Education Tech Research Dev (2008) 56:5–28
DOI 10.1007/s11423-007-9065-2

RESEARCH ARTICLE

# A design framework for educational hypermedia systems: theory, research, and learning emerging scientific conceptual perspectives

**Michael J. Jacobson**

**Abstract** This paper focuses on theory and research issues associated with the use of hypermedia technologies in education. It is proposed that viewing hypermedia technologies as an enabling infrastructure for tools to support learning—in particular learning in problem-based pedagogical environments involving cases—has particular promise. After considering research issues with problem-based learning related to knowledge transfer and conceptual change, a design framework is discussed for a hypermedia system with scaffolding features intended to support and enhance problem-based learning with cases. Preliminary results are reported of research involving a new version of this hypermedia design approach with special ontological scaffolding to explore conceptual change and far knowledge transfer issues related to learning advanced scientific knowledge involving complex systems as well as the use of the system in a graduate seminar class. Overall, it is hoped that this program of research will stimulate further work on learning and cognitive sciences theoretical and research issues, on the characteristics of design features for robust and educationally powerful hypermedia systems, on ways that hypermedia systems might be used to support innovative pedagogical approaches being used in the schools, and on how particular designs for learning technologies might foster learning of conceptually difficult knowledge and skills that are increasingly necessary in the 21st century.

**Keywords** Hypermedia · Hypertext · Technology design · Problem based learning · Conceptual change · Transfer

Internationally there has been increasing interest in the uses of technology to support and enhance education (Kozma 2003). Variously described as “e-Learning,” “information and communication technologies (ICT),” “cyber education,” “digital media,” and “learning technologies” (the term preferred here), these approaches employ hypermedia technologies that allow digitally encoded nodes of text, multimedia, dynamic computer models, and

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M. J. Jacobson (✉)
Learning Sciences Laboratory, National Institute of Education, Nanyang Technological University,
Singapore, Singapore
e-mail: mjjacobson@mac.com

even virtual reality simulations to be flexibly connected via hyperlinks in conjunction with digital communication technologies. However, as pointed out in the preface to this special issue, there has been surprisingly little empirical research documenting student knowledge gains associated with the use of educational hypermedia and there have been few attempts to generalize theory or research based design principles for these types of systems (Azevedo 2005; Dillon and Gabbard 1998; Shapiro and Niederhauser 2003). As a way to address concerns such as these, I discuss in this paper, as a case study, a program of research into cognitive, learning, and design factors associated with uses of hypermedia technologies to help foster learning outcomes such as conceptual change, knowledge transfer, and enhanced problem solving.

## Research on problems with problem-based learning

One way to explore these issues is to consider how hypermedia systems might be designed to support specific pedagogies. For example, a learner-centered pedagogical approach that has been receiving great interest recently involves students learning with cases and problems. Research has documented how problem-based learning (PBL) can help learners achieve important learning outcomes that include improved problem solving and knowledge transfer to new situations in university, legal, and business education. There are a variety of literatures from medical, business, legal, high school, and college education, as well as in the cognitive and learning sciences, that discuss research on learning with cases, examples, and problems (Albanese and Mitchell 1993; Cognition and Technology Group at Vanderbilt 1990; Duffy and Cunningham 1996; Hmelo 1995; Hmelo-Silver 2004; Schank et al. 1993/1994; Vernon and Blake 1993; Williams 1992). Not surprisingly, there are variations in terminology, such as “case-based learning,” “case method,” “problem-based learning,” “goal-based scenarios,” “anchored instruction,” and so on.

Whereas there are approaches to PBL that involve students in relatively open-ended inquiry types of experiences, which might be called “problem-based learning with inquiry” (PBLI), other approaches to PBL invite the learner to consider problems in the context of given cases or scenarios, which will be referred to as “problem-based learning with cases” (PBLC) in this paper. As an example of PBLI, typical case and problem based approaches to medical education have students use the case materials based on an actual patient’s illness or condition as a spring board from which to collaboratively consider areas of inquiry to better understanding the conceptual and diagnostic aspects of the case (Barrows 1986, 1996; Hmelo-Silver 2004). In contrast, examples of PBLC invite the learner to consider a problem or issue primarily based on information that is provided in a text (such as the short negotiation cases used by Gentner and her colleagues (2003) discussed in the next section) or computer mediated format (such as in Scaffolding Connected Knowledge Framework[1] (SCKF) for hypermedia discussed below). Note that based on current research, no assumptions are implied as to whether PBLC or PBLI approaches are “better,” rather, it is postulated that these pedagogical approaches may be complimentary components of overall curricula. A research question does exists however, as to whether appropriately designed PBLC might help prepare learners for more successful PBLI activities; if so, there may be

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[1] Earlier papers referred to this design framework for hypermedia as the “Knowledge Mediator Framework.” The phrase “Scaffolding Connected Knowledge Framework” is now preferred as it seems more descriptive of features of the framework for designing hypermedia systems for learning, as well as its potential use to inform designs of other educational digital media.

sequencing considerations for the deployment of these types of pedagogies (i.e., perhaps to use of PBLC activities before the more open-ended use of PBLI).

However, recent research has identified cognitive and learning difficulties associated with certain approaches to PBLC that would, in turn, have implications for the design of technological tools intended to support these types of pedagogies. In the next two sections, an overview is provided of two such problems areas related to (a) conditions that enhance or inhibit knowledge transfer, and (b) changing preconceptions and fostering conceptual change.

## Inert knowledge and fostering transfer in problem-based learning with cases

Gentner et al. (2003) at Northwestern University have revealed what might be called the “soft underbelly” of PBL, that is, they have empirically demonstrated particular conditions under which the use of cases and problems might result in either non-productive or productive learning. Previously learned or experienced cases can be very useful when people are faced with new problems, however, individuals frequently do not recall these relevant examples (Gick and Holyoak 1980). This is a particular problem when the surface features of two cases or examples differ in ways such as context or salient objects (Simon and Hayes 1976). The “inert” knowledge problem (Whitehead, 1929), as this phenomena has come to be called, has been the focus of considerable research in the learning and cognitive sciences communities (Bereiter and Scardamalia 1985; Bransford et al. 2000; Bransford and Schwartz 1999; Gick and Holyoak 1983, 1987).

A series of studies by Gentner’s group has been investigating issues related to the inert knowledge problem using the target domain of learning advanced negotiation strategies by undergraduate and graduate students (Gentner et al. 2003; Thompson et al. 2000). This research has demonstrated that there can be dramatically different learning outcomes in terms of knowledge transfer depending on how students studied two cases about negotiation strategies that varied considerably in terms of their surface features but that shared a common principle. Students in what might be called the “advise groups,”[2] who were instructed to study the cases separately and to propose a negotiation solution for each case scenario, were much more likely to use a common “naïve” negotiation strategy of compromise. Unfortunately, advise group students were less likely to use more sophisticated negotiation strategies such as trade-offs or contingency contracts that had been studied during a training period. In contrast, students in the experimental groups were instructed to contrast and compare two cases and to think about similarities between the cases. These students were significantly more likely to use the appropriate negotiation strategy on the transfer tests than were the students who studied the cases separately.

Gentner and her associates (2003) propose a theory of analogical encoding to explain these findings that inert knowledge was the result of studying cases in isolation while knowledge transfer of difficult concepts resulted from contrasting and comparing different cases. Analogical encoding is described as a variation of structure–mapping theory proposed by Gentner (1983, 1989) as the mechanism of analogical reasoning. In analogical reasoning, a set of correspondences is highlighted between the shared relational structure of two analogs

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[2] This summary paragraph simplifies the discussion of four different but related studies in which there were two “generic” treatment groups that were varied in each of the studies. Detailed discussion of all the treatment groups in these studies is available in the papers by Gentner and associates (Gentner et al. 2003; Thompson et al. 2000).

that might have different surface features, with a person's knowledge of the source analog (hopefully) leading to understanding of the target analog. However, with analogical encoding, a learner may only partially understand two cases, but the process of comparing two cases that share an underlying principle or concept helps the learner focus on the structural commonalities rather than the idiosyncratic surface features. It is further postulated that the process of analogical encoding promotes schema abstraction and thus enhances learning, recall, and transfer. In discussing the educational implications of these findings, they conclude with several suggestions for instruction involving cases, such as juxtaposing cases, facilitating active case comparisons, and the use of software to induce case contrasts, suggestions that are consistent with design features of the Scaffolding Connected Knowledge Framework (SCKF) (Jacobson and Archodidou 2000) discussed below.

