massachusetts, Amherst, where I did a research thesis on robotics and movement control. That prompted me to leave graduate school and I became a computer programmer at IBM Corp in 1989. That prompted me to go back to graduate school, which I did in 1990, to obtain a PhD with Professor Micki Chi at the University of Pittsburgh. I was motivated by Chi's earlier work in the study of physics misconceptions, and quickly took up the empirical effort to provide support for her (at that time) current theoretical efforts.

The topic of my doctoral research was concerned with the "persistent" nature of physics misconceptions: why are they so resistant to instruction. McClosky (1983), Driver and Erickson (1983) and many others had been remarking at the incredibly durable state of students' "alternative conceptualizations" of topics such as force, light, heat, and electric current. We began with a major review of all the literature relating to students conceptualizations of these topics (Reiner, Slotta, Chi and Resnick, 2000), and articulated something that was more or less clear, but perhaps had never been stated explicitly before: That physics novices appear to form a strong bias toward "matrerialistic" or "substance-based" conceptualizations of such topics. Perhaps this is because of biases in the language with which they first encounter the ideas as children (ie, "shut the door, you're letting all the heat out;" "throw some more light on it;" etc.).

Building on psychological notions of the categorical nature of concepts (e.g., Rosch, Murphy and Medin, Smith), and in particular on the notion that children form their conceptual categories based on "ontological attributions" Keil (1981, 1987, 1989), Chi made an important observation: that scientific conceptualizations. Ontological attributes are those of the most fundamental kind. When a child or a science novice encounters an unfamiliar term like "omentum" (the linning of the stomach), he or she looks for clues to try to understand it, and (following the concepts-as-categories literature) makes a categorization decision in order to "inherit" a bunch of helpful attributes. If the language treat omentum as a substance or a process or an attribute, the learner will commit to that ontology. Chi (1992; 2005) observed that, in the scientific theory, topics like heat and electric current are actually of the ontology "constraint-based interactions" or "emergent processes." BUt they are often talked about and reasoned about as direct processes, or even as substances themselves. This leads physics novices to make an ontological attribution error, committing to a substance-based ontology for these topics, and then having great difficulties with any subsequent instruction that tries to convey the emergent process view.

Note - most complex systems in science will include concepts of the emergent process ontology. So - this essay is potentially quite relevant to any learning of complex systems.

Part of the problem is that science novices simply do not HAVE the ontological category of emergent processes. There are no prior exemplars, and no way for the novice to abstract that category or ontology. SO its not possible for them to identify new concepts as having that ontology, because they don't even possess the ontological category. Slotta and Chi (1996; 2006) demonstrated empirical evidence for this hypothesis (my dissertation). We first demonstrated that physics novices do not speak about electric current as an emergent process (the statistical migration of electric charge alone a conducting medium in the presence of an electric field). We did this by "trapping" them into characteristic patterns of misconceptions in qualitative problems, as well as asking them to explain their choices of answers to those problems (always in the "substance-based language). Then, we provided them with a strong dose of "ontology training" - hitting them over the head with intensive treatment where they learned all about what a constraint-based interaction was (boring...!) - with animated examples of predatory-prey relations, the ideal gas law, and various other unrelated topics. A control group got a balanced task with no treatment of the relevant ontology. THEN we gave both groups some physics training in the topic of electric current. Low and behold, we found that the experimental group - who had been dosed up with the target ontology - was now able to make that attribution. They were able to learn that ontological aspect of electric current. And their choices to the qualitative physics problems changed. And their way of talking about those problems changed.

