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# *Complex systems in the geosciences and in geoscience learning*

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## ABSTRACT

**Expert geoscientists think in terms of systems that involve multiple processes with complex interactions. Earth system science has become increasingly important at the professional level, and an understanding of systems is a key learning goal at all levels of the earth science curriculum. In this paper, research in the cognitive and learning sciences is brought to bear on the question of how students learn systems thinking and on the challenges of developing effective instructional programs. The research suggests that learning systems concepts is difficult and that it involves extended learning progressions, requiring structured curricular integration across levels of K–16 instruction. Following a discussion of these challenges, current instructional innovations are outlined, and an agenda for needed research on learning and teaching systems thinking is proposed.**

## THE CENTRALITY OF COMPLEXITY IN GEOSCIENCE EDUCATION

The accompanying papers in this collection sketch three abilities (to think temporally, to think spatially, and to observe in the field) that characterize professional thinking in the geosciences and that must be nurtured in geoscience learning environments. The expert geoscientist or student must coordinate these cognitive skills in the effort to understand Earth and processes that affect it. This paper concerns a key fourth ingredient in geoscience thinking, an appreciation for and an ability to grapple with complex systems. Several facets of complexity important for learning and instruction are introduced in this section. The following section briefly reviews some fundamental research on learning and cognition. The remaining sections bring these fundamental ideas to bear on learning to understand complex earth systems.

Independent of any formal mathematical considerations, the geosciences concern complex systems in the sense that the phenomena under study arise from multiple interacting processes that are extended in time. The intrinsic complexity of the earth sciences is suggested by the expectation that even at pre–high-school levels of study, students should reach a basic understanding of explanations that involve entire systems. Further, research and teaching in the geosciences are increasingly influenced by the concept of "earth system science," which emphasizes the study of the connections and interactions among the atmosphere, hydrosphere, biosphere, cryosphere (ice and snow), solid earth, and anthroposphere (objects and processes produced by humans). Although each of these spheres taken alone is complex and is the subject of a discrete traditional discipline, earth system science is now a research frontier, and contemporary instruction must orient students to it, particularly given the pressing need to understand and address the problem of climate change.[1]

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[1]An increasing emphasis on complex systems is common across the sciences, with areas such as systems chemistry, systems biology, or systems neuroscience becoming increasingly important. Thus, there is no claim in this paper that systems thinking is unique to the geosciences or that the phenomena under study are intrinsically more complex than, say, physiological phenomena. In many respects, then, a similar paper could be written about teaching and learning in other sciences, such as biology (see, for example, Hmelo-Silver et al., 2007). The current paper seeks to characterize systems thinking in the geosciences without teasing out contrasts with other sciences. The same might be said about the other topics in this set of papers: time (cf. evolutionary biology or astrophysics), space (cf. anatomy or organic chemistry), and field experience (cf. bench experience in biology or field experience in ecology).

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Beyond the role of multiple processes in geoscientific phenomena, complexity derives additional, more technical meaning from the intricate, nonlinear interactions among processes, making the system behavior that emerges from the interaction unpredictable from an isolated understanding of the individual parts. The whole system is thus the necessary target for explanation, and mathematical and modeling tools for the study of complexity and system behavior offer key theoretical resources. A principal approach has been systems dynamics (Ford, 1999), which focuses on flows of matter and energy among reservoirs, the influences on those flows, and the resulting positive and negative feedback loops that drive reservoirs toward constancy or extremities, e.g., a positive feedback loop created by a rise in atmospheric temperature that causes more evaporation, which causes an increase in atmospheric water vapor concentration, which causes an additional rise in atmospheric temperature through the greenhouse effect, which causes more evaporation, and so on. Explanations can be extended to space as well as time by solving the relevant equations over a discrete three-dimensional grid, as in meteorological modeling. In recent years, several further resources in the theory of complex systems, such as cellular automata, fractals, and stochastic approaches, have been applied to earth systems that exhibit multiple stable states, self-similarity, chaotic behavior, self-organized criticality, and non-Gaussian output distributions (Turcotte, 1997, 2006). In this paper, ideas from systems dynamics, particularly feedback concepts, are used to illustrate the challenges of learning the deeper lessons of complex systems.

In considering learning and instruction about complex systems, it is important to note that the complexity of earth systems in most cases cannot be reduced or dissected through experimental control and replication. Evidence is largely observational and often historical in the strict sense that the phenomenon to be explained (or predicted) is a unique state in the time course of a single system. Without recourse to the experimental method, researchers must measure multiple variables in the field and tease apart causal relationships through reasoning with complex patterns in data, searching for "smoking gun" evidence (Cleland, 2001, 2002), and exploring simulation models. Thus, in addition to coping with complicated theories and novel, counterintuitive systems concepts, students in the geosciences must learn an approach to theory verification that differs in crucial respects from the canons of experimental science that dominate instruction on methodology in the rest of the science curriculum.

The following analysis involves all of these aspects of complexity: (1) Because they involve multiple processes and temporally extended causal pathways, explanations in the earth sciences are complex in the vernacular sense that they are complicated and conceptually rich; (2) geoscientific explanations involve technical concepts of complex systems that involve nonlinear relationships among processes and emergent system behaviors; and (3) empirical methodology in the geosciences involves combining and weighing multiple sources of evidence and typically does not involve the forms of simplification available in the experimental sciences. Each of these dimensions poses challenges for learners and for the designers of learning environments, and addressing those challenges is critical to effectively integrating time, space, and field-based learning into a curriculum.

## SOME CONTEXT FROM THE LEARNING SCIENCES

The present analysis is framed not only by the centrality of complexity to learning and teaching in the geosciences but also by some pivotal general findings from research on science learning. This general picture is briefly reviewed here to give readers some tools for reflecting on their own experience and to set the stage for the remainder of the paper, which attempts to weave together the requirements of complexity and the overall research base of the learning sciences to summarize what is known and what needs to be further studied in the domain of learning about complex systems.

Although it will come as no surprise to many readers of this paper, it is important to state at the outset that research on science learning across disciplines and age levels has shown consistently that learning science is difficult and that student outcomes from instruction often fall short of expectations. Hestenes et al. (1992), Gabel et al. (1987), Cañal (1999), and Schunn and Anderson (2001) are a few representative examples, from physics, chemistry, biology, and experimental psychology, respectively. On the one hand, research in the learning sciences provides a strong framework for effective teaching and for the design of successful instructional regimes. The references cited in this paper provide multiple entry points to the relevant literature. On the other hand, the research offers no shortcuts or simple algorithms for improving outcomes. Teachers of the earth sciences, or of any science, are perforce also learning scientists. The practice of learning science, like the practice of other sciences, is best pursued via a grasp of underlying concepts rather than by following fixed rules.

Educational settings aimed at introducing students to complexity concepts in the geosciences must respect some foundational findings from three areas of cognitive psychology and research in cognition and education: (1) memory: well-learned scientific concepts participate in interconnected, integrated memory networks; (2) reasoning: concepts that are useful in extended thought must be introduced and practiced in their contexts of use; and (3) metacognition: advanced cognitive skills involve metacognition, which includes an awareness of one's goals as a learner and the reflective, strategic application of one's knowledge in the service of overall goals.

