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STUDENT ECOSYSTEMS PROBLEM SOLVING WITH COMPUTER SIMULATION

by

Melissa A. Howse

A Dissertation
Submitted to the
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ADVISER - DR. LEONARD GINSBERG, Ph.D.

STUDENT ECOSYSTEMS PROBLEM SOLVING WITH COMPUTER SIMULATION

Melissa A. Howse, Ph.D.

Western Michigan University, 2003

Computer simulations, such as the BioQUEST Environmental Decision Making (EDM) program, represent a viable supplement or alternative to traditional science teaching approaches. This study concentrated on the manner in which knowledge is acquired and then disseminated through the use of the simulations. In addition, the study took into account the nature of science by revealing what notions of ecosystems and simulation were revealed when students encountered concepts imparted to them via this method. The following research questions guided this study:

1. What content knowledge do students use to solve ecology problems?
2. What procedural knowledge do students use to solve ecology problems?

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Melissa A. Howse

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CHAPTER I

INTRODUCTION

This dissertation investigates a problem in the teaching and learning of ecology. Without a tested ecosystems model for performance and teaching, teachers cannot know how best to proceed with the recommended changes they are given to use more problem-based methods (e.g., Michigan Science Teachers' Association, 2001; National Academy of Sciences, 1996). There has been a call for models for teaching and learning in problem solving, and there are a few related to ecology (e.g., Buckley, 2000; Waterman, 1998). A demand for students who are good problem solvers often includes the suggestion that they should be good "systems thinkers" (Mandinach & Cline, 1989; Kim, 1994; Salisbury, 1996). Although this idea is widely researched in education (e.g., Stratford, Krajcik, & Soloway, 1998), it comes from engineering (de Corte, Linn, Mandl, & Verschaffel, 1992). Existing literature describes systems thinkers as individuals who need to be able to understand and solve problems involving complex systems of interacting components, like ecosystems (Frick, 1991, 1993; King, 1998). There are few examples in the literature that show how relatively new problem solvers, novices, solve ecosystems problems (Wimsatt & Schank, 2001). First, these problem solvers must be taught how to solve problems (Reif, 1983; Nickles, 1985). Second, we do not have a model for how to teach ecosystems problem solving satisfactorily (Buckley, 2000; Waterman, 1998). As a result of concerns for the quality of learning of problem solving, rich problem solving simulations exist like Environmental Decision Making (EDM)

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(Odum, Odum, & Peterson, 1991). Underexplored areas exist in the knowledge base when it comes to understanding ecosystems problem solving. Problem solving research has covered chess, physics, and genetics well. Systems thinking heuristics (rules of thumb) (Nickles, 1987) have been named, but not much has been done with researching their uses yet. Existing field testing and use of EDM is documented, but research about student modeling and problem solving with EDM is lacking. The following research questions are explored in this study:

1. What content knowledge do students use to solve ecology problems?
2. What procedural knowledge do students use to solve ecology problems?

This study took place at a large Midwestern university. Seven paid volunteer participants were found in the end of an ecology course for biology majors. In this study, participants were given an open-ended pond simulation with which to work. First, they were told to thoroughly explore the simulation by posing and answering as many questions as they could. They were to make predictions and explain biologically the results they saw. Secondly, they were asked some brief interview questions about the nature of the model. Ericsson and Simon (1980) and Posner and Gertzog (1982) agree that retrospective reports of thinking should be treated with caution. This researcher treated these interview questions lightly. The participants were audio-taped as they solved problems and spoke their thoughts aloud, creating think-aloud protocols (Ericsson & Simon, 1980). The data was collected and represented in frames, including the statements, graphs, writing and drawings done by students. The analysis involved combing the transcripts for patterns of student knowledge and putting the knowledge into the categories exposed by expert analysis, like a rational analysis (Reif, 1983). Protocol analysis led to categories of high-,

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middle- and low-level conceptual knowledge, corresponding to statements about: definitions, combinations of definitions, and definitions related to complex processes, respectively. Protocol analysis also led to categories of high- and low-level procedural knowledge. High-level knowledge involved the use of more than two heuristics used in problem solving, and low-level knowledge involved the use of less than two. For question two, the same data were used. However, analysis of statements, data sorting and compilations assesses students' ideas about the nature of science.

The remainder of the dissertation describes the literature review, research design, presentation of data and data analysis, and discussion. This includes implications for teaching, with the use of an initial model of novice performance. First, systems thinking and meaningful moves are relevant to cognitive science's understanding of content and procedural knowledge because they make those areas of study fit knowledge together in one realm (Klahr, 1976). Second, the dissertation could aid in potential revision and improvement of ecosystems simulation programs.

Significance

Few researchers have tried to connect procedural and content knowledge, but Lavoie (1993) has provided one study. Lavoie studied prediction in college students via the theory of cognitive networks—networks that connect procedural and content (declarative or concept) knowledge. Lavoie gave science scenarios to both preservice elementary and secondary teachers. Lavoie's information-processing model of the prediction process presented procedural and declarative knowledge used in problem solving. Successful predictors seemed to fit this model. He concluded that improved

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skill at and instruction in prediction as a part of problem solving can lead students toward a greater understanding, use, and appreciation of science and the scientific process. If the participants in the present study are successful predictors, combining their procedural and declarative knowledge, they ought to be better problem solvers.

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CHAPTER II

LITERATURE REVIEW

The literature review relevant to this study includes first a description of ecology teaching and learning literature. Second, there is a description of the problem-solving research tradition. The concepts the researchers explored are cited below as used in the context of the research questions. Question one regarding ecology knowledge is discussed first. Procedural knowledge, related to question two, is then discussed. This chapter also describes potential learning outcomes, the specifics of EDM, and expert analysis as a theoretical construct which allows the categorization of student responses. The potential learning outcomes, description of EDM, and expert analysis show what ecology knowledge students can use with EDM.

Content Knowledge

The discussion in this section considers ecology knowledge to be comprised of both content and procedural knowledge (knowledge of how to do something) (Reif, 1983). The latter includes systems thinking and meaningful moves.