That work was done in 1993-5, published in proceedings of Cognitive Science (Slotta and Chi, 1996), and not appearing as a journal article until 2006, in Cognition and Instruction (Slotta and Chi, 2006 - sorry - long story!). Since 1996, the ontological attribution hypothesis has been researched by CHi and her colleagues, with several empirical and theoretical papers (see Chi, 2005 - major paper in Journal of the Learning Sciences). In 2005, I was invited to be part of an engineering education grant proposal to NSF, led by Prof. Ron Miller at Colorado School of Mines. They had read drafts-in-preparation of the Slotta and Chi paper, and were convinced that it was for EXACTLY such reasons that their undergraduates were having difficulties learning tropics of thermodynamics and fluid mechanics (because of they had made "classical commitments" to those topics. We began, essentially, a replication of my dissertation, with an ontology training for engineering undergraduates, and then some science instruction, with the aim of seeing if there was any improvement in their understanding of thermal transfer and microfluidics. This seems to be working - see the attached paper for a 2010 conference of the American Society for Engineering Education.

Since leaving Pittsburgh in 1995, I have moved into the field of education, although I maintain a perspective of cognitive psychology. I spent 10 years working in the University of California, Berkeley school of education, leading research projects in the use of technology for learning and instruction. This gave me a wealth of understanding about the "real world" of teachers, students, curriculum, etc. It also changed the way that I think about learning and instruction - now much less mechanistically (hmmm... maybe learning itself is an emergent process, and not so mechanistic like: "first establish the correct ontology, then they will learn better..."). One of the important technologies we developed in Berkeley was called WISE - the Web-based Inquiry Science Environment (Slotta and Linn, 2000; Slotta, 2004; and a recent comprehensive book: Slotta and Linn, 2009). This was a Web-based learning environment whose goal was to introduce inquiry science projects to a wired classroom. Using WISE, the teacher is free to walk around the room, interacting deeply with students as they engage with carefully designed inquiry materials. This allows the teacher to learn about what the students are thinking (as opposed to lecture, for example). WISE also allowed us to conduct a substantive research program concerning the design of such activities, particularly in the use of complex visualizations and simulations in science (INCLUDING COMPLEX SYSTEMS). In 2003, we won a major NSF center, called "Technology Enhanced Learning in Science " (see http://telscenter.org) - which sought to develop a wealth of new curriculum, assessments, and a new generation of technologies.

In 2006, I moved to the University of Toronto, where I now hold the Canada Research Chair in Education and Technology. One of my goals was to move beyond the WISE framework, where students are engaged primary with "curriculum in the window" - and to bring the technology out of the box, and into the classroom itself. I began a research program in the area of smart classrooms, with an emphasis on pedagogical models. I also wanted to explore a knowledge community model of learning, where students in a classroom are considered as a whole, and not as individual learning solos. This was partly motivated by the socially oriented software of "Web 2.0." One of the papers I attach is a book chapter about the first run of a "Knowledge Community and Inquiry (KCI) curriculum, written with one of my PhD students (Peters and Slotta, 2010). We are just beginning this process, but it is very exciting. The current KCI curriculum, which I will present briefly at the workshop, is concerned with helping high school students develop a deep understanding of the science of global climate change.

References

Chi, M. T. H. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Giere (Ed.), *Cognitive Models of Science: Minnesota Studies in the Philosophy of Science,* (pp. 129-186). University of Minnesota Press: Minneapolis, MN.

Chi, M.T.H. (2005). Common sense conceptions of emergent processes: Why some misconceptions are robust. *Journal of the Learning Sciences,* **14:** 161-199.

Driver, R. & Erickson, G. (1983). Theories -in-action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. Studies in Science Education, 10, 37-60.

Keil, F. C. (1981). Constraints on knowledge and cognitive development. Psychological Review, 88, 197-227.

Keil, F. C. (1987). Conceptual development and category structure. In U. Neisser (Ed.), Concepts and conceptual development. Cambridge, MA: Cambridge University Press.

Keil, F. C. (1989). Concepts, kinds, and cognitive development. Cambridge, MA: MIT Press.

McCloskey. M. (1983). Intuitive physics. Scientific American. 48. 122-130.

Reiner, M. Slotta, J. D., Chi, M. T. H. & Resnick, L. B. (2000). Naive physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction, 18(1), 1-35.*

Slotta, J. D. & Linn, M. C. (2009). WISE Science: Inquiry and the Internet in the Science Classroom. Teachers College Press.