### Memory: Learning That Persists over Time

We would like students to be able to recall material that they have learned. One of the most robust findings about human memory is that learned material that is more meaningful, better understood, and more richly interconnected with other contents of memory is more likely to be recalled (Anderson, 2009). Thus, a monolingual speaker of English will recall a studied list of English sentences better than a list of Portuguese sentences. The person

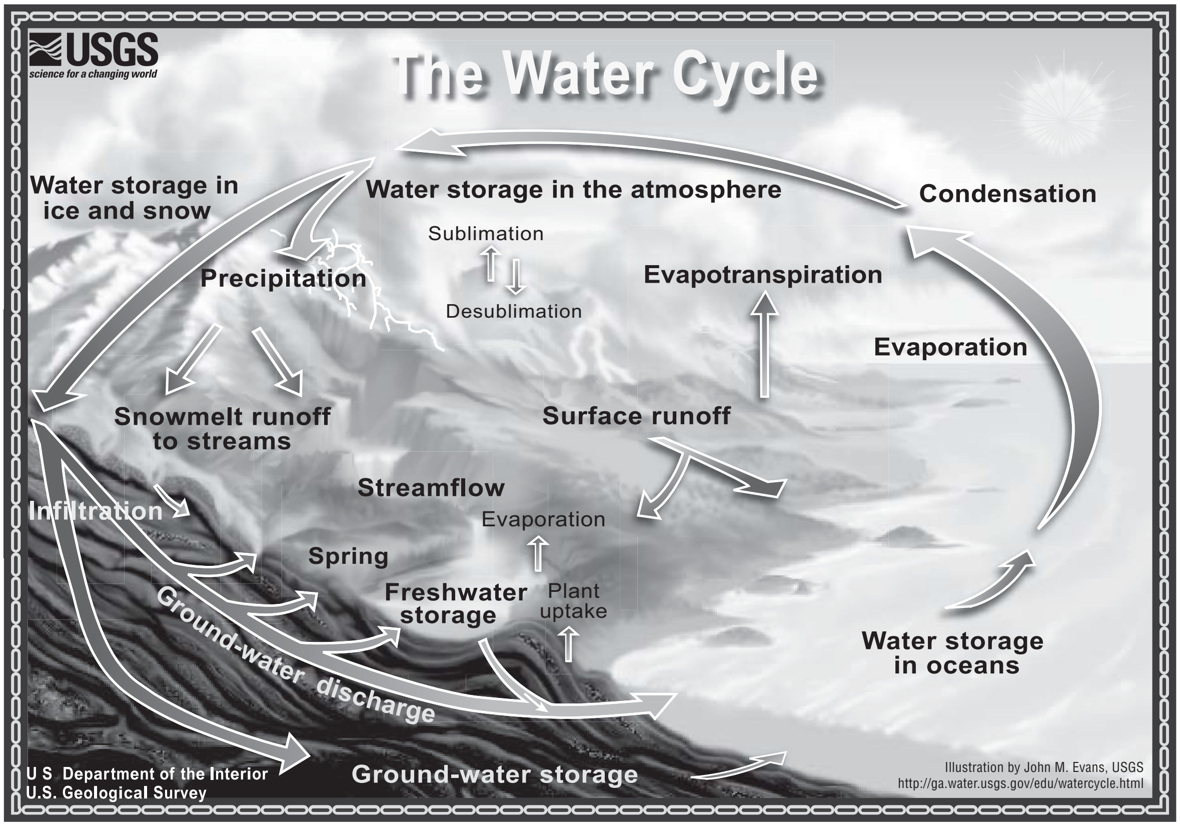


Figure 1. Diagram of the water cycle for students, based on a U.S. Geological Survey education web page. (Original color figure available at http://ga.water.usgs.gov/edu/watercycle.html. Used with permission.)

will recall a narrative passage in English better than a random list of sentences. If the narrative passage presents information about the person's grandmother that connects with known information about said grandmother, the new information is likely to be remembered better than the same information about a previously unknown person. Remarkably, these simple and profound facts about learning and memory continue to be ignored in many classrooms. In some classrooms, sentences about the hydrologic cycle might well sound like Portuguese to an English-speaking sixth grader. Facts about the 16 processes in Figure 1 can easily be taught and assessed in such a way that they are never meaningfully interconnected with each other, even though the student may score reasonably well on a multiple-choice exam. The result would be that no foundation is built for further learning in later grades.

## Reasoning: Using Scientific Concepts

Though memory for presented material is important, it is ultimately a support for thought and action. Assessments of science learning have traditionally been, and sometimes remain, memory oriented, but the goal of science education is not only that the student remember, in some sense, the concepts but be able to use them to solve problems, to make decisions, to interpret findings, to design research, and so on. Instruction and student assessment should be designed to promote uses of knowledge that are typical of the actual practice of science (Edelson et al., 2006; Edelson, 2001; Chinn and Malhotra, 2002a). There is considerable evidence of the ineffectiveness of instructional sequences in which students in introductory courses are taught facts about science, or taught how to solve stereotyped quantitative problems, and are then expected to learn to use the facts for scientific thinking in advanced courses (Trowbridge and McDermott, 1981; Crouch and Mazur, 2001).[2]

It is a mistake to think that simply asking students to do science rather than memorize facts solves the problem, however. Modern science is a hard-won cultural achievement. Although it necessarily rests on natural capacities of the human brain, it also involves specific refinements of those capacities that take time,

[2]Generalizations about the effectiveness of learning environments are statistical. Environments of particular types vary, and, perhaps more importantly, students vary. Some students do learn concepts and reasoning in memory-oriented introductory courses, most likely because they spontaneously organize the concepts and think through their significance. Many of today's college professors probably were such students and are therefore partially blind to the flaws in traditional environments.

guidance, and participation in a scientific community. Sciences seek to establish well-tested explanations of natural phenomena. Professional scientists are practiced at generating promising candidate models or hypotheses to explain classes of phenomena and at devising tests from which results upgrade or downgrade the explanatory prospects of a hypothesis relative to alternatives. This skill is composed of many abilities, including noticing interesting phenomena, thinking in terms of unobservable causal processes, deriving predictions from a model that distinguish it from competing models, designing controlled experiments that eliminate alternative explanations, and so on. Although nonprofessionals would not be expected to be fluent in these skills, it is surprising how sparsely represented they seem to be in the general population and how circuitously and indirectly they seem to be related to our natural capacity for causal reasoning (Kuhn and Pease, 2008; Kuhn, 1991).

Although humans do naturally form inductive generalizations and construct causal explanations, their reasoning tends to be marked by heuristics and biases that, although evolutionarily successful, are often inconsistent with canons of scientific and statistical reasoning (Tversky and Kahneman, 1974; Gigerenzer et al., 2000). They tend to notice and seek only confirmatory evidence (Wason and Johnson-Laird, 1972; Mynatt et al., 1977). They tend to reason poorly in situations that involve thinking through the possible influences of multiple independent variables on a single dependent variable (Kuhn, 1991; Kuhn and Dean, 2004). They have great difficulty overcoming prior conceptions of a phenomenon and reasoning with a scientific model of the phenomenon, e.g., they might believe that an object shot out of a curved track into space will follow a curved path (McCloskey et al., 1980; McCloskey and Kohl, 1983); that the blanket is hotter than the metal bed frame (Watson and Konicek, 1990); that the space between molecules is filled with vapor, or dust, or something (Novick and Nussbaum, 1978); or that positive feedback is always good, as when your teacher gives you positive feedback on a paper.

One implication of this overall picture is that using scientific concepts in the kinds of activities that scientists engage in should be a feature of science learning environments throughout students' educations. A second implication is that students' activities will have to be carefully structured and sequenced to provide developmental pathways that overcome the many barriers to learning to think like a scientist (Clark and Linn, 2003).