What is the nature of conceptual ecology knowledge? In the first studies, Leach, Driver, Scott and Wood-Robinson (1996a, 1996b) studied elementary students' conceptual knowledge of ecology. Leach et al. (1996a) denoted the misconceptions children ages 5–16 have regarding fundamental ecology concepts. They were as follows:

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1. There are no sources of matter for plant growth (i.e., children did not realize plants get water and nutrients from soil).
2. Plants do not need sunlight.
3. Predation and other ways of obtaining food are not sources of matter for animal growth.
4. There are no organisms in the decay process.
5. The role of decay in matter cycling is not prominent.

In a second study, Leach et al. (1996b) denoted more ecology misconceptions. They were as follows:

1. Communities are not composed of plant and animal populations.
2. Relative population size does not decrease with each step up the food web in communities.
3. There are no specific trophic relationships between organisms in food webs.
4. Organisms are not interdependent.

Some of Leach's studies (1996a, 1996b) showed that student misconceptions decreased with age, but remained in the majority of students. In the first study (N = 539), only 10% of 16-year-olds recognized that plants make their own food. Only 60% of 16-year-olds recognized organisms as causes of decay of an apple. None of the students recognized that matter is completely conserved in the decay process.

In the second study (Leach et al., 1996b), only 20% of 16-year-olds understood that the construction of a balanced community is the result of interdependence of factors between the populations. As examples of important concepts which students misunderstood, 50% of 16-year-olds understood that food webs contain more producers

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than consumers, and 20% of those avoided teleological reasoning and pointed to interdependent factors such as competition, symbiosis, and predation between the populations. Only 20% of 16-year-olds understood that interdependent factors explain why there are more mice and rabbits than owls in a food web. The studies concluded that students have considerable misconceptions about the most basic ecological concepts.

Conceptual ecology literature informs the design of this study, because it creates categories for sorting participant conceptual knowledge. It informs the analysis because we categorize participants in terms of their conceptual knowledge.

Procedural Knowledge

A second issue important to the understanding of ecology knowledge is Reif's (1983) two components of knowledge in his discussion of problem solving, in general. The first component is content or declarative knowledge, knowledge that (conceptual knowledge); the second component is procedural knowledge, knowledge how (Chi, Feltovich, & Glaser, 1981; Larkin, McDermott, Simon & Simon, 1980). Problem-solving heuristics, meaning rules of thumb (Nickles, 1987), must also be part of a knowledge state of experts and novices (Chi et al., 1981). Content-specific and procedural knowledge involved in decision-making during problem solving are important aspects to make explicit to students (Reif, 1983, 1990). Included in procedural knowledge are considerations of meaningful problems, as well as systems thinking. This is because they involve problem space search and heuristics, respectively (Nickles, 1987). They are both involved in knowledge of how to proceed in problem solving. The nature of knowledge as both conceptual and procedural informs the design of the study because

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the researcher has designed a method for categorizing both kinds of knowledge. It also informs the analysis because it answers the first and second research questions, respectively.

Meaningful Moves

The set of meaningful moves describes what knowledge is available in Environmental Decision Making (EDM). Meaningful problems—those attached to knowledge about the discipline (Nickles, 1987)—are a subset of all possible problems. These problems exist in the theoretical "problem space." Mayer (1983) and Newell (1990) define the problem space as the complete set of problems through which one can search to pose one's own problems. Problem space is used here in the identical way that cognitive scientists and computer programmers (Chi et. al, 1981; Larkin et. al, 1980; Mayer, 1983; Newell, 1990) use it. Denoting the problem space allows the researcher to provide a task that allows the problem solver to pursue the most meaningful moves more easily. Hereafter, meaningful moves, rather than meaningful problems will be used to describe the actions within EDM which reveal content knowledge. The EDM problem space allows participants to demonstrate their knowledge of general systems, and to show how systems are constructed. It also allows them to make predictions and explanations of ecosystems behaviors, including all the behaviors present in the later problems. Meaningful moves inform the design of the study because they show which problems the students are solving, and which moves are contained within them. They inform the analysis because they provide a problem-space search that can be quantified.

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Systems Thinking

Systems theory, the origin of systems thinking, focuses on an attention shift in the sciences. In ecology, there has been a shift toward attention to complexity (Odum et al., 1991). The shift was away from the description and classification of individual entities toward the explanation of entities that form structures and order (Laszlo, 1972; von Bertalanffy, 1968). The components, discussed below, are: emergence, causality, inside/outside constraints on the system, and self-stabilization.

Systems thinking (Mandinach & Cline, 1989; Stratford et al., 1998) is used to structure problem posing, problem solutions and pathways to solutions of problems (e.g., Checkland, 1981). There are four specific components of systems thinking that become apparent in ecosystems problems. All systems, and also the thinking used to interpret them, can be characterized by these components: emergence, specific types of causality (number of causes, directness, and degree of linearity), inside/outside constraints on the system, and self-stabilization.

These four components have been chosen as relevant to this study. They are aspects of systems thinking—different ways of looking at systems—and each aspect leads to specific perspectives on a given system (Mandinach & Cline, 1989; Stratford et al., 1998; also, see Appendices A, B, and C). The EDM problems chosen for the present study were picked to maximize the likelihood of eliciting conceptual and procedural systems thinking components (Checkland, 1981; Mandinach & Cline, 1989; Stratford et al., 1998). The EDM problems are used as examples throughout the description of systems thinking in order to clearly give concrete meaning to these abstract ideas.

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One of the systems thinking components, emergence, explicitly relates to the essence of biology (Mayr, 1982), and is notable in the context of this study. The emergence component, which suggests that the whole is greater than the sum of its parts, is the nature of biology. Emergent properties are those properties of a hierarchical level that emerge only at that level or above. Emergent properties come about when one examines the whole system rather than only parts. Emergent properties are defined by Allen and Starr (1982) as:

> (a) properties which emerge when a coarser-grained level of resolution is used by the observer; b) properties which are unexpected by the observer because of his incomplete data set, with regard to the phenomenon at hand; c) properties which are, in and of themselves, not derivable from the behavior of the parts a priori (p. 68).

The first systems thinking component, emergence, is discussed in terms of ecosystems simulation. Emergent properties exist at each successive level of the problems in this study. When a new entity is added, one or several new biological phenomena are emergent. The EDM computer simulation represents an ecosystem, made of a complex system, which affects how its behaviors are understood.