Slotta, J. D. & Chi, M. T. H. (2006). The impact of ontology training on conceptual change: Helping students understand the challenging topics in science. *Cognition and Instruction* 24(2). 261-289. Lawrence Erlbaum Associates.

Slotta, J.D (2004). The Web-based Inquiry Science Environment (WISE): Scaffolding Knowledge Integration in the Science Classroom. In M.C. Linn, P. Bell and E. Davis (Eds). Internet Environments for Science Education. 203-232. LEA.

Slotta, J. D. & Linn, M. C. (2000). The Knowledge Integration Environment: Helping students use the Internet Effectively. In Jacobson, M. J. & Kozma, R. (Ed.), Learning the Sciences of the 21st Century. 193-226. Hilldale, NJ: Lawrence Erlbaum & Associates.

Slotta, J. D., & Chi, M. T. H. (1996). Understanding constraint-based processes: A precursor to conceptual change in physics. In G. W. Cottrell (Ed.), Proceedings of the Eighteenth Annual Conference of the Cognitive Science Society. 306-307.

RIVERS AS COMPLEX SYSTEMS

Nikki Strong

My Research

I am an Earth scientist. I work on cross-disciplinary research (quantitative field, experimental, and theoretical) that applies the discipline of morphodynamics (how landscapes evolve in response to the erosion and deposition of sediment) and startigraphy (how those morphodynamic processes are preserved in the geological record). My research as well as my teaching focuses on understanding and finding solutions to pressing present day and paleo-environmental issues. I have worked mostly on fluvial systems, their dynamics and how they shape the Earth’s surface. For my PhD I worked together with a team of engineers and geoscientists to design, run, and analyze data from a large complicated experiment that examined fluvial landscape response to changes in sea level, climate, and tectonics. It is some of these experimental data sets that I bring to this workshop as examples of complex systems. Rivers like all natural systems are inherently complex. They are systems comprised of numerous interconnected components that both self-organize as well as respond to outside perturbations in complicated unpredictable ways.

Thoughts on Teaching

I think that the greatest challenge in teaching and learning about complex systems is reducing complex systems into simple components that are both understandable and tangible, i.e. translating complexity into not just an abstract idea, but rather a useful tool for understanding our natural world. For example, describing a system as having fractal (self similar) behavior may be intellectually interesting but at the same time seem useless if we can not also explain dynamically what causes a system to demonstrate that fractal behavior. But not knowing why a system is fractal does not take away from the fact that one can use the fractal nature of a system to predict its behavior. I think sometimes that we forget that there many systems for which we can predict their dynamical behavior very well, even though we have no idea at a finer, more detailed scale what drives that behavior. Newton’s law of gravity is a good example. It enabled us to land an astronaut on the moon, even though we have know idea how gravity actual works!

My favorite tools for deconstructing complexity are dimensional analysis, scale modeling, and frequency analysis. Most often I use the concept of scale to convey a sense of how to decompose a complex system into simpler parts. Also recently I have initiated a project with a fellow St. Olaf faculty member where we are translating complex signals/ patterns in natural systems into sound. I think that this is a very intuitive way to 'understand' complexity.

I hope to learn how others have approached teaching the concept of complexity. It is a topic near and dear to my heart.

I believe that understanding 'how one learns' is invaluable, is a critical tool, in designing an effective learning environment. As a faculty member teaching and a researcher working on this topic, I am very curious to know what the 'cognitive underpinnings’ of understanding complex systems' are!

Vanessa Svihla, Learning Scientist, UC Berkeley

My interest in systems is two-fold: I would like to better understand student learning of complex systems; and as a learning scientist, I strive to understand, explore, and represent learning as a complex system. My experience learning and teaching with complex systems therefore spans disciplines and goals. While working towards my masters degree in structural geology, I taught geology courses to non-science majors, including topics on earth systems science, such as climate change and plate tectonics. I was frustrated by the inadequacy of the materials available to me at the time, in terms of conveying a systems perspective of these topics.