### Metacognition: Awareness of the Nature of Science

Expert scientists' work is structured by a sense of the nature of the enterprise. Scientists distinguish between theories (hypotheses, models, interpretations, causal explanations) and the evidence supporting the theories (e.g., the distinction between observed magnetic anomalies and the explanation of their spatial distribution via seafloor spreading). They are aware that multiple kinds of data can bear on a particular theory or hypothesis (e.g., magnetic anomalies and direct geodetic measurements of seafloor movement support the seafloor spreading theory). They are aware that current theories are subject to change, and they are sensitive to degree of confirmation (ranging from contested research frontiers to ideas that, though once uncertain, are now accepted as fact and fundamental to a discipline, e.g., that Earth is more than 6000 yr old). They often think of ideas and knowledge in their disciplines hierarchically, recognizing major theoretical ideas that organize many findings and subtheories, that are foundational to the field, and that constrain new explanations and shape creativity (e.g., plate tectonics, evolution, the periodic table). Scientists know that they should be alert to the possibility of alternative explanations and often maintain multiple hypotheses simultaneously. They are aware of the strengths and weaknesses of particular research designs and methodologies, and to variability, error, and artifacts associated with particular measurement techniques. Thus, at least ideally, individual scientists are reflective about their work. Their work is guided by metacognitive abilities and by a scientific epistemology, i.e., ideas about the nature of scientific knowledge.

Students' scientific epistemologies often remain rudimentary relative to typical expert views[3] through K–12 study and well into college (Carey and Smith, 1993; Smith and Wenk, 2006). Younger students often fail to distinguish between theory and evidence (believing that scientists just observe facts about nature, or just know stuff). Older students sometimes divide science into what is "proven" and what is still hypothesis, or they become extreme relativists or doubters (believing that scientists are biased; that they can show whatever their corporate sponsors want them to show; that they don't *really* know anything; or that *X* is true for *me*). Thinking about science in a way that clearly resembles the way professionals think about science is a significant cognitive achievement, and there is still a paucity of evidence about learning environments that ease the path (Khishfe and Lederman, 2006; Khishfe, 2008; Chinn and Malhotra, 2002b).

Students' metacognitive skills seem to track with their general epistemological development, and their explicit views of the nature of science and their metacognitive skills may have a reciprocal causal relationship (Sandoval, 2005). Thus, students with a sophisticated epistemology will reflectively structure their thinking around seeking an explanation for data, seeking multiple sources of confirmation, thinking in terms of potentially disconfirming as well as confirming evidence, considering alternative hypotheses, trying to generate new, discriminating predictions, considering variability, and so on. Likewise, learning to employ these particular metacognitive skills might help to build one's overall epistemological view.

[3]The nature of scientific knowledge is not a settled issue in philosophy of science, and professional scientists' personal epistemologies vary by discipline and with individual research styles. Nevertheless, the epistemological stances of students show developmental change and typically will appear unsophisticated to any professional scientist and would have to be categorized as such under any contemporary philosophy of science (Carey and Smith, 1993; Smith and Wenk, 2006; Kuhn, 1991).

## BRINGING BASIC RESEARCH TO BEAR ON SYSTEMS-ORIENTED LEARNING AND INSTRUCTION

The foundational considerations just described have specific consequences for instruction intended to foster understanding of complex earth systems. The consequences are outlined in the following sections on model-based reasoning, learning progressions, learning complexity concepts, and system models versus reality.

### Model-Based Reasoning

Researchers on scientific cognition and science learning have argued that model-based reasoning, or reasoning organized around mechanistic, causal explanations, is central to contemporary science (Magnani et al., 1999; Nersessian, 2002). Theoretical models are both public entities (circulated in the form of texts, mathematical expressions, visual representations, computer programs, and physical models) and active psychological structures, or mental models. Experts or novices, of course, exercise their mental models in situations that involve things such as external symbolic and graphical representations, instruments, computer programs, and interaction with other people. The thoughts that come to individuals' minds and their overall behaviors are thus conditioned by the situation, and it might be said that cognition, and the model itself, is spread over the person and situation, or generated by the person-situation complex. Nevertheless, an individual's stable internal representation of a model, its coherence, correctness, depth, generality, and generativity are critical to performance in a given situation and across situations (Anderson et al., 1996; Vosniadou, 2007).

Although models, in the sense of explanatory constructs, are common across the sciences, understanding, reasoning with, and creating models are obviously central to and pervasive in sciences concerned with complex natural systems, such as the geosciences. Typically, to understand or to explain a phenomenon in the geosciences means to have a theoretical model of it that contains one or more of the elements of complexity outlined in the opening section. In systems-oriented fields, understanding how well a phenomenon is understood, why certain data are important, what evidence might be needed, how data are interpreted, and how the science informs policy decisions all hinge on understanding the model or models currently in play.

Given this centrality of system models to the geosciences, and referring back to the learning research context developed in the previous section, the learning goals for students will often include remembering the structure of a model and understanding the model well enough to reason with it, i.e., to use the model to answer questions or solve problems. On a metacognitive level, students must develop a reflective awareness of the importance of models for understanding complex systems and learn to use this awareness in organizing their thinking.

In general, research has shown that students' mental models are often incomplete or flawed relative to an expert standard (Raghavan et al., 1998; Stewart et al., 1992; White and Frederiksen, 1998; Williamson and Abraham, 1995; Michael et al., 2002; Harrison and Treagust, 1996; Gobert and Pallant, 2004; Bao and Redish, 2006). System models in particular have been shown to be difficult to understand in other fields, such as physiology (Rea-Ramirez et al., 2009; Hmelo-Silver et al., 2007; Michael, 1998; Feltovich et al., 2001). The challenge to curriculum designers and teachers in the earth sciences is particularly difficult. Systems concepts pervade the curriculum from the earliest levels, and the learning goals for mid- to upper levels of the curriculum require the mastery of relatively sophisticated system concepts. Finally, the centrality of complex systems to the geosciences requires that students develop a conception of the nature of science that expands on the principles that they are likely to acquire elsewhere in the science curriculum. The next three sections, on learning progressions, learning complexity concepts, and models versus reality, address some of the unique issues that arise in a curriculum that hinges on learning about complex systems.

### Learning Progressions

The literature on model-based reasoning and learning suggests that understanding and applying system models, and appreciating their central role in science, are ambitious learning goals that can only be reached in multiple steps with structured guidance, or scaffolding, for the student. The emerging concept of learning progression (Duncan and Hmelo-Silver, 2009) captures the instructional challenges by integrating several factors: (1) Systems concepts develop over time as learners integrate important features of the concepts and begin to apply them in reasoning contexts; (2) for most learners, successful learning trajectories depend on carefully sequenced instruction, i.e., complexity concepts do not develop spontaneously or in response to unsystematic instruction; and (3) the interval from initial knowledge states to desired cognitive and metacognitive outcomes will often exceed traditional planning units, such as the course, the school year, or the middle-school science curriculum. A focus on learning progressions thus acknowledges the need to integrate curriculum over extended time periods and the need to study typical intermediate states of knowledge and the instructional interventions that promote continued learning. At most points in a learning progression, students will have a partial understanding of the model. Care must be taken that these partial understandings are free of serious misconceptions and that they provide a foundation for further progress.