Systems thinking literature informs the design of this study because it creates categories for conceptual and procedural knowledge. It informs the analysis because participants can be categorized by their uses of systems thinking statements.

This study demonstrates how to integrate ecology content and procedural knowledge into ecology teaching. The description below links the students' ecology and model knowledge to potential learning outcomes.

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Potential Learning Outcomes

Stewart (1988) proposed four types of potential learning outcomes achieved through problem solving. These describe the knowledge teachers want problem-solving students to have (Stewart & Jungck, 1994). A problem-solving approach to teaching offers several advantages over traditional teaching (Voss, 1989). Further, algorithmic exercises are intended to teach laws, theories, and concepts of a discipline, but fall short in teaching other potential learning outcomes. Stewart's (1988) potential learning outcomes were:

> (a) the conceptual structure (theories, concepts, models, and their organization) of particular disciplines; problem-solving heuristics that are not specific to a particular discipline; (c) content-specific problem-solving procedures (domain-specific instantiation of general heuristics and problem-solving algorithms specific to the domain); and (d) insight into the nature of science as an intellectual activity (e.g., the knowledge that models are limited representations of the real world). (p. 75)

From Stewart, the following conclusions apply to this study. In practice, teachers often require students in the sciences only to solve algorithmic exercises at the back of a chapter (Reif, 1983, 1990; Voss, 1989). Teachers ask students to learn specific answers or uses of mathematical models rather than general heuristics (rules of thumb), theories, and domain-specific processes of science. In order to realize the potential learning outcomes, however, students need rich, real-world problem-solving environments (Buckley, 2000; Clement, 1994; Gentner & Stevens, 1983). Real-world problems,

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referred to in the rest of the study as "real-world" problems, are those which solvers in a domain would typically solve, or have real-world application (Wimsatt, 1987). The problems can either be well-or-ill structured. That is, they are problems which have at least one constraint versus problems which do not have any constraints.

Ill-or-well-structured problems that practitioners in a domain would solve are especially valued in a problem-solving environment (Voss, 1989; with respect to ecosystems ecology, see Jeffers, 1978; Kitching, 1983). Generally, real-world problems require the solver to reason from effects to causes. Effects-to-causes problems often allow the solver to generate his/her own data, and then use it to reason with concepts and general heuristics, as well as heuristics germane to a discipline. This knowledge is important because useful, real-world knowledge is more memorable and interesting to students (Nickles, 1987; Stewart & Jungck, 1994).

Students can gain insight into the nature of science relatively easily with the more real-world effects-to-causes problems, but not with causes-to-effects problems (Nickles, 1987; Stewart & Jungck, 1994). Researchers in problem-solving extensively use simulation problems and computer programs. Genetics Construction Kit (GCK) (Jungck & Calley, 1985) is one such effects-to-causes program (Appendix D). GCK is similar to EDM, in that both deal with effects-to-causes problems. These simulations present the solver with opportunities to create data (effects) and manipulate it until he/she infers the causes behind the effects. Extensive work on GCK (including Hafner & Stewart, 1995) links problem solving to our understanding of the teaching of genetics.

Teachers who give students well-structured, effects-to-causes, real-world problems to solve, engage students in the everyday work of scientists (Stewart & Jungck,

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1994). This gives students a good idea of what science looks like (Collins, Brown, & Newman, 1989). If they can see the structure of the discipline, they might have a better chance of learning and exploring that structure. Not only does this give teachers insight into the nature of student conceptual and procedural knowledge (Reif, 1983), but it gives teachers insight into student ideas about the fallibility of models (Palmquist & Finley, 1997).

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CHAPTER III

RESEARCH DESIGN

For creating analysis categories, expert analysis (Anderson, Carletta, & McEwan, 2000; Reif, 1983, 1990; Taatgen, 1997) was used. Miles and Huberman (1994) describe this process as "task analysis." For data collection, this researcher used the think-aloud (Ericsson & Simon, 1980) problem-solving method, where students solve problems as they talk about their thoughts. For analysis, this researcher used a version of protocol analysis described by Chi et al. (1981) and Ericsson & Simon (1980). These are described in this chapter. This study involved observing the solving of Environmental Decision Making (EDM) problems, along with participants' statements made during the solving. This researcher analyzed data by sorting statements and actions with the problems into categories, described below. This chapter also describes the specifics of the computer simulation used, EDM, and expert analysis as a theoretical construct which allows the categorization of responses.

Population: Description of Participants

The research participants were students who had successfully completed an introductory ecology course for biology majors at a large Midwestern university. Most students at this university were first-generation college students, who worked to finance their education.

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The students were junior-level, aged approximately 20 years. Volunteers were recruited by a letter that described the aims of the study and matters of confidentiality (Appendix E). Those students who indicated interest were offered $30 for participation in the research. Students were recruited at the end of a junior-level course, BIOS 300, Ecology, with prerequisites of botany or genetics. Participants were chosen because of the expression of willingness to participate. The seven participants included four males and three females. Three students were chosen for in-depth study, so all who volunteered were not used equally. The participants were all Caucasians, middle class, with the majority working part- or full-time based on interviews.

The syllabus for the ecology course (Appendix F) defines the set of knowledge to which students were exposed. The ecology course covered predator/prey dynamics, growth and reproduction in populations, carrying capacity, and competition, all of which were required background for the simulation. The Environmental Decision Making simulation (EDM) (Odum et al., 1991) used in this study was a closed pond ecosystem, consisting of sunlight, small plants and animals, sunfish, and bass.

Experiment/Research Design

Each participant was asked to sign a letter of consent (Appendix G) and attend two-hour, one-on-one sessions with the investigator. The minimum number of sessions performed by a participant was one and the maximum was three. Students were audio-taped. The setting was an introductory teaching laboratory equipped with computers. The students were asked to think aloud as they searched the problem space and solved

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problems using EDM, the simulation program that was used primarily to present an ecological pond scenario.