While completing coursework towards my PhD in science education, I learned about various system modeling tools, including STELLA and netlogo, and used these tools to model the course of innovations in social systems, including unintended consequences. I also participated in a graduate seminar exploring the teaching of evolution, focusing on the component understandings (e.g., deep time, variance, complexity) necessary to form an understanding of evolution.

In my research as a Learning Scientist, I apply integrated methods to understand learning as a fundamentally social and contextual process. As such, I apply network analysis and multi-level regression, and integrate these with qualitative data. I constantly seek – across disciplinary boundaries- ways of representing and analyzing data with a goal of moving away from fragmented reductionism and towards systems understandings of learning processes. A current limitation – and one that is well positioned to see rapid change in the near future- is that *models that move* (e.g., STELLA) are poorly understood by the general educational research community and when presented in static format, do not facilitate- and may even obscure- explanatory power. Increased use of hypermedia journals will *chauffeur* their use.

My approach to understanding the teaching and learning of complex systems is informed by neurological explanations for different mechanisms for human category learning that predict different pathways for learning explicit, rule based phenomena and for learning complex phenomena (Ashby & Maddox, 2005). This same line of reasoning can be seen in research exploring ontological differences across direct and emergent processes (Chi, 2005).

In my current position as a post doctoral scholar, I am designing and researching the impact of curricula related to global climate change and consulting on a project on plate tectonics. These curricula are intended for a middle school (~12 years old) audience, and generally taught by generalist teacher, not by a science specialist teacher. Additionally, these curricula are a part of an NSF-funded investigation on cumulative learning, and therefore are organized by a core idea of energy. The plate tectonics project teaches students about mantle convection as a driving force behind plate tectonics- with no mention of slab pull- and related convection of dye in water and density differences to the mantle. The global climate change project focuses on radiation and energy transformations, and uses netlogo models to allow students to observe energy transfer and transformations in a simple climate model. Model output is global temperature, and students interact with a series of models that include only one or two variables to understand how these variables relate to global temperature.

Two tools – Energy Stories and MySystem- serve as both assessments and as learning events. These embedded assessments focus on the core ideas of energy and are used across several projects that are part of the study of cumulative learning. Energy Stories ask students to synthesize their ideas about how energy is transferred and transformed. Students are asked to write about both everyday and scientific contexts. These afford students an opportunity to integrate understanding from a series of activities, and to apply this understanding to familiar experiences. MySystem is a tool that reflects Stella models, in that it asks students to show how energy flows from one object to another, but it lacks the mathematical engine that underlies STELLA, and makes STELLA such a powerful modeling tools. In this particular context, MySystem serves as a way for students to represent their understanding of a non-linear process, provided it occurs at a singular level. Current limitations are that MySystem cannot handle subsystems, making it challenging to represent many of the processes we are hoping to teach. Additionally, lacking a mathematical engine, there is no feedback to the student in terms of accounting for all flow in the system. In most cases, students create a MySystem in tandem with writing an Energy Story as a way to organize their thinking.

The current redesign of the global climate change project has focused on two aspects: explicating the component understandings and identifying the nonsalient aspects (Liu & Hmelo-Silver, 2009) that are mechanistically consequential for understanding the climate systems.

Challenges in my particular context relate to determining what constitutes an appropriate level of systems science given:

- The age and experiences of 6th grade students
- Pressures to cover the scope/breadth of the curriculum
- Pressures to teach to California State Science Standards
- Desire to represent topics in ways that reflect disciplinary perspectives
- Integrating energy as a core idea

There may be tensions and therefore a need to consider optimization across these needs and goals. Future goals for redesigning curriculum include integrating across curricular projects, such that more standards can be revisited/foreshadowed. This might include, for instance, integrated models of earth systems, from plate tectonics to climate change, or from photosysnthesis to climate change.

Ashby, F. G., & Maddox, W. T. (2005). Human Category Learning. *Annual Review of Psychology, 56*(1), 149-178.