### Conceptual change in problem-based learning with cases

There is another critical yet little considered "problem" with problem and case-based pedagogical approaches: the difficulty of conceptual reorganization in particular domains. Extensive research on conceptual change (Bransford et al. 2000; Chi 1992; Chi et al. 1994; Chinn and Brewer 1993; Smith et al. 1993; Thagard 1992; Vosniadou and Brewer 1992, 1994) has shown how often the conceptions a student has about how the world functions are based on personal experiences and observations that are frequently limited or inaccurate, and that these conceptions form constraints on the ability of the student to learn new concepts, particularly in certain challenging science subject areas. Chinn and Brewer (1993) have proposed a taxonomy of seven ways learners might respond to anomalous data: (a) *ignore* the anomalous data, (b) *reject* the data, (c) *exclude* the data from one's initial personal theory, (d) hold the new data in *abeyance*, (e) *reinterpret* the new data while retaining one's personal theory, (f) reinterpret the data and make *peripheral changes* to one's personal theory, and (g) accept the data and *change one's personal theory*. Unfortunately, the least likely response to anomalous data is the last. Thus, there is the danger in domains for which a learner has robust preconceptions that the learner is much more likely to read a case with the inconsistent information and then employ one of the Chinn and Brewer assimilative strategies such as ignoring the inconsistent information or discrediting it, rather than changing her or his preconceptions.

Fortunately there has been research on techniques that can foster conceptual change, such as the use of bridging analogies (Brown and Clement 1989), or the use of thought experiments to reveal gaps in the student's solution followed by seeding new concepts that are plausible to the learner (Horwitz et al. 1994; Strike and Posner 1990). Another conceptual change approach of special relevance to PBLC involves the use of "extreme cases" (Zietsman and Clement 1997). Obviously a learner cannot transfer what was not learned, so it is important that appropriate techniques for fostering conceptual change be employed with PBLC in subject areas where learners may need to undergo the process of conceptual reorganization (e.g., areas of science where concepts are counter intuitive) in order to construct a robust understanding of the knowledge.

## Designing hypermedia to support problem-based learning with cases

Given the increasing use of problem- and case-based pedagogies in pre-college, university, and professional education, as mentioned above, the learning sciences issues of transfer and conceptual change that are discussed in the previous two sections have implications for enhancing the quality of learning when using learner-centered pedagogies and learning technologies. The finding that knowledge transfer can be greatly enhanced by contrasting and comparing cases is of particular importance because there is reason to believe that in the majority of regular classroom implementations of problem- and case-based approaches, the cases are studied in isolation and rarely are the students asked to contrast and compare the cases.[3] But how might teachers interested in using PBLC pedagogies address the issues of conceptual change and transfer? One approach is to use the flexibility of hypermedia technologies to develop tools for PBLC that provide appropriate design features to support conceptual change and transfer during learning and problem-solving activities.

For several years, there has been interest in ways that technologies such as hypermedia or case-based reasoning tools might support learning with cases, such as the work of Spiro and associates (Spiro et al. 1988, 1991, 1987; Spiro and Jehng 1990) and of Kolodner (1993). These research programs provide important theoretical perspectives for technological designs that juxtapose cases and induce learners to contrast and compare cases (indeed, these theories predate some of the recommendations of Gentner, Loewenstein, and Thompson (2003) mentioned above). Other research has explored how a hypermedia-based cognitive modeling tool might enhance problem-based learning (Pedersen and Liu 2002). However, there has been little research on ways to design hypermedia systems that take into account the PBLC issues of both conceptual change and knowledge transfer mentioned at the end of the previous section.

To illustrate how hypermedia tools might be designed to foster conceptual change and to enhance knowledge transfer, in the balance of this paper a case study is discussed of a multi-year program of research related to the Scaffolding Connected Knowledge Framework (SCKF) (Jacobson 2006; Jacobson and Archodidou 2000; Jacobson et al. 1996a; Jacobson and Spiro 1995). Next, an overview of SCKF hypermedia design features and their respective theoretical and research rationales is provided with an emphasis on embedded scaffolding that is intended to support conceptual change and transfer, followed by a discussion of ongoing research that is investigating how scaffolding in a SCKF hypermedia system might enhance learning of conceptual perspectives about emerging scientific knowledge related to complex adaptive systems.

## Scaffolding connected knowledge framework hypermedia tools for learning

The Scaffolding Connected Knowledge Framework (SCKF) is a set of theory and research-based design recommendations for developing hyperlinked cases in which a student receives scaffolding support for problem-based learning activities in order to enhance the learning of conceptually challenging knowledge (Jacobson and Archodidou 2000). SCKF hypermedia systems are not intended to "deliver" content per se or to "cover" entire curricula. Rather, as one of many tools and resources in the overall learning environment, these systems focus on targeted knowledge that is difficult to learn. The framework is also intended to help address the need of designers who must confront the often-difficult challenge of bridging from general theory and research principles to specific design features for useable systems (Jacobson 1994).

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[3] This observation is based on conversations with university faculty colleagues who have been active in medical problem-based learning and the use of cases in university business schools.

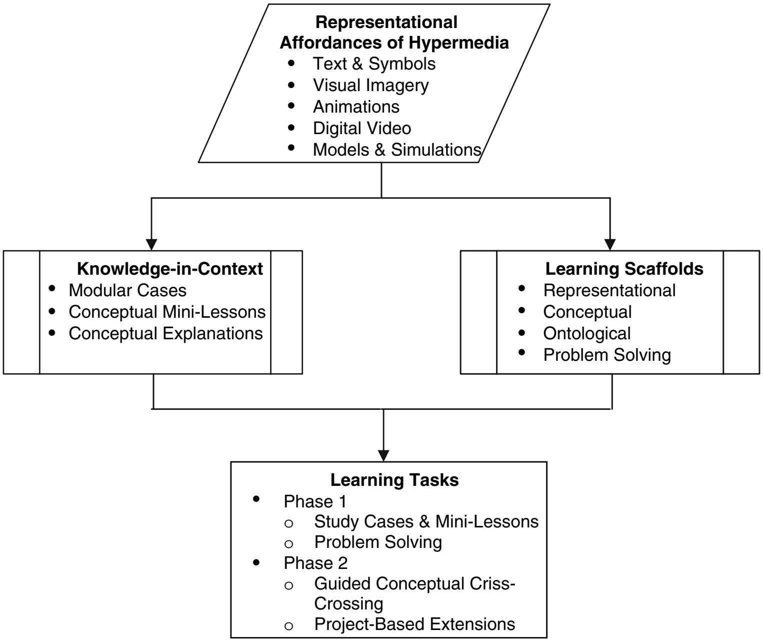

**Fig. 1** Schematic of the main functional elements of Scaffolding Connected Knowledge Framework hypermedia. Figure adapted from Jacobson (2006)

### Scaffolding connected knowledge framework functional elements

The primary functional elements in SCKF hypermedia systems are represented schematically in Fig. 1. Three of these elements—Representational Affordances of Hypermedia, Knowledge-in-Context, and Learning Scaffolds—are design features for the link-node organization of SCKF hypermedia systems. The fourth element, Learning Tasks, refers to specific types of learning activities that are optimized for these design features. The arrows in the figure are intended to depict the interconnected ways in which the design features reinforce each other, as well as the one-way directional flow of information from a non-adaptive hypermedia system to the learner and the learning activities.[4] These SCKF features, which are based on a series of studies (Jacobson 2006; Jacobson and Archodidou 2000; Jacobson et al. 1996a; Jacobson and Spiro 1995), are briefly discussed in turn.

The first SCKF design element, Representational Affordances of Hypermedia, is shown in the top box of Fig. 1. As noted above, from a technical perspective, hypermedia systems consist of *links* between *nodes* of digitally encoded representations of knowledge such as text and symbols, visual images, animations, video, and 2D and even 3D computer models and simulations (Jacobson and Archodidou 2000). These representational features are well suited for depicting cases in rich and interesting ways that also embody disciplinary conventions for representing knowledge.