Professionals in science teaching or research, e.g., most readers of this paper, have little memory of their own learning progressions and have difficulty imagining novice states of knowledge, which are incomplete and which often contain misconceptions that are hard to uncover and repair. It is worth reflecting for a moment on the likely length and the possible intricacies of the learning progressions for systems concepts. The water cycle can serve here as an illustration. Supporting students in building an integrated memory representation of the model and applying it with increasing sophistication will involve structured sequences of materials and activities that include text, diagrams, discussion, problems and other kinds of assessments, data interpretation, and exercises with computer-based simulations. Several visual representations of the water cycle in Figures 1–3, which might be used at three different points in a learning progression, make a good illustrative focus, since diagrams are central to thinking and teaching about the water cycle. The representational choices in these figures, and their implications for the associated learning goals, are a good way to begin to appreciate the extended learning progressions that are required of students who are learning about systems. Similar points could be made about other instructional materials, of course.

To begin with, it is worth noting that visual representations of natural phenomena or scientific models often pose unexpected challenges to students. Understanding scientific illustrations or figures involves complex conceptual processes that go well beyond merely seeing (Carpenter and Shah [1998] document this point for seemingly rather simple graphs). For example, the pictorial/graphical conventions observed in a figure typically depend on the very concepts the student is trying to learn. The student can misinterpret meaningful graphical elements or impose a mistaken interpretation on elements of the figure that are pictorially mandated but conceptually irrelevant (e.g., a ball and stick diagram in chemistry has to assign a color to oxygen, but oxygen is not in fact red). The student working with a figure is thus in a bootstrapping situation, where the figure can help the student learn some target concept, but the proper interpretation of elements of the figure depends on understanding aspects of the concept (Tversky et al., 2000; Jones et al., 2001, 2005).

Depictions of cyclical earth systems pose such problems. Quasi-realistic pictorial diagrams, such as Figure 1, overlay the names of process concepts and arrows depicting flow relationships on a picture of a scene. This kind of pictorial diagram is probably useful, even necessary, to engage young students in the material and to scaffold their understanding, but care must be taken that they are not confused or distracted (Mayer et al., 2008): Do some students think that it never rains over the ocean? Do some fail to grasp the relationship between evaporation and condensation, thinking that all water in the atmosphere is in the form of clouds? Do some misinterpret the arrows underground as underground rivers? Do students in Kansas think the water cycle only occurs at the seaside? Do students grasp the relationship between fluxes and reservoirs from the diagram? Do some fail to appreciate the truly cyclic nature of the system, in which matter is conserved? Many such misconceptions or naïve alternative conceptions are discussed by Ben-Zvi-Assaraf and Orion (2005a). Clearly, a pictorial diagram cannot establish a cognitively robust conception of the water cycle, and any single diagram has, of necessity, the capacity to reinforce incorrect conceptions. Recognizing this, the materials accompanying Figure 1 on the U.S. Geological Survey Water Science for Schools website augment the figure with further explanation of the cycle, but assessment of student outcomes would be necessary to establish whether the explanation is successful.

Teachers and designers of curriculum must decide what would constitute success for students at this level of instruction. For example, one goal that might be considered as a foundation for further learning is that the student has truly grasped the conservation of mass in the cycle. This mastery can be assessed in carefully worded multiple-choice or short answer questions or in discussion. During, or after, instruction, some students who have studied diagrams such as Figure 1 might assent to a statement that increased evaporation due to global warming is leading to an overall loss of water (Ben-Zvi-Assaraf and Orion, 2005a). Some students might assent to the statement without reasoning with what they have learned; others might actually reason their way to the conclusion with a faulty conception of the system; others might be reasoning with a mental model that is truly cyclic, but they have misinterpreted the statement. The key point is the need to create instructional materials, practices, and assessments that result in most students emerging with a rudimentary but accurate mental model that they can reason with and that provides a platform for further learning. Structuring early curriculum to give students a beginning metacognitive appreciation of the importance of complex systems is an interesting additional challenge for curriculum designers.

Figure 2 is a depiction of the water cycle that is intended for people involved in water management or water policy, who are assumed to be more sophisticated than the roughly K–8 students for whom Figure 1 was designed. The lack of realism in the drawing signals its abstraction—it is less a realistic depiction of a natural scene than it is a diagram of the system model with pictorial icons. Implicitly, the figure envisions a student who does not need a vibrant, realistic picture to be engaged but whose

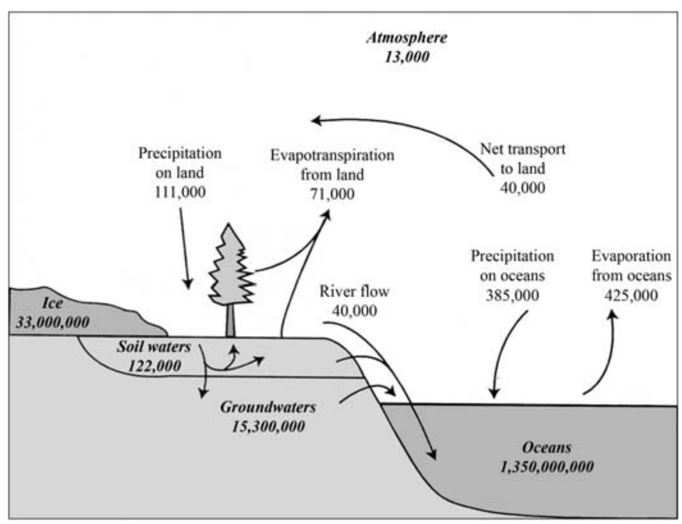


Figure 2. Diagram of the water cycle. Reservoirs (shown in italic) are in cubic miles. Fluxes (shown in roman type) are in cubic miles per year. Image is from Winter et al. (1998), used with permission. In original, reservoirs (pools) were in blue, and fluxes were in black; view online at http://pubs.usgs.gov/circ/circ1139/htdocs/natural_processes_of_ground.htm.