Chi, M. T. H. (2005). Commonsense Conceptions of Emergent Processes: Why Some Misconceptions Are Robust. *Journal of the Learning Sciences, 14*(2), 161-199.

Liu, L., & Hmelo-Silver, C. (2009). Promoting Complex Systems Learning through the Use of Conceptual Representations in Hypermedia. *Journal of Research in Science Teaching, 46*(9), 1023-1040.

Complex Systems Essay

Jeff Wilson
The University of Texas at Brownsville/Texas Southmost College

Q: Why are you late to class?

A: I am late because:

a) My child was sick and I had to call my grandmother to watch her; or
b) The border bridge was backed up again.
c) All of the above.

I start with this question/answer set to communicate a bit of context around the unique University community in which I live and conduct my work. The University of Texas at Brownsville/Texas Southmost College is 93% Hispanic and is situated on the US-Mexico border at the southern tip of Texas. My students live in the poorest region in the United States by several census measures, including per capita income. I can have a bistek taco in Mexico in less than 10 minutes from my office door and 10-15% of my students walk or drive across the international border bridge to class every morning.

In this context, we as professors face many challenges. Students enter university (open-enrollment) with little math or science training from the local high schools. They are often first-in-family college attendees, and they have immense commitments at home. Despite this, ironically, I have found that the 'intuitive' fashion of linking together ideas and concepts through complex system models (presented in a simple fashion) comes more naturally than at other institutions where I have taught – perhaps because their lives are so complex.

Every semester, I teach a lower-level class and lab called 'Earth Science' as well as an upper-level course (we don't have a graduate program). In the lower-level class, I have mostly non-science majors taking the course as a required program and this is where I currently apply systems-learning techniques for the most part. This class is comprised of students that do not like science in general (that is, if they are interested enough to care). By the end of the class, my two goals for them are: (i) to appreciate and enjoy science; and (ii) to see the world more systemically through science. On point (ii), I utilize mind (concept) maps at the start of each class to both link together the points in the lecture while linking into other key systems. The most naturally applicable systems concept that I teach is plate tectonics linked in to various phenomena (earthquakes, etc).

Key questions I hope to answer in this workshop include:

a) What are examples of best practices for approaching systems thinking within a poor, minority, first-generation college environment?
b) How can I develop inter-lecture content into a holistic system?
c) What are some case study best practices for communicating complex systems?
d) Who can I team up with to share/further develop my complex systems teaching experiences as we move forward?

The other participant essays that I have reviewed indicate a rich pool of colleagues at this workshop – I have been inspired. I look forward to the experience and the opportunity to learn from others and from the organizers so that I can bring these skills back to the educators and students of our college community in South Texas.

Teaching About River Systems to High School and Undergraduate Students

Project:
Data Sets and Inquiry in Geoscience Environmental Restoration Studies (NSF GEO-0808076)

Authors:
Daniel Zalles, Center for Technology in Learning, SRI International
David Montgomery, Dep't of Earth and Space Sciences, University of Washington

With collaborators from the University of Washington, we have designed a curriculum on the subject of environmental restoration in the Puget Sound area of Washington State with an emphasis on river geomorphology and its systemic relationship to biodiversity and to the history of human interaction with the environment. There is a high school and undergraduate version of the curriculum. The high school version is in the process of being implemented on an Indian reservation near Seattle and the undergraduate version is being implemented in a University of Washington spring quarter course co-listed through the Departments of Earth and Space Sciences and American Indian Studies.

The curriculum aims to build student understanding of these systemic relationships through a combination of lectures, case studies, field trips, and analyses of GIS-based river basin data produced by the University of Washington's River History Project (http://riverhistory.ess.washington.edu/). The GIS map layers show changes to the rivers and the surrounding land starting in the last Ice Age up to the present time, using a combination of historical survey maps and geospatial data sets. Figure 1 shows an example.