Environmental Decision Making (EDM)

EDM presents a simulated pond which allows the users to pose their own problems and seek satisfying solutions. H. T. Odum's circuit diagrams, which have evolved into a specific form used in EDM, allow a user to indicate the behavior of the components in a system. Odum's electrical diagrams are largely confined to his own publication, but similar diagrams are used by most ecosystems ecologists. A user can (or the default function on a computer can), for example, designate components as storage bins, producers of material, and consumers of material and energy. When a simulation is run, the system as a whole exhibits dynamic behaviors. Ecosystems ecology simulations for the classroom include several models similar to EDM, but there are also more complex simulations for graduate-level ecologists and theorists. Odum et al. (1991) describe the program in their manual:

> Using computer simulation, working with whole systems can be practical and real-world. First, you diagram a model of the system showing parts and connections among them. Each component is linked to the others with a mathematical relationship. Then the system is simulated so that a graph shows what happens over time. In understanding mathematical models of ecosystems, there are three major considerations. First, there are the outside sources, such as the sun, which is the stimulus for plants to change light energy into chemical energy. Second, there are the

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> relationships among the components, such as the direct connection of the sun to the plants and the indirect relationship of the sun to animals through the plants. Third, specific values are used that characterize the interactions of the components, such as the amount of sunlight used and its efficiency in photosynthesis. (p. 3)

The pond ecosystem in EDM is the system of interest in this study for two additional reasons: (1) The researcher has the most experience with using the pond simulation (used it previously as a teaching tool), and (2) the pond simulation leaves out economic entities which are present in addition to the ecology, such as money for selling useful products to humans. This is relevant because economic entities can confound the ecology content. EDM's pond also has a user-friendly interface.

A student who is using systems thinking with EDM is performing general heuristics, lending support to the claim that EDM problem solving could allow a student to demonstrate Stewart's (1988) outcome (b), problem-solving heuristics not specific to a discipline. Next, in order to fully understand outcome (b), it is necessary to briefly describe systems thinking again as a set of general heuristics that solvers may use to explore the problem space. Systems thinking shows an understanding of: (a) emergence, (b) causality, and (c) inside/outside constraints and (d) self-stabilization.

Emergence

In EDM, for example, the trophic pyramid is the emergent property which is apparent at the bass (predator) level of problems. As a specific example, when bass are added to a sunfish pond, a trophic pyramid emerges in the density proportions between

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populations; the densities of each entity are inversely proportional to their own level of the pyramid. So bass are always fewer than sunfish, and sunfish are fewer than pond life, and the differences are approximately one order of 10 (pond life/10 = sunfish, sunfish/10 = bass). The regularity with which trophic pyramids decrease by one order often for each level was once considered a law. The "law of tens," as it has been called, is now generally discredited and considered to be only a loosely valid principle, even by one of its early expositors, L. B. Slobodkin (1992). However, in order to simulate a simplified reality, EDM falsely treats this idea as a regularity in balanced systems. Each new level of problems displays more of the total properties inherent in ecosystems simulation.

Causality

The second systems thinking component, causality, allows the tracing of causes of events to a place, or places, in the hierarchy. Causality can occur along single, dual, or multiple lines. All combinations of types of causality are possible in problem solving. Causality could come from a single entity, while at the same time being indirect, and so on. Causality itself can arise or appear at various levels of problems.

In some EDM problems, the pond life is affected by dual causes, for example, directly by sun and indirectly by the bass density. The pond would also be affected directly by sunfish density.

Inside/Outside Constraints

The third systems thinking component, inside/outside constraints, are phenomena the solver notices about open and closed systems. In both open and closed systems, the

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inside/outside constraints on the system allow the inside entities to behave as a system of components and allow outside entities to act directly upon them. The sum of outside plus inside entities provides the environment in which the inside ones operate; together, they determine the limits of all the inside entities' behaviors. In increasingly open systems, other outside factors such as pollution or runoff become factors in the inside system's behavior.

In EDM's closed system, the amount of sunlight entering into a system largely determines the behavior of all entities within that system. Sunlight is a constant source of energy that is outside the living components of the system, per se. Although sun is part of the problem, it is not a part of the actual pond system. It is the source of all its energy, and so must be considered part of the closed pond system. Energy sources such as nutrients running off into the pond, however, would be possible in open systems because the outside constraints are completely outside the problem that can be posed in EDM. Inside constraints are also present which come from within the closed system and have effects upon it.

While the EDM pond can be considered a system with the sunlight as an outside constraint (Odum et al., 1991), some aspects of a real pond's behavior can break out of the constraints, or be viewed as outside a given system or problem. For example, some pond life plants may actually live on the edges around the pond, functioning as producers outside the immediate pond system, but at times participating in nutrient cycling (Odum et al., 1991). The inside constraints of the EDM pond, however, would only include the limit of growth within the pond life which never can be sustained above carrying capacity.

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Self-Stabilization

The fourth systems thinking component, self-stabilization, similar to the homeostasis of the body, is realistically found in ecosystems which exist in dynamic equilibrium (Salisbury, 1996). Laszlo (1972) suggested that self-stabilization is a tendency of systems at all scales, from molecules to galaxies; i.e., natural systems adapt to their environments through self-stabilization around steady states. Of course, ecologists recognize that such an equilibrium is often questionable because some real ecosystems have been destroyed or rendered unstable (Odum et al., 1991). However, even open systems, e.g., biological systems, which are permeable to processes outside themselves, may tend toward steady states (Laszlo, 1972). While systems tend toward stabilization, the equilibrium they reach at any moment can be perturbed by numerous forces before they return to a stable point.

EDM models the concept of carrying capacity, the self-stabilization of a population at a given level, in almost every problem (Odum et al., 1991). The realistic dynamic equilibrium that exists in real ecosystems is only modeled in EDM at certain sensitive thresholds. Otherwise, the entire system reaches a stable point eventually. The first problem with this is that on rare occasions, a problem solver may find the sensitive thresholds at which a system oscillates wildly for a year or more before reaching a stable point. Second, the amount of time the system takes to stabilize is directly related to the amount and intensity of perturbations caused by starting values of the entities. In EDM, the pond life stabilizes first, which is often followed by the entities successively higher up the trophic pyramid.

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Causes of phenomena in EDM travel through the system and affect all of the entities involved (Odum et al., 1991). This is where there is a combination of emergence, causality, inside/outside constraints, and self-stabilization. For example, at the level of sunfish problems, oscillating predator and prey dynamics emerge (emergence). The qualitative effects of the changing population size of a predator on its prey also travel to the level of the producers feeding that prey (dual causality). Changing population size affects the rate and ultimate value of carrying capacity (self-stabilization). Sunlight ultimately determines the carrying capacities of all entities (inside/outside constraints).