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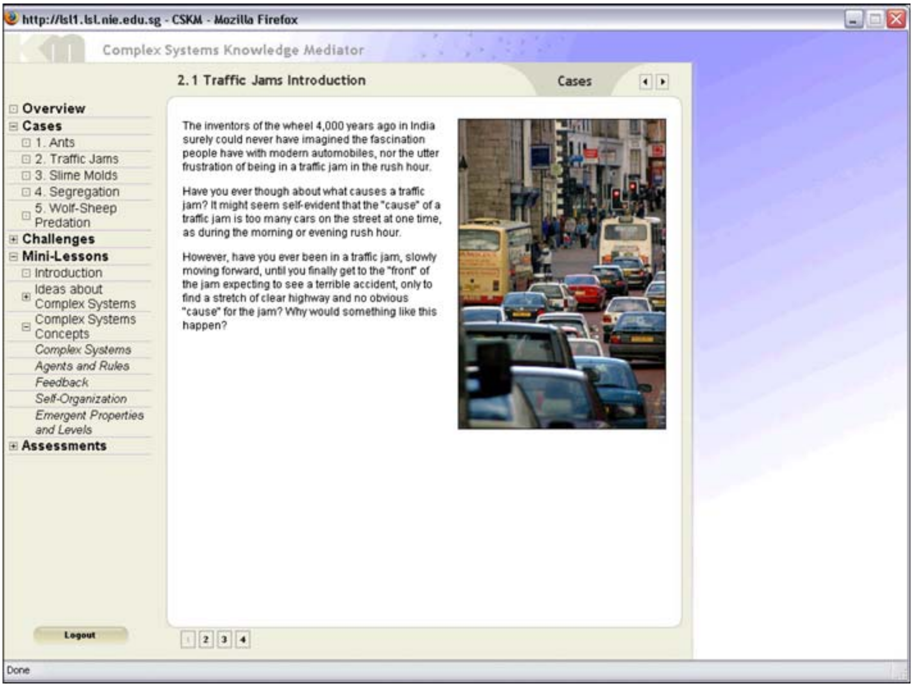
[4] See Jacobson (2006) for how embedding an intelligent learning agent module might enable an adaptive bi-directional relationship between the learner's actions in Learning Tasks and the content and scaffolding in the SCKF system.



The inventors of the wheel 4,000 years ago in India surely could never have imagined the fascination people have with modern automobiles, nor the utter frustration of being in a traffic jam in the rush hour.

Have you ever though about what causes a traffic jam? It might seem self-evident that the "cause" of a traffic jam is too many cars on the street at one time, as during the morning or evening rush hour.

However, have you ever been in a traffic jam, slowly moving forward, until you finally get to the "front" of the jam expecting to see a terrible accident, only to find a stretch of clear highway and no obvious "cause" for the jam? Why would something like this happen?

**Fig. 2** First screen of the Traffic Jams case in the Complex Systems Knowledge Mediator that includes a set of contrasting cases (highlighted in box on the left)

Knowledge-in-Context denotes the importance of (a) providing opportunities to experience knowledge that reflect different contexts or situations, and (b) making explicit to learners the important conceptual perspectives or “big ideas” of relevance to a particular unit of study. To the first point, SCKF systems primarily use a library of modular cases that are computer-mediated contexts the learner may explore as part of various learning tasks. Cases may be authored as texts or as combinations of text with images, multimedia, simulations, computer models, and so on. Cases for SCKF systems are authored and selected to have contrasting surface features while sharing important structural conceptual components related to the particular domain being studied (i.e., “big ideas”). For example, the Hypermedia, Evolution, and Conceptual Change study (Jacobson and Archodidou 2000; Jacobson et al. 1996b) employed four different evolutionary biology cases, while in a recently completed study of conceptual change and knowledge transfer related to learning about complex systems (discussed below), a set of five contrasting cases are used to represent different domains in the physical, biological, and social sciences (see Fig. 2). The use of contrasting cases is consistent with recommendations derived from cognitive flexibility theory (Spiro et al. 1992), case-based reasoning theory (Kolodner 1993), and the analogical encoding theory of Gentner and associates (Gentner et al. 2003; Thompson et al. 2000) that was discussed above.

There are two different design sub-elements related to reifying conceptual dimensions of knowledge: (a) Conceptual Mini-Lessons[5] and (b) Conceptual Explanations. First, a set

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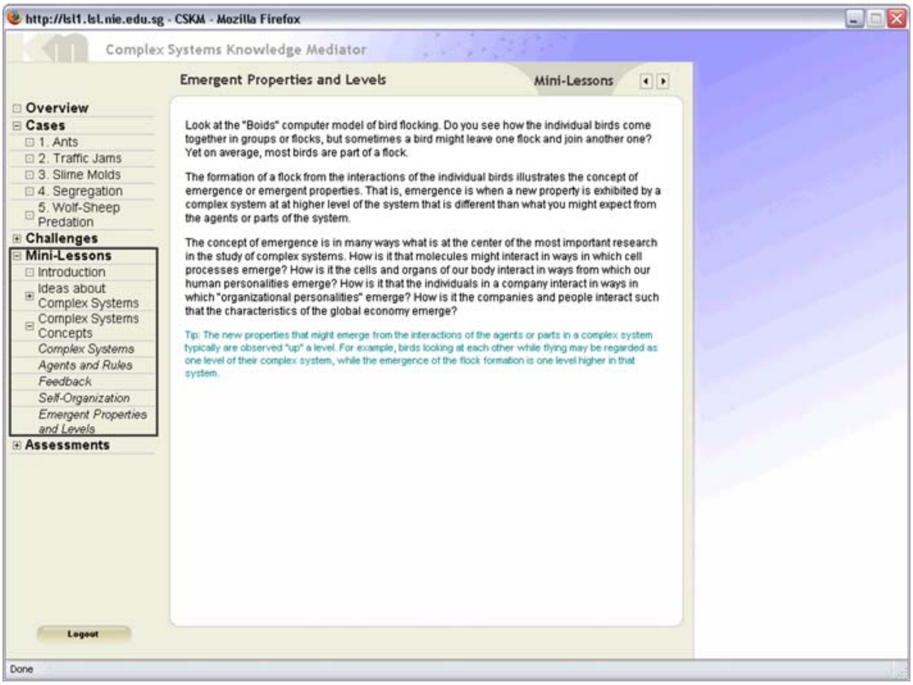
[5] In some SCKF systems, the abstract concepts the students need to understand are covered in a textbook or as part of a teacher’s class presentations. In these situations, the abstract concepts may be called a “Glossary” where the learner obtains short explanations of the concepts with references to where additional information may be obtained.



Look at the "Boids" computer model of bird flocking. Do you see how the individual birds come together in groups or flocks, but sometimes a bird might leave one flock and join another one? Yet on average, most birds are part of a flock.

The formation of a flock from the interactions of the individual birds illustrates the concept of emergence or emergent properties. That is, emergence is when a new property is exhibited by a complex system at at higher level of the system that is different than what you might expect from the agents or parts of the system.

The concept of emergence is in many ways what is at the center of the most important research in the study of complex systems. How is it that molecules might interact in ways in which cell processes emerge? How is it the cells and organs of our body interact in ways from which our human personalities emerge? How is it that the individuals in a company interact in ways in which "organizational personalities" emerge? How is it the companies and people interact such that the characteristics of the global economy emerge?

Tip: The new properties that might emerge from the interactions of the agents or parts in a complex system typically are observed "up" a level. For example, birds looking at each other while flying may be regarded as one level of their complex system, while the emergence of the flock formation is one level higher in that system.

**Fig. 3** Complex Systems Knowledge Mediator screen showing the general concept explanation for Emergent Properties and Levels with the Mini-Lessons highlighted in the box on the left

of abstract concepts, themes, ideas, principles, and so on are specified by the author that reflect important perspectives in the area of study and are made available in the Mini-Lessons section. For example, in the Complex Systems Knowledge Mediator, four core concepts related to the new multi-disciplinary field of complex systems are focused on: Agents and Rules, Feedback, Self-organization, and Emergent Properties and Hierarchies. Figure 3 shows these concepts listed on the left side of the screen under Mini-Lessons with the text for Emergent Properties and Levels being displayed in the middle of the screen.