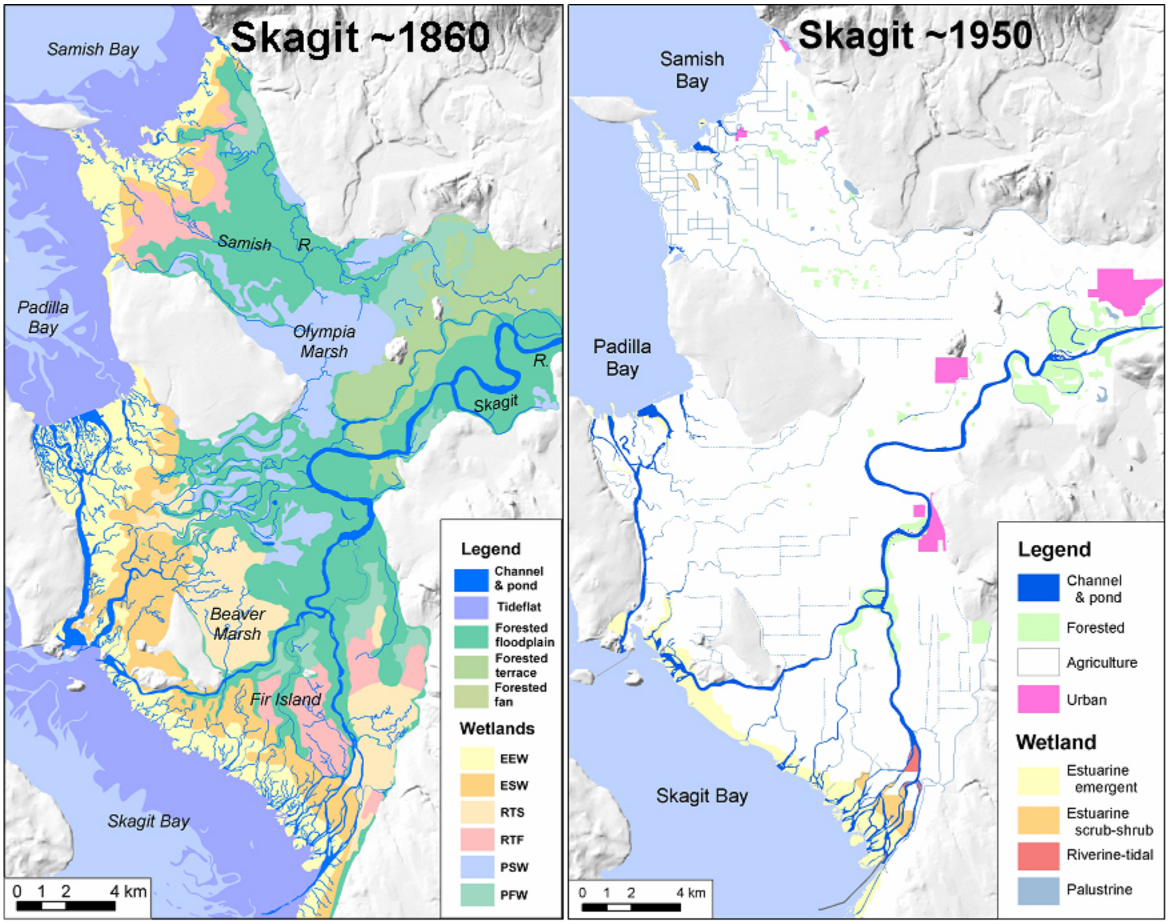


Figure 1. Historical changes to the Skagit River environment. © *2010, University of Washington Puget Sound River History Project.*

Students learn the history of manipulations of the rivers by white European settlers, the impacts of those manipulations on the biodiversity, and what scientific and policy challenges face contemporary decision-makers about how to address the problems introduced by these manipulations (e.g., extreme flooding events, loss of native plant species, pollution, loss of salmon habitat, loss of economic options for the region's Indian communities). The course addresses:

- The geologic origins, geomorphic and hydrologic processes, and ecosystems and resources associated with the Puget Sound's rivers and estuaries
- Methods for detecting and evaluating environmental change
- The nature and extent of anthropogenic changes to rivers
- The changing relationships between rivers, people, and natural resources such as salmon
- The historical context of resource management and restoration, including how Native American treaty rights influence resource management and restoration issues in Puget Sound rivers
- The potential impacts of population growth and climate change