EDM's Systems Thinking

Included in the decision-making about what problem sets to use is that EDM simulates more than just ecology. EDM does not let the system crash completely (Odum et al., 1991). This means that attempts to destroy the system merely results in very low numbers. The constraints on EDM reflect the infallibility portrayed by the model, a fact that students may or may not notice.

There are an infinite number of values which can be entered into the starting value of EDM components. For example, sunfish can start at 0.001 kg/hectare, or 100,000 or more kg/hectare. Realistic ranges are not provided (Odum et al., 1991). However, ecology knowledge might inform a student that realistic proportions are relative to available sunlight. The infinite capacity of starting values was therefore desirable.

EDM itself has constraints of its own. Since fishermen are removed, the components used are the only ones realistically available in the pond. Further constraints involve the degree of reality portrayed by EDM. EDM uses a consistent amount of

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sunlight each day, not accounting for cloudy or rainy days. Other variables, which are theoretically infinite, interacting with a pond are not included. These include pollution and runoff.

Systems thinking is germane to some kinds of problem solving. Systems thinking can be used to decide how to approach a problem space. For example, some computer simulations used in ecosystems (e.g., EDM) and genetics (Genetics Construction Kit) are themselves systems. The pond ecosystem is made of living components of a pond that interact as a system. Ecosystems simulations further model systems. A problem solver may use systems thinking to build an ecosystems problem (Mandinach & Cline, 1989). Systems thinking may determine both how to proceed in searching the problem space, and how to give explanations and predictions of the system's behavior. Of course, the problem is relating the limitations of systems thinking to the behavior of real systems. Problem solvers should be able to notice the limitations of the model. If they were to fail to be aware of the limitations, they could be unsuccessful problem solvers.

For example, systems thinking in EDM helps a user to proceed in the problem space search by informing her/him that changing more than one variable at a time introduces too much complexity. So a solver who is aware of the need to partition complexity builds only one component at a time into an open-ended simulation and changes only one variable at a time in a pre-built simulation. Therefore, ecosystems problem solvers using systems thinking change only one variable each time they run a simulation.

EDM fails to account for multiple variables. The EDM model fails at leaving sunlight invariable in a given area. In addition, the "rule of tens" should not and need not

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be reflected in simulations, and may lead to student misconceptions. There is a type of stabilization in EDM that is artificial. However, the success of EDM to simplify and model a complex set of interactions should not be understated. When students use EDM aloud, we need theoretical constructs for identifying meaningful moves and analyzing their thoughts. The constructs, expert analysis and protocol analysis, are described below.

Expert Analysis

Originally defined by Reif in 1983, an expert analysis of the tasks participants perform in problem-solving research is used to choose a subset of meaningful moves in meaningful problems (see also Anderson et al., 2000; Reif, 1990; Taatgen, 1997). Expert analysis is a process that locates and "specifies the thought processes and representations (pictures, equations, etc.) of knowledge that create a path to desired performance" (Reif, 1983, p. 8). The justification for the categories used is Begon, Harper, and Townsend (1989) for conceptual ecology, and problem solving and teaching experience for the procedural knowledge. Appendix C describes how they are used to shape the inferences that are presented.

Since EDM was chosen and constrained, running many problems with EDM provides knowledge about its behavior (Odum et al., 1991). This leads to an understanding of the range of sensitivity for each of the carrying capacities (equilibrium values) and at what thresholds each entity might die out. Then the diagrams used to create the systems are separated into causal parts. The conceptual ecology knowledge embedded in the EDM problems shows which basic ecology knowledge is included. By

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examining expert knowledge such as that in the concept list for the Life Science for Elementary Education course, the researcher determined the ecology principles (content knowledge) inherent in the problems. The principles were used to verify that the set of meaningful moves includes basic conceptual ecology knowledge. The specific statements related to: (a) low-level, (b) middle-level, and (c) high-level knowledge are defined in Appendix C. During the development of the expert analysis, expert biologists were consulted to evaluate the forms of the problems and the nature of the expected solutions. These biologists were not familiar with the analysis protocol, but are expert ecologists and educators, as defined by having ten years of more experience in their disciplines (Chi, Glaser, & Farr, 1988).

The researcher conducted an analysis of the systems thinking components, as defined by Kim (1994) and Salisbury (1996) (emergence, causality, inside/outside constraints, and self-stabilization) in order to sort out problems that were amenable to modeling.

1. Biological emergent properties. These are traits that become obvious only when looking at a specific level of the system.
2. Causality. Causality in ecosystems is complex, but if it is properly understood it explains many behaviors.
3. Inside/outside constraints. Changes in entities are strongly affected by outside constraints. A change in one entity generally affects all others.
4. Self-stabilization. Ecosystems are considered self-stabilizing; even within random fluctuations, equilibrium is always the goal of systems.

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Protocol Analysis

The method used in the problem-solving research tradition is typically (R. Hafner, personal communication, December 6, 1998) to obtain "think aloud" protocols (Ericsson & Simon, 1980). This occurs when solvers complete their task while saying their thoughts aloud. The problem solvers' words are recorded and referred to as protocols. The protocols are later analyzed to suggest the mental processing that took place during the problem-solving process. Procedural knowledge and the understanding of conceptual relationships used in solving problems are identified.

Encoding of protocols involved sorting segments of data into categories created by expert analysis. The following example shows some of Pat's statements which were sorted, using Ericsson and Simon (1980). The concept of population growth was stated, followed by the concept of reaching a point where the population would "level out" or reach equilibrium.

The conceptual framework (Miles & Huberman, 1994) for categorizing data sorted conceptual knowledge into objects, states, and processes (Hafner & Stewart, 1995), where some ecology concepts were considered nouns, adjectives, and verbs, respectively. Procedural knowledge was sorted into meaningful moves and heuristics (see Figure 1).

According to Chi (1997), the method of coding and analyzing verbal data consists of the following eight functional steps:

1. Reducing or sampling the protocols.
2. Segmenting the reduced or sampled protocols (sometimes optional).
3. Developing or choosing a coding scheme or formalism.