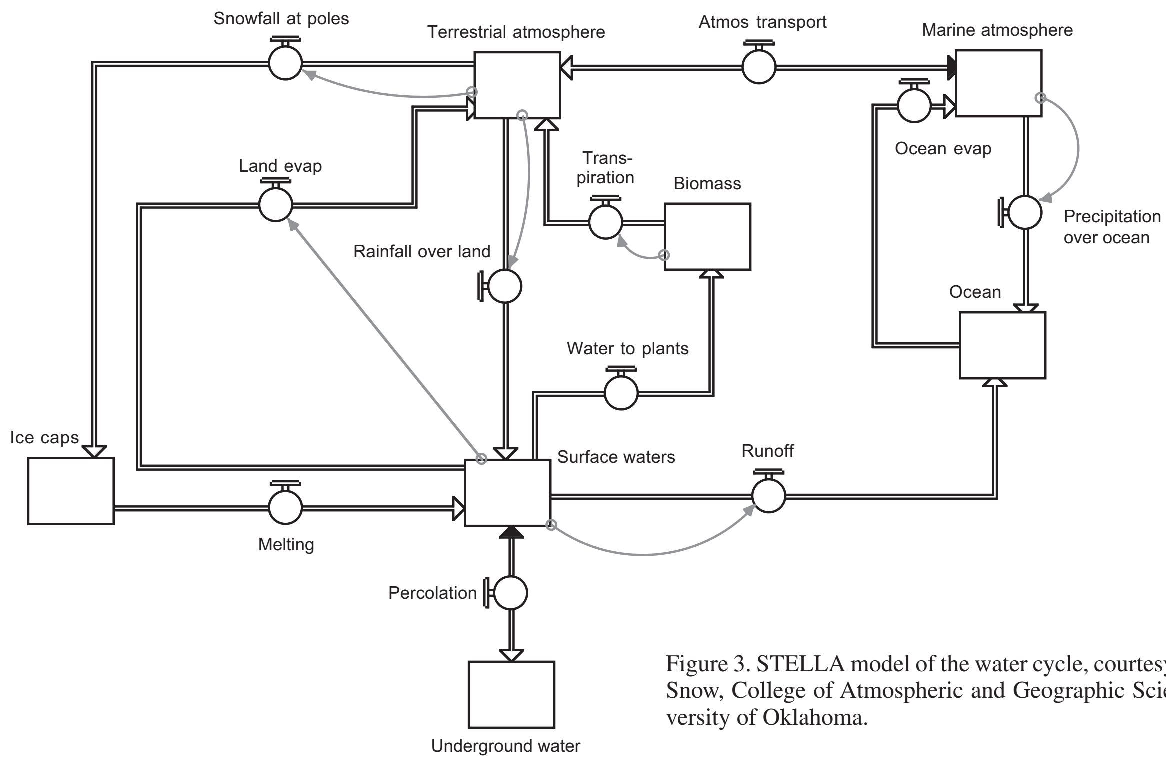


Figure 3. STELLA model of the water cycle, courtesy of John T. Snow, College of Atmospheric and Geographic Sciences, University of Oklahoma.

understanding will be scaffolded by seeing and reflecting on the association of pictorial elements with the font-based coding of terms for reservoirs (bold italic font) and flows (roman font), and with global totals expressed in physical units. The association encourages the insight that the picture is a communicative convenience and that the natural system encompasses all the oceans, groundwater, ice, and atmosphere of Earth. Interestingly, in the context of groundwater and surface-water management, the text accompanying Figure 2 refines the model to note that there are important local variations in the processes depicted.[4] Could Figure 1, intended for young students, be improved by incorporating some of the aspects of Figure 2, such as the font coding, the explicit reference to all Earth's water, or the reference to and distinction between precipitation on oceans and land, or would young students be overloaded? It is impossible to know without classroom experimentation.

As with the young students for which Figure 1 is intended, the learning goals for the more advanced students exposed to Figure 2 should be interrogated. Do the numbers presented in the figure actually support an increased ability to solve quantitative problems concerning the water cycle? Can students exposed to this curriculum correctly evaluate simple, but conceptually probing, statements such as the one above asserting that global warming leads to a global loss of water? Can students emerging from this curriculum reconcile global conservation of mass in the water cycle with regional and local variability in precipitation and water supply? For example, could a modal student write an insightful short essay commenting on the following: *Jessie says that global warming doesn't change the total amount of water in the world. How could this be true, if global warming causes a massive permanent drought in the American Southwest?* Can problem sets or assessments be constructed at this level of instruction that compel students to consider the interplay among multiple processes in the system, thus reinforcing a metacognitive awareness of the importance of systems thinking in the geosciences?

Figure 3 is the visual representation of a computer model of the water system implemented in the STELLA modeling environment.[5] It can be seen as a translation of the processes in

[4]"The hydrologic cycle commonly is portrayed by a very simplified diagram that shows only major transfers of water between continents and oceans, as in Figure [2 in this paper]. However, for understanding hydrologic processes and managing water resources, the hydrologic cycle needs to be viewed at a wide range of scales and as having a great deal of variability in time and space. Precipitation, which is the source of virtually all freshwater in the hydrologic cycle, falls nearly everywhere, but its distribution is highly variable. Similarly, evaporation and transpiration return water to the atmosphere nearly everywhere, but evaporation and transpiration rates vary considerably according to climatic conditions. As a result, much of the precipitation never reaches the oceans as surface and subsurface runoff before the water is returned to the atmosphere. The relative magnitudes of the individual components of the hydrologic cycle, such as evapotranspiration, may differ significantly even at small scales, as between an agricultural field and a nearby woodland." (from http://pubs.usgs.gov/circ/circ1139/htdocs/natural_processes_of_ground.htm)

[5]STELLA is a commercial software package sold by isee systems of Lebanon, New Hampshire: http://www.iseesystems.com/index.aspx.

Figure 2 into a system diagram that utilizes rigorous notational conventions with direct mappings to simulation code (in fact, one can program in STELLA by constructing such diagrams in a graphical user interface). The diagram is conceptual rather than pictorial, containing no representation of geography. It envisions a student who can think in terms of global masses without the pictorial scaffolding. The representation of reservoirs (boxes) and flows (double arrows) reflects a strong generalization that many complex dynamic systems can be thought of in these terms. More importantly, perhaps, it envisions a student who grasps the distinction between the real system and the model of the system, and who can think about the causal mechanisms that are actually being included in the model. STELLA notation may scaffold this attention to mechanism by explicitly distinguishing between the storage and movement of material (boxes and double arrows) and hypothesized causal influences, represented by converters (circles) and connectors (single arrows). Thus, in Figure 3, some converters are influenced by more than one connector. The student must understand each of these mechanisms both qualitatively and ultimately quantitatively.

The expected cognitive outcomes of instruction involving modeling environments, such as STELLA, are likely to be ambitious. Given that students understand the nature of each of the reservoirs and flows, and the cyclical nature of the system, they are expected to understand or learn the causal mechanisms involved in the connectors (single arrows). Given this overall understanding, they are in a position to explore nonlinearities, interactions among processes, and emergent system properties by running the model with different parameter values. That is, they are in a position to begin to grasp some of the deep lessons of the systems perspective. The prospect of bringing large numbers of students to this level is exciting, but there are significant questions about the necessary prior level of learning, about where in a learning progression modeling is best introduced, and about effective assessments.

The example of the water cycle demonstrates that complex systems instruction at any given level involves assumptions about students' entering states of knowledge, the selection of learning goals that will provide a stable foundation for future learning, and choices about how to present conceptual content and assess outcomes. The visual representations in Figures 1–3 suggest both the kinds of choices that are made and the need for instructional fine-tuning that inevitably follows. Returning to the context from the learning sciences established at the beginning of this paper, for each stage of a learning progression, we must ask the following: (1) What is the partial but accurate mental model of the system that the student should retain? (2) What sorts of reasoning or problem solving should the student be able to accomplish using the model? (3) How should the instruction enhance the student's metacognitive awareness of the nature of science? Constructing effective learning progressions for systems geoscience is partly a matter of knitting together work that has been done at different levels of instruction with attention to learning goals and thorough assessment, but there is also a frontier of educational research that is defined by the special nature of complexity concepts. This frontier is considered in the next two sections of the present paper.

**Learning Complexity Concepts**

It is clear from the previous discussion that extended learning progressions for complex systems arise in part because many concepts are involved, but an additional challenge is that system models involve sophisticated, initially counterintuitive conceptions of causality and mechanism that are known to be difficult to learn and that lie on the cutting edge of research in the learning sciences. The issues will be sketched briefly here mainly in terms of the learning of feedback concepts, again with reference to the water cycle. Feedback relationships in reservoir and flow models might be considered the simplest case of extending a naïve linear conception of a mechanism into new conceptual territory. Similar points could be made concerning other complexity concepts, such as chaotic behavior or self-organization.