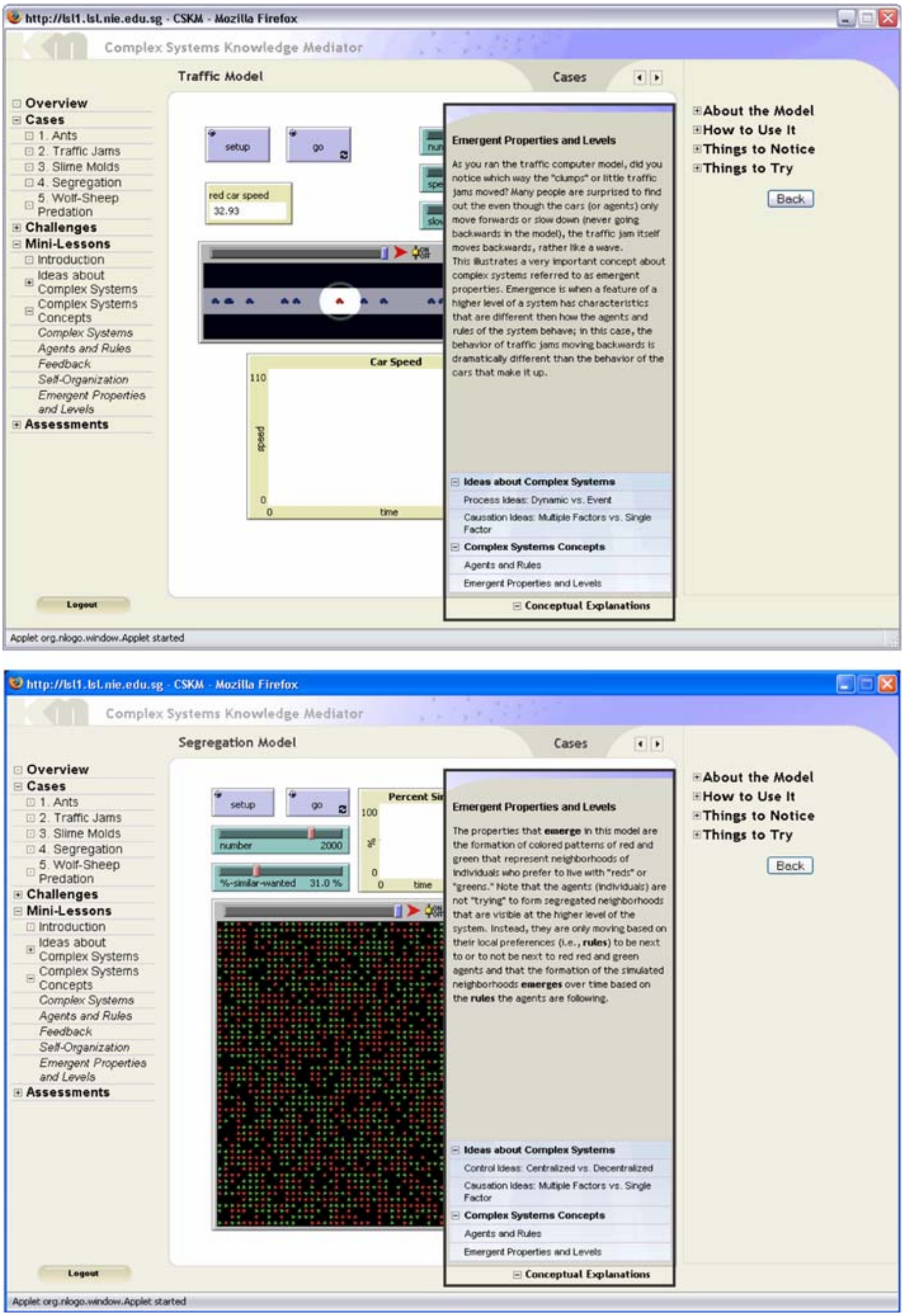
Mini-Lessons about concepts are intended to provide *cognitive preparation* by directly focusing on naïve ideas or pre-conceptions learners are likely to have in certain domains in addition to providing information about particular concepts. The use of conceptual change techniques in the Mini-Lessons is particularly important when there is reason to believe that students may have ways of thinking about the area of study that are qualitatively different from experts, such as a Lamarckian view of evolution (Bishop and Anderson 1990; Samarapungavan and Wiers 1997), an impetus mental model of the movement of physical objects (Hestenes et al. 1992), or a "clockwork" mental model of how complex systems function (Jacobson 2001; Jacobson et al. 2007). Mini-Lessons on concepts may incorporate techniques that have been found to help foster conceptual change, such as thought experiments, cognitive visualizations, and online problem-solving activities that are intended to make the learner's ideas explicit, illustrate gaps or deficiencies in these ideas, and seed new ideas and concepts that are relevant to the cases in a particular SCKF unit of study (Jacobson 2004; Jacobson and Archodidou 2000).

SCKF hypermedia systems also include a Knowledge-in-Context design feature known as "Conceptual Explanations" in which context-specific discussions of the abstract concepts are provided. The top screen shot in Fig. 4 displays the Conceptual Explanation for Emergent Properties and Levels in the context of the Traffic Jams case, while the Conceptual Explanation for the same concept related to the Segregation case is shown in the bottom screen shot of Fig. 4. Note that while the abstract concept is the same, the instantiation of the concept is different in each case. Conceptual Explanations are intended to provide "expert-like" contextual nuances about important concepts and are shorter than the general explanations of concepts provided in the Mini-Lessons.

The third SCKF design element is Learning Scaffolds (see Fig. 1). Surprisingly, despite arguments that hypermedia systems would benefit from the use of scaffolding techniques to enhance learning (Tergan 1997), to date there have been relatively few studies of hypermedia scaffolding discussed in the research literature (Shapiro and Niederhauser 2003). Whereas a number of different approaches to scaffolding may be used in learning technologies (Davis and Miyake 2004; Jacobson et al. 2000; Pea 2004; Quintana et al. 2004), SCKF hypermedia materials to date have mainly provided *representational, conceptual*, and *problem-solving* scaffolding (Jacobson and Archodidou 2000). The types of learning scaffolds listed in Fig. 1 are not intended to be exhaustive; they merely are the ones that prior and ongoing research has investigated. There are other types of scaffolding that could be integrated into SCKF systems, such *metacognitive scaffolding*, which could build on work by researchers such as Azevedo and colleagues (Azevedo et al. 2004, this volume).

*Representational scaffolding* refers to the use of various representational forms such as text, images, video, graphs, and computers models in SCKF cases and conceptual Mini-Lessons. Recent research has shown that experts, particularly in the sciences, exhibit *representational flexibility*, that is, that they work with the affordances of different types of textual, visual, and symbolic representations and that they easily integrate conceptually important knowledge across these representations when working professionally (Kozma 2000; Kozma et al. 2000). By authoring SCKF hypermedia learning objects that employ various linked domain appropriate representations, it is hoped learners may enhance their understanding of and skills with the representational forms of a discipline. It may be that helping students to develop representational flexibility could be an important compliment to the cognitive learning of domain knowledge with SCKF hypermedia.

The linking of different types of representations in SCKF hypermedia is shown in Fig. 5 involving the Slime Molds case from the Complex Systems Knowledge Mediator. Because the macro-level behavior of slime molds (i.e., the slow movement of what appears to be a type of fungus or plant) can only be understood through an awareness of the micro-level dynamics (i.e., collective dynamics of single cell organisms), different representations are provided such as an "everyday" level picture of a slime mold and a mid-level magnified movie of a pseudoplasmodium that shows both micro- and macro-level movements (Fig. 5, top screen). This case also includes an embedded NetLogo agent-based computer model of the aggregation of slime mold amoeba that provides a color-coded visualization of varying concentrations of the chemical cyclic AMP that the amoeba produce when they are in a low nutritive environment. Under such conditions, amoebas begin to converge toward a "center of attraction" and eventually form the pseudoplasmodium that consists of tens of thousands of single cell amoebae. Using the embedded NetLogo slime molds model (see Fig. 5, bottom screen), the learner may run computational experiments about factors that can cause simple single cell organisms to self-organize into slime molds by changing different parameters (e.g., number of cells, "sniff threshold," dispersion rate of cyclic AMP), and then observing changes in different runs of the model.