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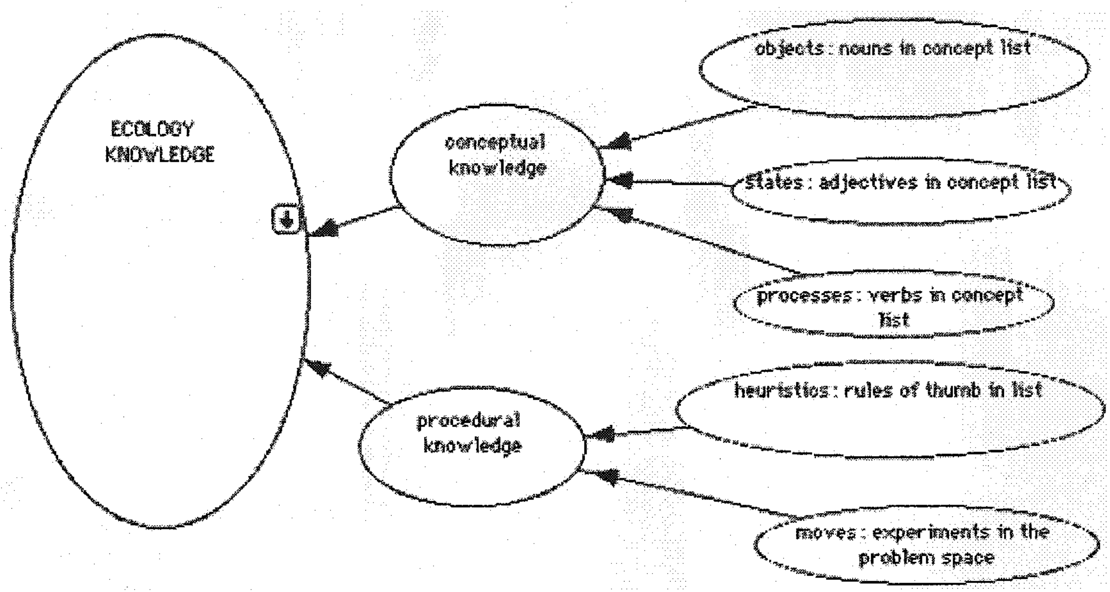

Figure 1. Ecology Knowledge.

4. Operationalizing evidence in the coded protocols that constitutes a mapping to some chosen formalism.
5. Depicting the mapped formalism (optional).
6. Seeking pattern(s) in the mapped formalism.
7. Interpreting the pattern(s).
8. Repeating the whole process, perhaps coding at a different grain size (optional). (p. 298)

A description of the EDM simulation is first provided here. The research tool called expert analysis, which defines the boundaries given in the simulation, is then described. Ecology knowledge includes both content and procedural knowledge in systems thinking, which is discussed in the next chapter.

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Method

The script was read to all students (Appendix H) before they began their problem posing and solving. Students were told to think aloud as they solved problems. The researcher audio-taped the comments students made without voice activation, so that the entire session was audio-taped live. Pauses were noted, but not measured. After completing a practice problem, participants were presented a series of problems, which they were asked to solve, using EDM. Students created graphs, and the researcher saved a copy of each new graph. The researcher later fit graphs to the data generated by students, so that the graphs were easy to read. Figures 2 and 3 represent an early piece of problem solving by a participant (Pat), during which she ran a bass pond, containing sunfish and small plants and animals ("pond life"), with a bass competitor, named gar.

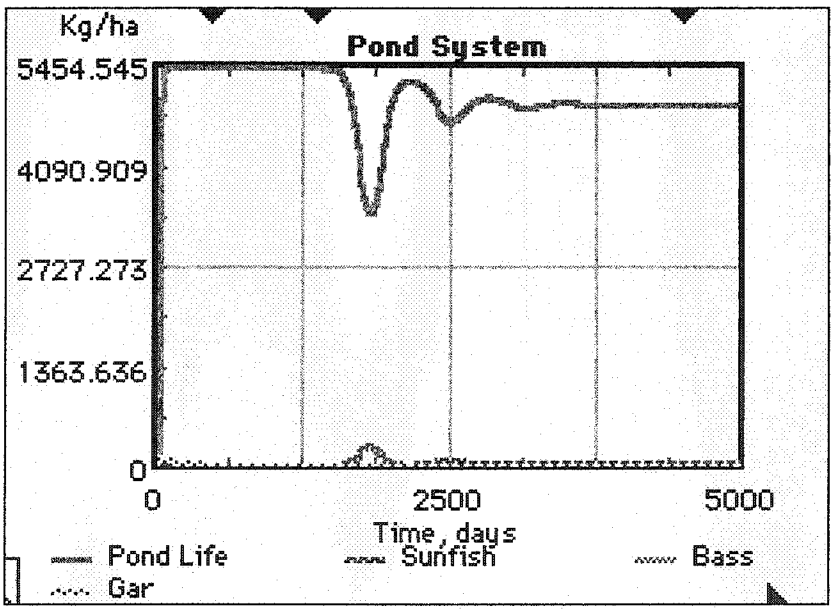

Figure 2. Sample Protocol Number 1.

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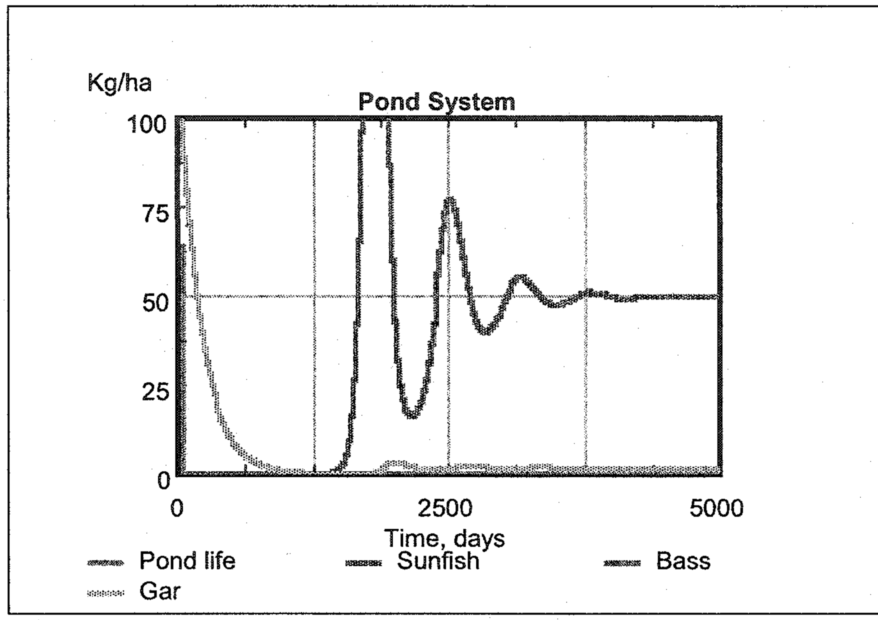

Figure 3. Sample Protocol Number 2.