Feedback loops are pervasive in and central to models of earth systems. Whatever the initial points in a learning progression may be, it seems difficult to argue that students *understand* a model of a complex system if they do not ultimately understand the influence of feedback loops on its performance, at least qualitatively. For example, it seems possible that one point in a typical learning trajectory for an earth system is knowing the names of the reservoirs and flow processes, being able to connect them in a diagram, and knowing something about at least some of the processes (e.g., evaporation converts water from liquid to gaseous form, transporting it to the atmosphere). Thus, a student's diagram of a piece of the water cycle might look something like Figure 4.

The diagram sums up what the student knows about how water in the ocean and water in the atmosphere are related by the process of evaporation. From the systems point of view, however, the dynamics of the flow are crucial. Does evaporation occur at a constant rate? If not, what drives the rate up or down? A crucial conceptual advance for the student would be a qualitative understanding of the kinds of feedback relationships diagrammed in Figure 5, which augments a part of Figure 3, presenter earlier.

An understanding of these two feedback loops represents a significant conceptual advance. The double arrows, for material flow or flux, now explicitly represent the variable rate of evaporation in the form of the converters attached to the evaporation arrows. As pointed out already, the diagram now contains a sec-

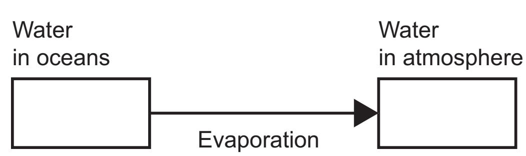


Figure 4. Hypothetical student diagram of a portion of the water cycle.

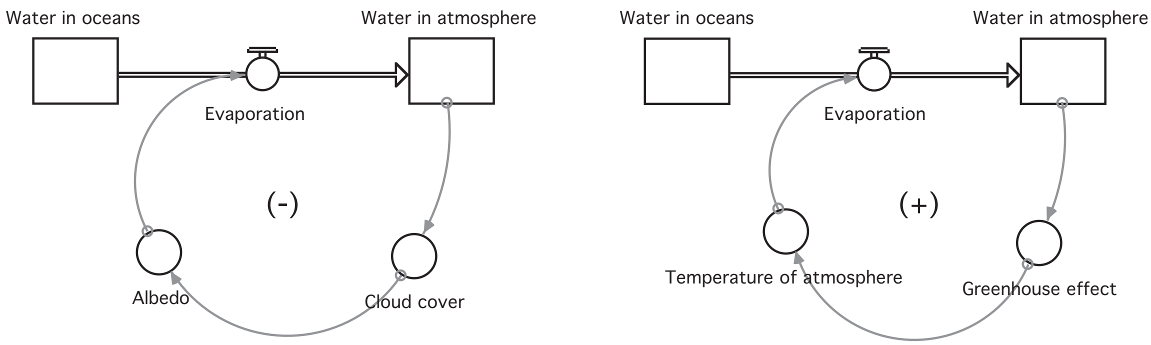


Figure 5. Illustrative negative (–) and positive (+) feedback loops for a portion of the water cycle in STELLA notation (courtesy of Kim Kastens, Lamont-Doherty Earth Observatory and Department of Earth and Environmental Sciences, Columbia University).

ond kind of arrow, which represents direction of causal influence rather than flow of material. The causal pathways show that the amount of water in the atmosphere can influence the rate of evaporation, which controls changes in the amount of water in the atmosphere. In the negative loop, increasing amounts of water in the atmosphere decrease the rate of evaporation, which tends to decrease the amount of water in the atmosphere. In the positive loop, increasing amounts of water in the atmosphere increase the rate of evaporation, which tends to further increase the amount of water in the atmosphere.

In addition to introducing new causal pathways, the feedback loops involve additional processes that were not part of the initial description of the water cycle, and since the arrows are causal, the student has to understand *the mechanism* of *how* the processes involved in the feedback create the effects. Mechanisms are at best implicit in systems diagrams. For example, the presence and sign of a feedback loop are not obvious from the way a network diagram looks. The presence of a converter and its connector arrow in a STELLA diagram is a sign that a submodel of the overall system model has to be understood.

Like many other aspects of complex systems, the learning of the concepts of negative and positive feedback seems to be a seriously under-researched problem. Although the practical application of negative feedback goes back at least hundreds of years to the invention of the centrifugal governor to control mechanical systems, the generalized understanding and detailed mathematical treatment of feedback processes began in the late nineteenth century, and the interpretation and proper use of feedback processes in earth systems models are subjects of current discussion at a professional level (Roe, 2009; Bates, 2007). It is possible that the transition from understanding the flow of material in a complex system, at the level of Figure 4, to understanding the causal relationships that affect the dynamics of flow, particularly those that involve feedback, is a significant cognitive challenge. Sibley et al. (2007), for example, found that students in a university general education geology course had a decent understanding of reservoirs and fluxes in the water cycle, but they stated that feedback loops are a more advanced concept and did not test understanding.

An understanding of feedback concepts appears to involve changes in typical common-sense conceptions of causality (Perkins and Grotzer, 2005; Grotzer and Lincoln, 2007). People tend to think of phenomena as having unitary causes and to think of causality as unidirectional (A causes B, or A causes B, which causes C). Grasping that chains of causality can loop in such a way that the current output of a process can affect its later inputs requires a reorganization of the simplest notions of cause. Since most psychological and educational research on causality concerns how people process empirical evidence to infer simple cause-effect relationships,[6] we know little about how students come to understand the workings of complex system models or relate them to observable evidence. For example, it is possible that many students who appear to understand homeostasis in K–12 biology do not understand the idea of a recurrent causal chain that constitutes a feedback control signal but instead think that the body just intentionally restrains itself.

Understanding system models requires students to overcome a natural preference for plausible, unitary causal mechanisms. The macroscopic behavior of complex systems is typically the result of multiple interacting processes, some of which are nonobvious or counterintuitive. A particular feedback loop, for example, is often one of several influences on a process. In Figure 5, two different loops, one negative and one positive, compete in their influence on evaporation. In contrast to biological and engineered control systems, feedbacks in earth systems are often counterintuitive or invisible, e.g., in Figure 5, the effect of water vapor as a greenhouse gas and the influence of clouds on Earth's albedo are both nonobvious relative to an initial understanding of the cyclical relationship between evaporation and precipitation,

[6]Beginning with Hume in the modern period, a normatively satisfying solution to the problem of induction has been recognized to be notoriously difficult. Nevertheless, humans, beginning in infancy, and at least some other organisms, seem to have a natural tendency to make causal inferences from finite experiences. Examples of work on the inference of simple causal processes from evidence may be found in Waldmann et al. (2006) and Kuhn and Dean (2004).

which many students might interpret as the obvious "loop" present in the system.

Understanding the consequences of rates and nonlinearities in processes that are not immediately visible requires an expansion or revision of a basic binary, temporally immediate notion of a cause or process (either A causes B or it does not, and the effects on B are easily and quickly observable). The top-level macroscopic behavior of a system over time can be markedly affected by changes in the assumed rates or functional descriptions of underlying lower-level processes. Time lags, nonlinearities, stabilities, and instabilities in top-level behavior are often emergent properties of the system in the sense that they are not contained in the lower-level driving processes or obviously predictable from them (Turcotte, 2006; Herbert, 2006). It seems clear that understanding the quantitative behavior of system models and the properties of emergence can only be achieved by working with them, typically in the form of computer-based simulations. Working with simulations of earth systems requires understanding numerical expressions of mass, concentration, and rate, with units of measurement, as well as some understanding of differential equations or graphical stand-ins for them. K–16 curricular sequences that lead students to this level are not well established.