**Emergent Properties and Levels**

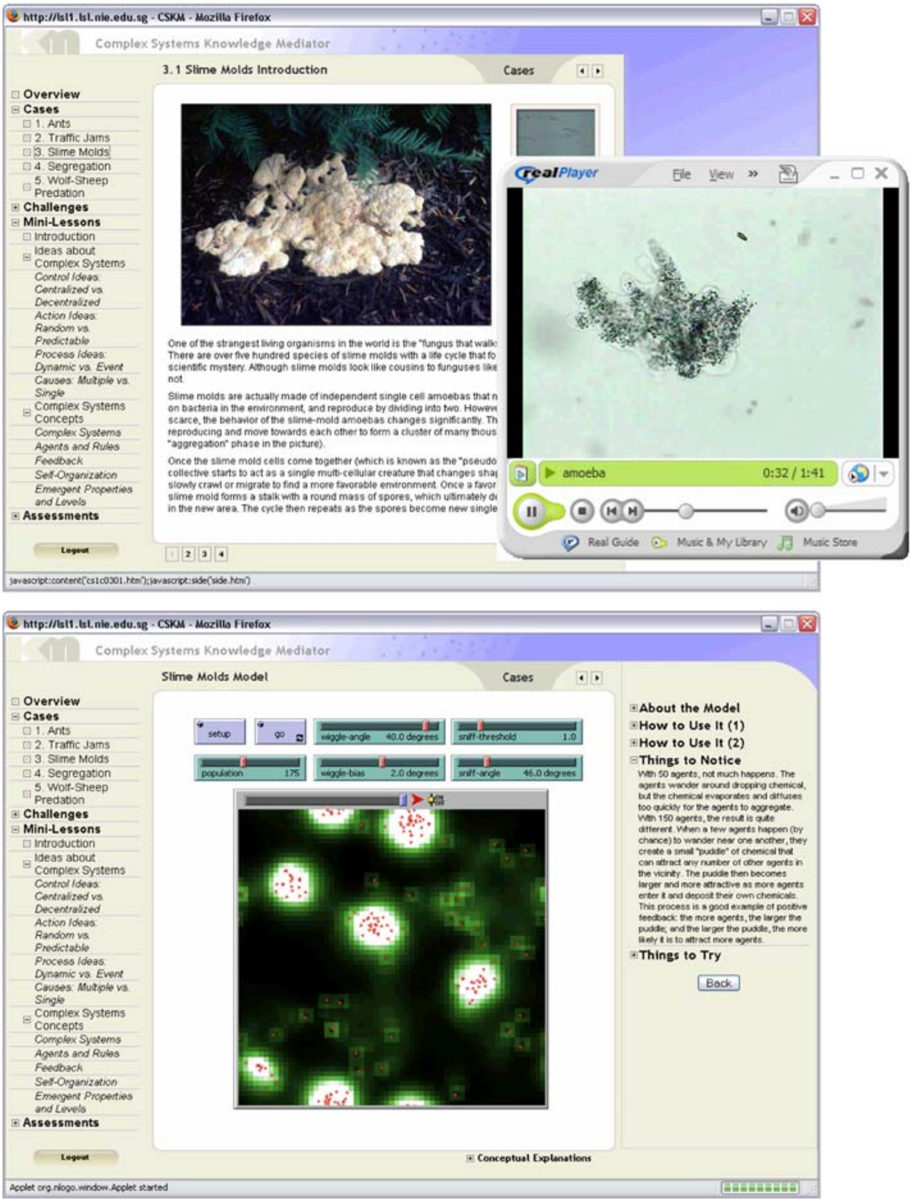
As you ran the traffic computer model, did you notice which way the "clumps" or little traffic jams moved? Many people are surprised to find out the even though the cars (or agents) only move forwards or slow down (never going backwards in the model), the traffic jam itself moves backwards, rather like a wave.

This illustrates a very important concept about complex systems referred to as emergent properties. Emergence is when a feature of a higher level of a system has characteristics that are different then how the agents and rules of the system behave; in this case, the behavior of traffic jams moving backwards is dramatically different than the behavior of the cars that make it up.

**Emergent Properties and Levels**

The properties that **emerge** in this model are the formation of colored patterns of red and green that represent neighborhoods of individuals who prefer to live with "reds" or "greens." Note that the agents (individuals) are not "trying" to form segregated neighborhoods that are visible at the higher level of the system. Instead, they are only moving based on their local preferences (i.e., **rules**) to be next to or to not be next to red red and green agents and that the formation of the simulated neighborhoods **emerges** over time based on the **rules** the agents are following.

**Fig. 4** The Conceptual Explanations for Emergent Properties and Levels for the Traffic Jams and Segregation cases highlighted in the boxes



One of the strangest living organisms in the world is the "fungus that walk
There are over five hundred species of slime molds with a life cycle that fo
scientific mystery. Although slime molds look like cousins to funguses like
not.

Slime molds are actually made of independent single cell amoebas that n
on bacteria in the environment, and reproduce by dividing into two. Howev
scarce, the behavior of the slime-mold amoebas changes significantly. Th
reproducing and move towards each other to form a cluster of many thous
"aggregation" phase in the picture).

Once the slime mold cells come together (which is known as the "pseudo
collective starts to act as a single multi-cellular creature that changes sha
slowly crawl or migrate to find a more favorable environment. Once a favor
slime mold forms a stalk with a round mass of spores, which ultimately d
in the new area. The cycle then repeats as the spores become new single

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With 50 agents, not much happens. The agents wander around dropping chemical, but the chemical evaporates and diffuses too quickly for the agents to aggregate. With 150 agents, the result is quite different. When a few agents happen (by chance) to wander near one another, they create a small "puddle" of chemical that can attract any number of other agents in the vicinity. The puddle then becomes larger and more attractive as more agents enter it and deposit their own chemicals. This process is a good example of positive feedback: the more agents, the larger the puddle; and the larger the puddle, the more likely it is to attract more agents.

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**Fig. 5** Linking different representations. Top screen: Micro- and macro-level representations of slime mold aggregations: picture (left) and digital video clip of a moving slime mold aggregation with individual amoebas visible (right). Bottom screen: screen shot of the Slime Molds NetLogo model embedded in the slime molds case

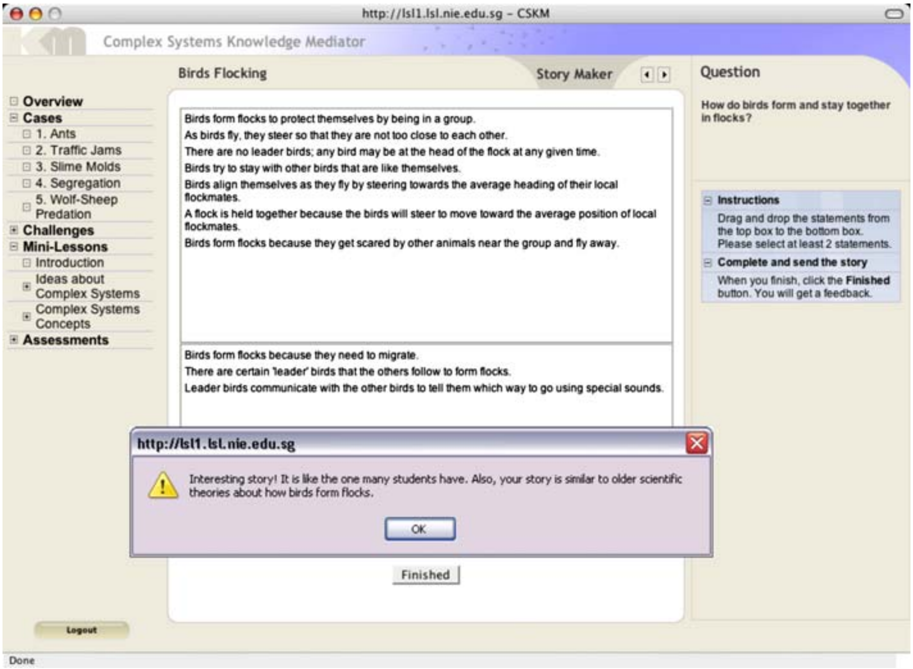
*Conceptual scaffolding* refers to techniques that are intended to make important conceptual aspects of domain knowledge cognitively salient to the user. This type of scaffolding is important as learners inevitably have various types of pre-conceptions and alternative conceptions about new subject areas they are learning. Thus, there is a need to scaffold an organizing conceptual framework that is more aligned with those who are skilled and accomplished in a domain (Bransford et al. 2000). In SCKF hypermedia, one way this is done is through the use of the Mini-Lessons (described above) in which important information about the targeted concepts or themes is provided.

A second type of conceptual scaffolding in SCKF systems is Conceptual Explanations, also described above. Considerable research has demonstrated that unlike experts, novices and intermediate learners often focus on the surface features of a case or problem and have difficulty "seeing" the deep structure of relevant concepts or principles (Bransford et al. 2000; Chi et al. 1981, 1988; Gentner 1983; Gick and Holyoak 1987). Conceptual Explanations provide context specific discussions of how abstract concepts from the Mini-Lessons are instantiated in the various cases. Thus Conceptual Explanations not only provide important additional information related to the cases, but they also function as scaffolding that models for the learner how to link surface feature information in a case to important abstract domain concepts.