The subsequent tasks created involved two primary components: a construction of problems, a constrained task of making moves in problems, and a set of preposed problems intended to elicit specific conceptual and procedural knowledge. Figures 2 and 3 and the following text capture Pat's experiment.

Pat: Okay, so let's see. If I wanted to level this out I would need to minimize the peak there. I probably need more plant life to begin with. Well, I've got it at 20 now, if I double that to 40 let's see what just changing the plant life would be. Cause I think, yeah.

Interviewer: Run that?

Pat: Yeah. Okay, change the plant life to 40. And see what the graph looks like, it should make the this peak of the, of the big, the very large peak of what do you call it, sunfish, it should make that go

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higher. It should make the drop look less, of the plant life. Yeah, I think, okay. I don't know how right that is.

Interviewer: That's all right, you don't have to right every time.

In the problem in Figures 2 and 3, starting values were: 3000 kcalories of sunlight/square meter, 40 kg/hectare pond life, 66 kg/hectare sunfish, 100 kg/hectare each of bass and gar. They reached a carrying capacity of 5 kg/hectare, 100 kg/hectare, 7.72 kg/hectare, and 7.72 kg/hectare in 3229 days. The text includes the statements Pat made about creating the experiment as well as the graphs she generated.

After the problem solving sessions, all notes and drawings were collected. Experiments were defined as individual runs of the simulation. Therefore each time the students changed the starting values of the pond populations, a new experiment was begun. Students were consistently presented with the problems. They were ordered in terms of complexity and open-endedness (Figure 4).

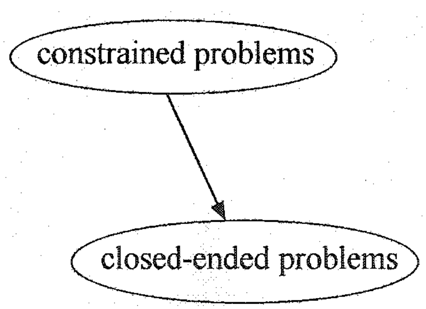

Figure 4. Outline of Problems.

All participants were given a set of constrained problems where the entities involved, such as pond life, sunfish, bass, and gar, were already given. The researcher analyzed the data for the order and subset of problem space searched and moves made.

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To address the second research question, the researcher used the defined categories of concepts and heuristics (rules of thumb) (Nickles, 1985) to categorize closed-ended problems that were run for the participants. The participants' task in this instance was to simply explain what they saw. Some of the inferences drawn were from statements made by the solver, and others were drawn from studying the moves the solver made through the problem space.

Categories and Constructs: Describing the Expert Analysis

Meaningful Moves

The researcher used the definition (Klahr, 1976; Nickles, 1985) of the meaningful problems as that set of problems which enables a problem solver to most completely explore all available conceptual relationships as well as systems thinking components. Meaningful moves reveal these conceptual relationships within problems. Thus, meaningful moves are within the meaningful problems. The best way to ensure that all conceptual knowledge is available is to explore the pond from the smallest system to the largest, adding one component at a time. It may be possible for some problem solvers to change more than one variable at a time without getting overwhelmed by complexity.

Constructs/Protocol Analysis

The following description is illustrative of the process of protocol analysis. Each problem set represented phenomena with different attributes and aspects. The participants were not informed of the rationale for the ordering of the problems, so that

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the researcher would not lead them into particular ways of constraining the problem space.

To address the research questions, students were asked to explore the pond system using pond icons that have not been posed into problems. The screen shot in Figure 5 shows what EDM looked like when students started.

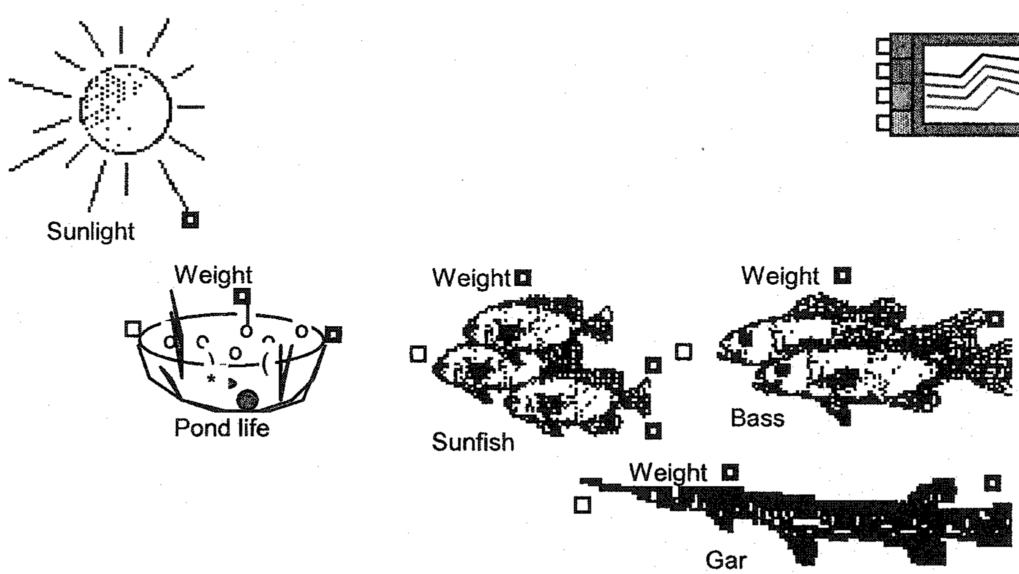

Figure 5. Explore Problems.