The challenges of understanding emergent or subtle behavior in system models are not only mathematical or formal, however. Wilensky and Resnick (1999) argued that it is a significant conceptual change to think about systems in terms of levels of analysis, where patterns of behavior at the top level can emerge from distinct processes occurring at lower levels. In other disciplinary contexts, it has also been argued that the conceptual change involved in understanding emergent phenomena is ontological in the sense that the student must form a concept of a new *kind* of phenomenon as opposed to adding a new instance of an already familiar kind (Chi, 2005; Slotta and Chi, 2006). Libarkin and Kurdziel (2006) presented evidence that many beginning college students do not think in terms of causal processes that underlie earth phenomena (e.g., fossilization, formation of continents) and argued that learning to think in terms of processes is an ontological change that underlies the systems perspective. Raia (2005, 2008) presented evidence that undergraduate students tend to misinterpret systems phenomena in piecemeal linear causal terms, arguing that their conception of cause must be reorganized and expanded to include the interactive causal networks typical in complex systems.

Levels of analysis, process interactions, and feedbacks in earth systems involve the coordination of molecular and molar conceptions of matter and of the interaction of states or processes that are both visible and invisible. Students' difficulties with these coordinations are well established across the curriculum (e.g., Gabel et al., 1987). Well-known student misconceptions about photosynthesis (Barker and Carr, 1989; Cañal, 1999) (e.g., that the wood in a tree trunk came from material in the soil or that plants breathe) suggest, for example, that students have trouble with the idea of carbon in the atmosphere, and that it can somehow be transformed and transported to/from the atmosphere and other, unlike objects (plants, animals, bodies of water, cars). The immediate surfacing of these issues for geoscience instruction is suggested by Ben-Zvi-Assaraf and Orion's (2005b) finding that students had difficulty integrating visible and invisible processes into a systems conception of the water cycle and in appreciating conservation of mass in the cycle.

The challenges of understanding learning progressions for systems sciences are neatly suggested in a series of studies by Sterman and Sweeney (Sterman, 2008; Sterman and Sweeney, 2007), who found that Massachusetts Institute of Technology graduate students had fundamental misunderstandings of accumulation in simple systems involving a single stock with an inflow and outflow and no feedback loops. Students appeared to be using a pattern-matching heuristic for reasoning in which it is assumed that levels of an independent and dependent variable are directly correlated, or have a direct cause-effect relationship. For example, most reasoned that if carbon emissions were stabilized at current levels, then the amount of $CO_2$ in the atmosphere would stabilize, whereas in fact it would continue to increase. These elite, highly educated students had not learned to recognize situations that involve reservoirs and flows and had not acquired basic strategies for reasoning with them, such as thinking in terms of accumulation, mass balance, and comparison of rates of inflow and outflow.

### System Models versus Reality

The previous section concerns students' understanding of and ability to reason with models of earth systems. Establishment of successive levels of understanding for at least some of the models in a discipline is a primary goal of a science education curriculum. A second, equally important, goal of science education is for students to understand the nature of theories and hypotheses in science and their relationship to evidence that bears on them. The understanding of theory and evidence shows a complex developmental progression, and many college students fail to reach an epistemological stance that is akin to that of professional scientists (see, e.g., Kuhn, 1991; Smith and Wenk, 2006).

Models of complex systems are in many ways a novel kind of scientific hypothesis. In an era where traditional limits of mathematical tractability or practical computability have disappeared, professional scientists grapple with how to make choices about what to model, what processes to include in a model, what spatial and temporal grain to select, how to explore parameter settings, and how to understand the space of consequences or predictions covered by a model. At some points in the curriculum, students must be made aware of these issues and experience them through constructing, altering, and running variant models (see, e.g., Bice, 2006).

The bulk of the psychological and educational literature on students' reasoning with evidence concerns the mastery of the experimental method and distinguishing between correlation and causation in situations involving simple, one-step causality (Kuhn and Dean, 2004). This literature has restricted applicability to students' understanding of empirical verification in observational, historical disciplines, such as the geosciences. Although, some of the relevant issues are dealt with in the accompanying papers in this volume, most likely, metacognitive attention to the nature of evidence in the geosciences could be increased in geoscience courses and curricula. Students should learn not only *that* a particular hypothesis or theory is well established but also something about *how* it was established and the general lessons to be drawn concerning confirmation or disconfirmation in the geosciences.

The relationship between complex earth systems models, as hypotheses or theoretical constructs, and evidence that bears on them is not straightforward. The validation of system models is at the cutting edge of contemporary scientific practice and epistemology. Professional scientists are working to articulate the nature of the support for particular claims, as well as hard-won general lessons about testing complex models.[7] In the areas of climate change and environmental management, the nature of evidential support or disconfirmation for system models has become an enormously important policy matter and is therefore a significant educational issue that deserves increased attention from instructors. On the one hand, students must understand the distinction between models and reality in an era when models often produce impressively detailed, visualizable output. On the other hand, they must learn not to dismiss all models as merely models.[8] Issues such as averaging over multiple models or parameter sets and weighing the relative accuracy and importance of potentially relevant data series deserve attention throughout the college curriculum and possibly careful introductory treatment in the K–12 curriculum, as well. Maintaining the distinction between models and reality, understanding the nature of choices about the processes to include in a model, and grasping the distinctions among the well-confirmed and more hypothetical aspects of a model are all critical metacognitive accomplishments and potentially challenging instructional issues.

## FUTURE PATHWAYS FOR CURRICULUM AND INSTRUCTION IN COMPLEX EARTH SYSTEMS

The previous sections developed a framework for thinking about science learning and complex systems instruction, including a theoretical analysis of why systems thinking is difficult to learn, an introduction to the key educational issues, and numerous entry points to the relevant literature. In this section, some implications of this framework are summarized, and an agenda for future research is proposed. The following items relate to key points of the framework, summarized here:

1. Integrated conceptual memory—Science instruction should be designed in such a way that students learn multidimensional, integrated, meaningful concepts, which will persist in memory, rather than isolated facts, which tend to be forgotten. Systems concepts are central to the geosciences. Students should finish a major unit of instruction knowing all the elements and processes in a system and the ways in which they fit together, as opposed to unsystematic fragments.

2. Reasoning—Instruction should promote active reasoning with the target concepts. Reasoning with system models is a central goal of earth science instruction.

3. Metacognition—Instruction should promote students' awareness of the nature of science and their ability to use this knowledge to guide their thinking. For example, students who have absorbed the systems perspective should approach problems by asking, "What are the relevant systems here?"

### The Course and the Classroom

Although there is a need for new lines of research on learning and for discipline-wide changes in curriculum design to address systems thinking, new developments are likely to begin with the innovations of individual instructors and departments.

#### *Attention to Systems Thinking*

Given the centrality of systems thinking to the geosciences and the difficulty of the concepts, instructors should resist the impulse to think that students develop a systems mindset spontaneously or that systems ideas are taught in someone else's course or sometime later in the curriculum. A useful counter-impulse would be to ask how to introduce or strengthen elements of systems thinking in one's own courses and how to reinforce concepts that are taught concurrently or at other times in other courses.

#### *Assessment*

Given the difficulty of systems concepts, careful assessment of student learning is particularly important. Early in an instructional cycle (term, unit, etc.), a formative assessment of target systems concepts can allow the instructor to adjust the approach or the pace of instruction to correct for any widespread deficiencies in student understanding. Low-stakes quizzes or in-class small-group exercises that are quickly diagnosable are examples of such assessments. Classwide deficiencies in systems concepts on summative assessments, such as final examinations, should be addressed in refining course materials for the following year.[9] Both formative and summative assessments should probe

[7]Serious discussions of climate models, for example, tend to involve an interplay among model assumptions and the properties of different data sets. An arbitrary example of such a discussion might be Rahmstorf and Vermeer (2009).