A third type of scaffolding used in SCKF hypermedia systems supports problem solving. For example, one approach to scaffolding or supporting a learner during problem solving is the Story Maker module that employs what may be called "non-intelligent AI" (Nathan and Resnick 1994). The Story Maker module is based on cognitive research into the nature of the conceptual representations that learners at different age and developmental levels commonly use when solving problems in a particular domain. However, no attempt is made for the system to use sophisticated artificial intelligence knowledge representation techniques such as production rules to construct intelligent models of the user, subject area, or pedagogy. Rather, the Story Maker design provides the learner with a set of possible solution statements to a given problem in which some of the statements are consistent with common preconceptions, some statements are consistent with expert understandings, and some statements are neutral, and then an algorithmic approach is used to evaluate the response.

To illustrate the Story Maker, Fig. 6 shows the solution to the problem "How do birds form and stay together in flocks?" that was constructed by an undergraduate participant during a recent study. The selection statements listed at the top of the screen were written in three ways: (a) to be consistent with a novice "central control" mental model of flocking (i.e., that there is a leader bird in control), (b) to be consistent with a scientific expert "decentralized control" mental model of flocking (i.e., any bird might be in front of the flock at a given time, but simple rules are followed by birds that result in flock formations), or (c) to be neutral statements. The participant dragged and dropped the statements he wanted to use in his response from the top box to the bottom box on screen. After he clicked on the "Finished" button, the algorithm in Story Maker totaled up the values associated with the selected statements, and then a pop-up window provided feedback. In this example, the participant was provided feedback that the answer—which reflected an older view of flocking with statements like "Leader birds communicate with the other birds to tell them which way to go using special sounds"—was similar to answers many students (and probably many adults) would provide.

A second type of problem-solving scaffold in SCKF systems is Guided Conceptual Criss-Crossing that is provided for the challenge problems. In this approach, which is discussed further in the next section, the learner is given a problem to answer and then provided access to a set of conceptually based hyperlinks to portions of the cases, conceptual Mini-Lessons, and Conceptual Explanations in the system that are relevant to answering a challenge problem.



How do birds form and stay together in flocks?

Birds form flocks to protect themselves by being in a group.
As birds fly, they steer so that they are not too close to each other.
There are no leader birds; any bird may be at the head of the flock at any given time.
Birds try to stay with other birds that are like themselves.
Birds align themselves as they fly by steering towards the average heading of their local flockmates.
A flock is held together because the birds will steer to move toward the average position of local flockmates.
Birds form flocks because they get scared by other animals near the group and fly away.

Birds form flocks because they need to migrate.
There are certain 'leader' birds that the others follow to form flocks.
Leader birds communicate with the other birds to tell them which way to go using special sounds.

**Instructions**
Drag and drop the statements from the top box to the bottom box. Please select at least 2 statements.

**Complete and send the story**
When you finish, click the **Finished** button. You will get a feedback.

Interesting story! It is like the one many students have. Also, your story is similar to older scientific theories about how birds form flocks.

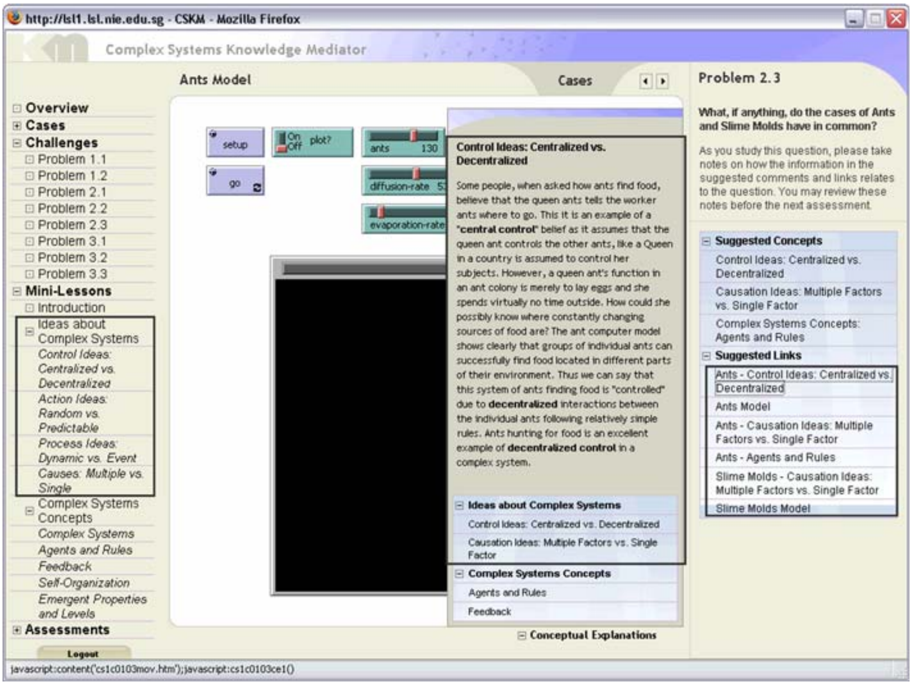
**Fig. 6** Story Maker response constructed by a university student to answer the question about how birds form flocks

## Knowledge mediator learning tasks

The final functional element of a SCKF hypermedia system is Learning Tasks (see Fig. 1). Prior research involving Knowledge Mediator systems has employed iterative cycles of two phases of learning tasks. In the Phase 1 tasks, students primarily work though a case or two as well as read the conceptual Mini-Lessons. The cases are authored to have contrasting surface features, as seen, for example, with the Traffic Jams case and the Slime Molds case that have different surface features even though they share important structural properties since they are both examples of complex systems. Although Phase 1 learning tasks are typically completed in a relatively "linear" manner (i.e., students usually read through the sections of a case from the first section to the last section, or go though the Mini-Lessons in the order of the list from top to bottom), these learning tasks are also authored to have dynamic elements with the system, such as interactive problems for students to consider (e.g., Story Maker problems discussed above) and interactive computer simulations and multimedia segments. Overall, the activities in cases and the conceptual Mini-Lessons allow the learners to begin to construct or to enrich their understandings of an organizing conceptual framework of the domain and the application of these ideas in multiple case contexts.

The first of the Phase 2 learning tasks, Guided Conceptual Criss-Crossing, is actually a type of problem solving with conceptual scaffolding (see section *Learning Scaffolds* above) that involves inter-case explorations of the SCKF cases, conceptual Mini-Lessons, and case-specific Conceptual Explanations. Guided Conceptual Criss-Crossing provides the learner with a problem or challenge question (e.g., "contrast and compare how the concept of self-organization applies in the Slime Molds and the Wolf–Sheep Predation cases”) that requires the integration of knowledge distributed across multiple cases and conceptual lessons in the SCKF hypermedia knowledge base. Each challenge problem has a set of conceptually based links that are intended to support “expert-like” non-linear navigation through the learning objects in the SCKF knowledge space.

An example of Guided Conceptual Criss-Crossing from the Complex Systems Knowledge Mediator hypermedia system is shown in Fig. 7 with a challenge problem intended for learners who have worked on two of the program’s five cases. When a challenge problem is selected, the Guided Conceptual Criss-Crossing Panel is displayed on the right side of the screen with the problem, suggested concepts, and suggested links. As discussed above, learners frequently have difficulty in identifying relevant concepts or principles in a problem or case, so additional conceptual scaffolding is provided through the list of Suggested Concepts for the problem. Also, problem-solving scaffolding is provided through the Suggested Links (see Fig. 7 right side of screen) that are a set of conceptually based hyperlinks for non-linear navigation to different sections of the program relevant to the conceptual dimensions of the question. Earlier research has established that studying problems using Guided Conceptual Criss-Crossing helps foster knowledge transfer (Jacobson and Archodidou 2000; Jacobson et al. 1996a; Jacobson and Spiro 1995). Guided Conceptual Criss-Crossing is a design feature that explicitly scaffolds learning in a way that is consistent with the implications of the research by Gentner and associates discussed above about the cognitive efficacy of inter-case learning activities.



**Control Ideas: Centralized vs. Decentralized**

Some people, when asked how ants find food, believe that the queen ants tells the worker ants where to go. This it is an example of a **"central control"** belief as it assumes that the queen ant controls the other ants, like a Queen in a country is assumed to control her subjects. However, a queen ant's function in an ant colony is merely to lay eggs and she spends virtually no time outside. How could she possibly know where constantly changing sources of food are? The ant computer model shows clearly that groups of individual ants can successfully find food located in different parts of their environment. Thus we can say that this system of ants finding food is "controlled" due to **decentralized** interactions between the individual ants following relatively simple rules. Ants hunting for food is an excellent example of **decentralized control** in a complex system.

**What, if anything, do the cases of Ants and Slime Molds have in common?**

As you study this question, please take notes on how the information in the suggested comments and links relates to the question. You may review these notes before the next assessment.