Week-by-week lesson topics include:

- Geography and geologic origins of the Puget Sound river landscapes,

- Evolution of the Holocene world: Rivers, fish, plants, and people after the glaciers and before the treaties
- The geomorphology of rivers and watersheds
- The river histories since the signing of land rights treaties between the American government and the Indian tribes
- Who has rights to salmon and to manage salmon habitat?
- Case study: The Nisqually River and the Boldt Decision.
- Case studies on restoration and management issues with rural rivers
- Case studies on restoration and management issues with urbanized rivers
- Using the past to inform alternative futures

The course also addresses how different characteristics of the environment are measured. Students are introduced to the challenges of how geospatial data are interpolated and the implications of these different interpolation methods on making evidence-based conclusions.

The high school version of the curriculum shares the broad goals of the undergraduate version but strips the content down to big ideas:

- understanding how relationships between the rivers' natural and human histories, geomorphological characteristics, and biological characteristics are systemic and how systems constitute webs of interdependent characteristics
- understanding how changes to one element of the system impact other elements, and that these changes can either be good or bad for the healthy sustainment of the environment
- understanding how correlations between variables in the system are not necessarily indicative of causation
- understanding how policymaking that impacts the environment needs to include attention to the environment's systemic relationships

It is being piloted in classes composed of large numbers of at-risk students. Through field trips and small group hands-on classroom tasks, the students identify systemic interrelationships among different environmental factors. They apply these understandings to analyzing potential policy options for local environmental restoration.

Tasks are scaffolded to support deep student thinking. For example, in a brainstorming activity that asks students to identify the effects of what settlers of European descent did to the rivers of the Puget Sound, students are provided with a list of effects that they need to connect to lists of causes, then explain their reasoning for each connection. The presentation of selection choices is a scaffolded alternative to simply asking students to come up with open-ended explanations of impacts. The use of selection as a scaffold is also applied to the objective of getting students to think about policy options for their tribe for environmental restoration. Choices of possible restoration policies are presented and students select from the choices. However, before selecting, they make a list of questions for which they would want answers before making a final decision on which choice is best. Then, the process of decision making is further scaffolded by being broken into two stages. The two stages are represented by two different yet related evaluative questions: "How would your choice serve the tribe the best?" and "Why would your choice likely be the one that is most successful?"

Both the high school and undergraduate versions introduce important concepts through analogies. In the undergraduate lesson about alternative futures for environmental systems, students are presented with analogous alternative future scenarios pertaining to unrelated topics (e.g., the relationship between taxation policies and school funding in a particular community and the relationship between the economic health of polluting companies and the physical health of community members affected by the pollution). The point of first introducing these less cognitively demanding analogous scenarios that call up prior knowledge is to cultivate in the students a deep understanding about how alternative future scenarios represent the interests of different stakeholders in a particular system and how analysis of findings from the alternative future models present an opportunity for different stakeholder groups to negotiate policies that serve their mutual interests. By presenting the less cognitively demanding analogous scenarios first, the curriculum makes it easier for students to understand the essential characteristics of alternative future modeling first, then apply that understanding to the more cognitively demanding topic of river restoration.

In the high school version of the curriculum, this practice of introducing less cognitively demanding analogies about a big idea prior to engaging students in thinking about the big idea is applied to the broad theme of what constitutes a system. A definition of how a natural environment is a system is introduced, followed by references to other examples of systems such as the human body, a business, a machine, and an ocean. Students are asked to pick one of these examples and explain how it is a system, then think of a different system and describe its interrelated characteristics. Hence, the scaffolding occurs through the process of prompting selection followed by generative brainstorming. Once these preliminary broad exercises are carried out for thinking about the nature of the system, the more cognitively demanding task of understanding how the students' river-dependent natural environment is also a system is introduced.