[8]Both a failure to distinguish between hypothesis and evidence and an extreme skepticism are common stages in the development of students' understanding of the nature of science (Carey and Smith, 1993; Smith and Wenk, 2006). In the first case, a system model might be thought of as just something we know, or found out, about Earth, and its outputs would be thought of as equivalent to observations. In the second case, students might think that models can be used to show anything and would greet all models with equal skepticism.

[9]For example, if students from the 50th to 85th percentile of a total-score distribution fail all of the systems items that require some conceptual understanding, a reasonable conclusion would be that the instruction failed to convey the concepts.

conceptual understanding. For example, do students truly understand conservation of mass in a cycle? Do they understand the causal mechanism that drives a feedback loop? Can they reason qualitatively with a model to a conclusion? Can they identify and label as positive or negative a feedback loop in a model diagram? Many of the educational research papers cited here can serve as sources of ideas for the assessment of model and systems understanding. Useful starting points might be Ben-Zvi-Assaraf and Orion (2005a, 2010), or Mohan et al. (2009).

#### *Models versus Reality*

As students confront the challenge of understanding system models, their metacognitive grasp of the distinction between models and reality should be maintained. The distinction can be difficult to maintain in introductory contexts, where the processes included in a classroom model are often unassailable reference assumptions, such as conservation of mass, and students may have difficulty simply understanding the behavior of the model itself. Nevertheless, it is advisable to introduce students to (1) the degree of correspondence between model predictions and empirical measurements and the assessment of fit, and (2) the refinement of models via the inclusion of additional processes, for which empirical significance may be less well established or more poorly understood, e.g., one of the feedback loops in Figure 5. Ultimately, students' futures as professional geoscientists, policy makers, or citizens depend very much on their grasp of this distinction. Schwarz et al. (2009) addressed some of the relevant issues.

#### *Nature of Science*

Complexity in the geosciences is intertwined with the observational/historical nature of the geosciences, which mandates complex models and the simultaneous evaluation of multiple interacting processes and multiple data sources. Students whose only model of science is single-process, one-step causality and the experimental method are unlikely to understand hypothesis formation and confirmation in the geosciences. A key metacognitive goal of the curriculum should be to develop students' understanding that the geosciences are in some ways a different "kind" of science. In many respects, the current set of papers explores this issue in some detail. Cleland (2001, 2002) provided a rigorous philosophical analysis of the historical aspects of the geosciences.

### Complexity Curriculum

The increasing importance of complexity science across disciplines raises the question of coordination across areas of instruction in teaching complexity concepts and methods. Concepts of feedback, levels of analysis, emergent phenomena, self-organization, and so on could be introduced, cross-referenced, and reinforced in multiple courses across the curriculum. Complexity-oriented instruction is gaining attention in other disciplines (e.g., Wilensky and Reisman, 2006), and interdisciplinary or general-purpose courses in system modeling or complexity science are a possibility that has an intellectual rationale and is under active exploration (Wilensky and Resnick, 1999; Jacobson and Wilensky, 2006; Schwarz et al., 2009). These ambitious ideas depend in part on funded research for development, but they can also be driven by innovative collaborations across departments at particular institutions. The ultimate success of the ideas hinges on whether learning about complex systems in general, or in the context of a particular stock of examples, transfers to new contexts.

### Instructional Technology

Although many earth systems concepts can be introduced effectively to students without depending on computers (e.g., Ben-Zvi-Assaraf and Orion, 2005b), computers, modeling software, and appropriate software-based instructional protocols offer rich opportunities for teaching and learning about complex systems, and it is arguable that they are required for intermediate-to-advanced levels of instruction. Models are central to the practice of earth systems science at the professional level, and students' understanding of the behavior of complex systems, and of the systems perspective, is potentially greatly facilitated by running simulation models, altering them, and comparing their output to real data sets. As in many other disciplines, the use of instructional technology, and more specifically of simulations, seems to have stabilized in the geosciences at the level of numerous local or sparsely distributed national efforts (e.g., Bice, 2006; Edelson, 2001; Chandler et al., 2005). There appears to be a need for broader experimentation with best practices (as introduced, for example, by Bice, 2006) and for more widespread availability and use of accessible global climate models (exemplified by the EdGCM project of Chandler et al., 2005).

### Systemic Change

Understanding complex earth systems appears to be an extended intellectual challenge from introductory through advanced levels. Effective instruction is therefore likely to require curricular coordination across grade levels in the K–16 curriculum. Educational research collaborations between learning scientists and geoscientists and college-school partnerships in middle- and high-school curriculum development and assessment are particularly important in fostering the needed developments.

### Research Agenda

The discussion in this section and the overall themes from the present paper point to several issues that might form a core research agenda on understanding complexity. None of the items on the agenda is completely unexplored, but they could all use further and more cumulative, coordinated work.

#### *Learning Complexity Concepts*

Although the literature in the learning sciences points clearly to the conclusion that complexity concepts are difficult to learn, there is very little research on student conceptions of particular complexity concepts in earth systems, particularly on positive and negative feedbacks, levels of analysis and emergent phenomena, and complex causality. Some recent papers (e.g., Raia, 2005, 2008) point in a promising direction.

### *Learning Progressions*

Research on extended learning progressions that scaffold and assess the acquisition of earth systems concepts is badly needed at the precollege and college levels. Mohan et al. (2009) and Ben-Zvi-Assaraf and Orion (2010) are model efforts in this direction.

### *Robust Instructional Software*

Instructional materials and software packages that progressively deepen students' exposure to modeling complex systems remain an under-researched area. At an intermediate-to-advanced undergraduate level, Bice (2006, 2012) has constructed learning sequences that attempt to scaffold a progressive introduction to modeling earth systems using STELLA with great care to the pitfalls and nuances of modeling and to the substance of the science. EdGCM (Chandler et al., 2005) is a striking effort to make a realistic global climate model available to the instructional community. Efforts such as these require more substantial support, persisting infrastructures, and serious assessment and refinement research.

### *Nature of Geoscience*

There is a need for explicit attention to introducing students at various levels of instruction to different models of the scientific enterprise and of causality. Recent work in philosophy and history of science provides some support for developing sound curriculum in this area (e.g., Cleland, 2001, 2002; Mitchell, 2009). Perkins and Grotzer (2005), Grotzer and Lincoln (2007), and Raia (2005, 2008) have done relevant initial work on the associated learning issues.

### *Policy Integration*

Climate change is the premier public issue in the science of complex earth systems. Increasingly, climate change will be central to earth and environmental science curricula. Student understanding of systems concepts is a critical outcome of these curricula. Work on teaching the concepts and assessing student understanding in the context of policy-motivated science instruction is badly needed.

## CONCLUSION

Engaging with the complexity of physical, biological, and social systems is a hallmark of contemporary science. Complexity is particularly central to the study of earth systems for both students and professionals. Complexity concepts constitute a stiff challenge for both learners and teachers, yet increasing mastery of these concepts must be considered a sine qua non of the geoscience curriculum and an essential element of educating a citizenry for the rest of the twenty-first century. The intrinsic complexity of earth systems and the deep experience of the geoscience community in thinking and teaching about these systems make the geosciences a particularly exciting environment for educational innovation.

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