**Fig. 7** Guided Conceptual Criss-Crossing Panel is shown on the right side of the screen with ontological scaffolding provided in the Mini-Lessons (“Ideas about Complex Systems”), the cases in Conceptual Explanations, and the Suggested Links section beneath the problem statement

The second type of Phase 2 Learning Tasks may be termed project-based or inquiry-based extensions (i.e., problem-based learning with inquiry or PBLI; see above). As was discussed in Jacobson and Archodidou (2000), students could use a SCKF authoring tool to create their own “Knowledge Mediators” on a topic in which they were interested for a term project, such as global warming or possible bird flu pandemic. Students could conduct their own research (individually or perhaps better, in small groups) to gather and organize information from books, papers, Web resources, interviews, and so on, and then create their own cases, conceptual Mini-Lessons, Conceptual Explanations, and challenge problems with conceptual criss-crossing hyperlinks for their classmates to use to learn about their research project area.

An area of research that could be explored related to project-based extensions is the use of SCKF authoring “templates” to provide *metaconceptual scaffolding* to the learners, that is, an awareness of their mental representations and their processes of making inferences. Learners have been found to lack metaconceptual skills (Carey 1995), and it has been proposed that the lack of a metaconceptual awareness may make it difficult for a learner to undergo a process of conceptual change when trying to learn challenging or counter-intuitive knowledge (Vosniadou 1996). Perhaps SCKF projects could metaconceptually scaffold learners (a) to be aware of knowledge-in-context, that is, case specific facts and information and an organizing conceptual framework, (b) to understand contextual nuances of concepts as expressed in Conceptual Explanations, and (c) to construct interconnected knowledge relationships across different cases by creating their own conceptual criss-crossing problems.

## Complex systems and problem-based hypermedia research

New research involving Scaffolding Connected Knowledge Framework hypermedia systems is investigating student learning about emerging scientific knowledge related to the study of complex systems. The use of complex systems as a content domain for research on problem-based learning with hypermedia cases has several advantages. Such a domain provides an opportunity to explore issues related to learning challenging conceptual knowledge, as well as the opportunity to investigate cognitive and learning issues associated with conceptual change and knowledge transfer, which, according to the arguments presented earlier in the paper, are two special difficulties associated with learning with problems and cases. These areas are considered in turn.

### Conceptual change and the potential of hypermedia-enabled ontological scaffolding

Many of the core ideas associated with new scientific conceptual perspectives about complex systems may be challenging for students to learn (Charles and d’Apollonia 2004; Jacobson 2001; Jacobson and Wilensky 2006). Research suggests that not only do individuals with expertise in complex systems have specialized conceptual understandings that novices do not (which is to be expected), but also that complex systems novices and experts use different ontologies when constructing solutions for “everyday” problem examples of complex systems such as how ants can successfully forage for food or why do traffic jams form (Jacobson 2001). For example, experts were found to solve complex systems problems using ontological beliefs such as order in a system results from decentralized interactions that often have non-linear and random factors, whereas novices solved these problems using a set of “clockwork” ontological statements that described system order as a function of a central control agent or force and regarded system outcomes as being linear and predictable. These findings are consistent with research on expert-novice differences (Bransford et al. 2000; Chi et al. 1988; Larkin et al. 1980) and with other proposed cognitive structures such as ontologies (Chi 1992, 2005; Vosniadou 2002; Vosniadou and Brewer 1992, 1994) or p-prims (diSessa 1993) that might enhance or constrain learning of difficult domain knowledge such as that related to complex systems.

The research and theoretical perspectives discussed above relate to the conceptual and ontological challenges students are likely to experience when learning certain complex systems concepts. To address these issues, the Complex Systems Knowledge Mediator (CSKM) hypermedia system, which employs SCKF design features, not only provides representational, conceptual, and problem-solving scaffolding as discussed above, but also *ontological scaffolding*. Ontological scaffolding refers to information about basic beliefs learners might have about how the world functions, such as the nature of control in a system or the predictability of outcomes. The CSKM program refers to a set of ontological beliefs as “Ideas about Complex Systems” that in the current version focus on beliefs about control, actions, processes, and causality. In the Mini-Lesson section on “Ideas about Complex Systems” (see Fig. 7), the learner also has access to context-specific explanations about ontological ideas such as centralized versus decentralized control in a system and random versus predictable actions that are also provided as Conceptual Explanations on individual cases (see Fig. 7, pop-up window “Control Ideas: Decentralized vs. Centralized”). In addition, there are Suggested Links on the Guided Conceptual Criss-Crossing Panel on the right side of the screen that may include links to Conceptual Explanations about ontological beliefs relevant to the problem being considered.

## Complex systems conceptual perspectives and the possibility of far transfer

The issue of learning for transfer related to problem-based learning is an important theoretical and research issue that is also of considerable practical relevance in general educational settings where PBLC pedagogical approaches are used. There have been some promising findings to date in this area. As noted above, research on PBLC by Gentner’s group and by my research group has demonstrated within-domain or near transfer, such as applying negotiation strategies learned in one case to a different case or situation (Gentner et al. 2003) and to being able to solve new problems about evolutionary biology using Neo-Darwinian concepts that had not been studied in the case materials (Jacobson and Archodidou 2000).

A more challenging research problem relates to learning in ways to foster *across domain* or *far transfer*, that is, the ability to use conceptual ideas from one domain in what is regarded as a different knowledge domain. Helping students to learn in ways that promote far transfer is generally regarded as very difficult (Bransford et al. 2000; Gick and Holyoak 1987). Because complex systems concepts and methods are being used in a multidisciplinary manner across what traditionally have been conceptualized as separate scientific domains as diverse as physics, chemistry, biology, economics, and climatology, it has been proposed that it may be possible to have students learn a core set of complex systems principles as they study, for example, biological systems, and to “see” that these ideas (e.g., self-organization and emergent processes) also apply in other subject areas that involve physical systems and even social systems (Jacobson 2001; Jacobson and Wilensky 2006). The metaphorical use of perception in this sentence is deliberate. Kuhn has pointed out that although scientific paradigms may change, the world itself does not (Kuhn 1971). Put another way, in a new scientific paradigm, scientists begin to "see" the phenomena they are studying with new conceptual lenses. Goldstone (2006) suggests that this process of "seeing the world differently" may not only apply to scientists, but also to students' learning and that this would in fact represent a technique for fostering far transfer. Similarly, researchers have argued that if students learn to "see" how complex systems principles learned in one domain may apply to a different physical or social science domain, then this would constitute far transfer (Goldstone 2006; Jacobson and Wilensky 2006).

## Recent SCKF hypermedia research

Two studies have been recently completed that involved slightly different versions of the Complex Systems Knowledge Mediator (CSKM) described above. The first study explored how different scaffolding design features for the system might influence learning of conceptually challenging ideas about complex systems. Participants were 60 paid undergraduate students who were randomly assigned to one of three treatment groups. All groups used versions of the CSKM with five different hypermedia cases about complex systems with embedded NetLogo agent-based models along with a set of challenge problems involving the cases (see Fig. 7). The main design feature that varied across the groups was the amount of scaffolding. The High Scaffold group received four of the types of scaffolding described earlier in the paper: representational, conceptual, ontological, and problem solving. The Moderate Scaffold group was similar to the High Scaffold except that no ontological scaffolding was provided (e.g., Control Ideas: Centralized versus Decentralized, Process Ideas: Dynamic versus Event). The Minimal Scaffold Control group used a version of the system that had only the base CSKM design features (i.e., hypermedia cases, representational scaffolding, embedded NetLogo agent-bared computer models, challenge problems); however, no, conceptual, ontological, or problem-solving scaffolding was available.

Ten pairs of participants were randomly assigned to each of the three treatment groups where they collaboratively worked as dyads (each with a computer) using the version of the CSKM developed for their respective groups. The study involved three different sessions that were each approximately two hours in duration. After completing a pretest to probe their understanding of conventional science and complex systems knowledge and an initial set of problems to solve, the participants were given an introduction to the CSKM, completed one case on Ants, and worked on two challenge problems. The second and third sessions each involved working on two new cases, three to four challenge problems, and an end-of-session assessment test. The Morae screen capture software was used in conjunction with web cams and microphones to record all screen activities and dialogues of the participants in each dyad. Also, selected pairs of participants were video recorded using external ceiling mounted usability cameras to compliment the Morae videos that were made with the web cams.

As the study was only recently completed, coding and analysis of the open-ended complex systems problem solutions are ongoing. Preliminary examination of the answers provided at the pretest by the participants suggests, not surprisingly, that they did not know about complex systems concepts such as chaos and emergence, but that overall they were familiar with science concepts such as homeostasis and evolution by natural selection (although many indicated they had low confidence about how well they understood such traditional science knowledge). On a set of usability items asked at the end of session three, participants in all three treatment groups answered questions about whether they found the cases to be interesting and if they found the program to be easy to use in a positive manner. The preliminary analysis of the data indicated that the participants in all three groups were reasonably positive about their experiences with the CSKM as the mean responses were between approximately 2.90 to 3.35 on a Likert scale of 1 (low) to 4 (high). Interestingly, on a question about how difficult it was to find information in the computer program (scale of 1 "very difficult" to 4 "very easy"), a significant difference on the mean responses was found between the three treatment groups (High Scaffold $M = 3.10$, $SD = 0.55$; Moderate Scaffold $M = 3.30$, $SD = 0.66$; Minimal Scaffold Control $M = 2.75$, $SD = 0.72$; $F = 3.72$, $p = 0.03$). Post hoc analysis indicated that there was a significant difference favoring the Moderate Scaffold over the Minimal Scaffold Control groups ($SE = 0.20$, $p = 0.025$) and that there was no significant difference between the mean responses for High Scaffold and Moderate Scaffold groups.

These findings may be due to scaffolding differences between the three groups. The High Scaffold and Moderate Scaffold groups each received problem-solving scaffolding during the challenge problems they worked on after each of the cases, whereas the Minimal Scaffold Control group did not. As the main reason a participant would need to find information in the CSKM would be to answer the challenge problems, these self-report findings suggest the participants in the two experimental groups that received the problem-solving scaffolding felt they could more easily find the information they needed, whereas the Minimal Scaffold Control group found it more difficult to find information. As mentioned above, more detailed coding and analysis of learning outcomes and the process data that was collected are being conducted.

The CSKM has also been used as part of a graduate seminar class on complex systems that was taught at a university in Israel. Five students used a six-case version of the CSKM that consisted of the five cases used in the first study in addition to a case with an embedded NetLogo model on chemical equilibrium. The students worked on the CSKM Mini-Lessons, cases, and challenge problems over a four-week period in conjunction with a set of seminal papers and books on complex systems and on learning about complex systems. In addition to the CSKM and the readings about different conceptual perspectives related to complex systems, the course had the students do a variety of model explorations of complex systems, a collaborative mini-research project, and several focused and general discussions. In interviews at the end of the class, students indicated they liked the design features of the CSKM hypermedia system that allowed flexible access to information and "wandering and meandering" as part of the learning activities. Students also found that the CSKM provided useful background knowledge to the readings, and mentioned ideas such as *non-predictability*, *decentralization*, and *multiple causes*. As discussed above, these ideas are presented in the CSKM as ontological scaffolding in Ideas about Complex Systems and are ways of thinking about how the world functions that differ between novices and complex systems scientists. It is of interest that the students mentioned these ontological ideas during the interviews as research suggests beliefs such as these are correlated with understanding complex systems conceptual perspectives and with being able to appropriately solve complex systems problems (Goldstone and Wilensky 2007; Jacobson 2001). In addition, the instructor of the class commented that a particular value of the CSKM was the approachable way the foreign complex systems concepts were explained with several modalities and representational tools that support both graduated and open-ended learning.

In closing this section, the small-scale empirical and qualitative classroom studies reported here represent discussions of ongoing research into learning about complex systems with SCKF hypermedia. Of course, further research is clearly needed, and the results of those studies will be used to iteratively revise and hopefully enhance the Scaffolding Connected Knowledge Framework for designing learning technologies such as hypermedia.

## Conclusion

I have argued in this paper that there is an opportunity to conceptualize the use of network-mediated hypermedia technologies as an enabling infrastructure for tools to support learner-centered pedagogies such as problem-based learning with cases (PBLC) and problem-based learning with inquiry (PBLI) that are of increasing interest in professional, university, and pre-college education. The paper focused on issues related to learning with PBLC, such as the development of inert knowledge from studying isolated individual cases, as well as ways that technology systems for PBLC might be designed to foster learning of challenging conceptual knowledge, conceptual change, and knowledge transfer. An overview of the hypermedia design features and earlier research involving the Scaffolding Connected Knowledge Framework (SCKF) was provided, as well as a discussion of preliminary findings from a recent empirical study and a qualitative use of the system in a graduate seminar class that explored hypermedia scaffolding design features and cognitive outcomes related to learning advanced scientific conceptual perspectives from the field of complex adaptive systems.

In terms of directions to extend research discussed in this paper, methodologically, future SCKF hypermedia work could employ design research (Brown 1992; Collins et al. 2004) in order to collaboratively work with teachers for developing cases and problems aligned with the curriculum and to better understand how learning technologies such as SCKF hypermedia might be used in complex classroom learning ecologies. Other research might enhance the functionality of SCKF systems, perhaps by exploring how new technologies such as animated pedagogical agents (Baylor and Kim 2005; Baylor and Rosenberg-Kima 2006) might provide SCKF scaffolding in conjunction with intelligent adaptive hypermedia functionality. Another potentially important area for future research could focus on scaffolding issues. To date, most educational hypermedia and other types of learning technologies that provide scaffolding do not *fade* or withdraw the scaffolds, rather like leaving the training wheels on the bicycle. Thus research could explore ways that an adaptive SCKF hypermedia system with an embedded intelligent agent might be able to adaptively provide scaffolding and then fade the scaffolds as the learner becomes more competent in the subject domain (Jacobson 2006).

Other future research might explore recent findings that suggest more productive longer term learning gains may result from *less* scaffolded early learning activities in which initially the learner actually fails to a degree, but followed in turn by activities with increased scaffolding and then fading (Kapur 2006). Thus research could explore the design of adaptive SCKF hypermedia systems to implement what Kapur (2006) refers to as *productive failure* as part of the trajectory of low and high scaffolded learning activities a student would experience and investigate learning outcomes such as depth of conceptual understanding, problem solving, and knowledge transfer skills.

In closing, it is hoped that the program of research discussed in this paper will stimulate further work on the characteristics of design features for robust and educationally powerful hypermedia systems, design features that may also be adapted for other new learning technologies such as multi-user virtual environments and hand held devices. By grounding designs for educational technology on theory and research based principles, such as the SCKF attempts to do, research involving technologies with particular design features should be able to contribute to important learning and cognitive sciences issues such as how students might understand challenging conceptual knowledge, domain specific problem solving, and knowledge transfer to new situations. Such research, in turn, should help inform ways to develop real world learning tools that will compliment innovative pedagogical approaches being used in the schools, and on how these systems might support students as they learn conceptually difficult knowledge and skills that are increasingly necessary in the 21st century.

**Acknowledgments** The preparation of this paper has been supported in part by the Singapore Learning Sciences Laboratory at the National Institute of Education, Nanyang Technological University. Research projects by the author that were discussed in this paper have been supported in part by grants from the Singapore Learning Sciences Laboratory, Korea IT Industry Promotion Agency, Allison Group, National Science Foundation (RED-9253157 and RED-9616389), Spencer Foundation, the University of Georgia, and the University of Illinois at Urbana-Champaign. Special thanks are extended to Dr. Sylvia d'Apollonia who produced the digital video clip of a moving slime mold aggregation for the Complex Systems Knowledge Mediator. Dr. Sharona Levy and Dr. Elizabeth Charles provided very helpful feedback on the content in an early version of the Complex Systems Knowledge Mediator (although any content errors remain the responsibility of the author), and Dr. Manu Kapur contributed challenging questions and thoughtful suggestions on an earlier version of this paper. The assistance of Phoebe Chen Jacobson, HyungShin Kim, Keol Lim, Foo Keong Ng, Seo-Hong Lim, June Lee, and Sok-Hua Low on recent research and development activities discussed in this paper is gratefully acknowledged.

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**Michael J. Jacobson** Ph.D., is a faculty researcher at the Singapore Learning Sciences Laboratory and an Associate Professor in the Learning Sciences and Technology Academic Group at the National Institute of Education (NIE), Nanyang Technological University in Singapore. His research has focused on the design of learning technologies such as 3D multi-user virtual environments and hypermedia to foster deep conceptual understanding, conceptual change, and knowledge transfer in challenging conceptual domains. Most recently, his work has explored cognitive and learning issues related to the design of learning technologies to help students understand new scientific perspectives emerging from the study of complex and dynamical systems.