Each participant was then given a set of constrained problems, illustrated by Figure 6. Problems were presented in order from smallest to largest. The second problem set is above; the subsequent problem sets add bass and gar. This problem asks, "what if pond life and sun are the only components, over time, with starting values of 4000 kcalories of sun and 1000 kg/hectare pond life to start?" There were problems involving pond life, sunfish, bass, and gar, as well as problems involving grassland-fire and forest systems. These problems contain the possible conceptual ecology knowledge

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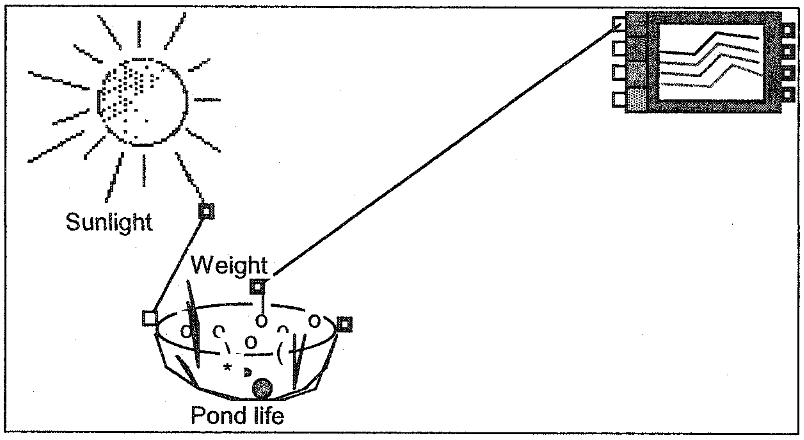

Figure 6. Constrained Problems.

available in EDM. The researcher analyzed the data for the order and subset of problem space searched, as well as the moves made, which assessed procedural ecology knowledge.

If a participant paused in her/his audio-taped process, termed "think-aloud protocol" (Ericsson & Simon, 1980) during problem solving, the researcher would prompt the participant to continue speaking. First, students were given practice with a think-aloud activity (Appendix H). During problem solving, a phrase suggested by Larkin and Rainard (1984) was used: "Can you tell me what you're thinking?" This question elicited introspective comments. The researcher used the phrase "Keep talking" as a less intrusive way to encourage participants to continue thinking aloud without prompting introspection. Larkin and Rainard (1984) corroborated with Ericsson and Simon (1980) that this does not shape responses. If there were periods of silence while the participant was working, the researcher was allowed to say only a clarifying statement, such as "Can you tell me what you're thinking?" The researcher could also

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make clarifying statements answering questions about the task, or regarding calibration of graphs or the instructions participants gave about calibration.

Their comments, graphs, and notes were organized into "frames" (Kowalski, 1979) similar to Figures 2 and 3 and the text associated with them. Frames are defined as segments of writing, statements, and actions organized by one problem at a time.

There are two problem types: (1) open-ended problems, where participants search the problem space within unposed problem scenarios or make moves within a limited set of entities; and (2) closed-ended problems, where participants interpret problems that the researcher pre-posed (Figure 7).

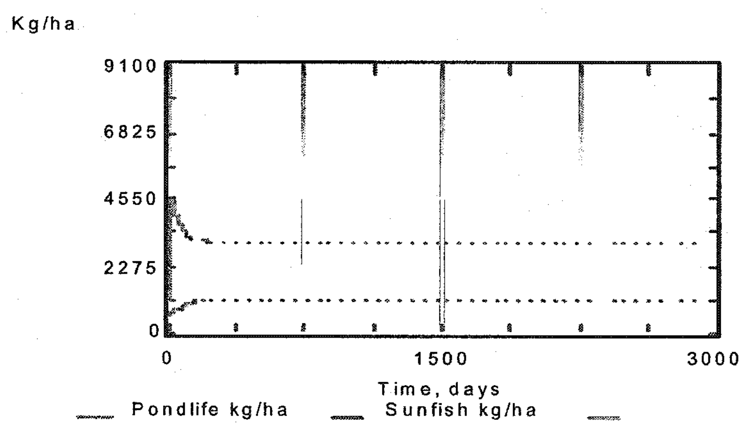

Figure 7. Closed-Ended EDM Run Graph.

Instrument

EDM was used in the study to have a strictly ecological scenario, not an "environmental" one as defined by economic elements. The most open-ended problems give participants a blank worksheet, with a set of pond entities, and allow participants to explore a system in their own way. Figure 8 includes the principles of conceptual

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I. Energy exchange

II. Trophic levels

III. Predator/prey dynamics

IV. Carrying Capacity

V. Systems behavior

VI. Competition

VII. Population growth

A. Definition statement (low-level knowledge)
B. Relates concept to others (middle-level knowledge)
C. Connects concept to complex processes (high-level knowledge)

Figure 8. Principles of Conceptual Ecology Knowledge Embedded in EDM.

ecology knowledge arranged in order of problems where the knowledge first employed corresponds to the set of meaningful moves. The second category, closed-ended problems, were given in order to assess whether participants could portray specific aspects of systems and ecosystems knowledge (given in Figure 8 and elaborated in Chapter IV). These closed-ended problems were ready to run with parameters that the participants did not change. The participants' task in the second category, therefore, was to bring biological interpretation to the problems, and not to search the problem space.

Detailed Expert Analysis

Expert analysis, a procedure for creating categories to sort data, was performed (Reif, 1983). This is where all possible meaningful moves available in the simulation are

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identified. A resulting set of problem tasks was given to participants. In this process, the procedural knowledge used by the participants was determined. For example, when EDM simulates the growth of "pond life" in a sunny environment, it provides a rich growth of pond life. This might prompt an experimenter to pose a question about a less sunny environment, by contrast. This next question posed would reflect procedural knowledge (Figure 7).

In order to address the second research question, the researcher used the defined concepts and heuristics to categorize closed-ended problems that were run for the participants. The participants' task in this instance was to simply explain what they saw. After the conceptual knowledge was described, the next step in the researcher's expert analysis was to run at least ten-to-twelve simulation problems for each problem type. For example, the problem in Figure 6 represents one experiment run by the researcher, which would be followed by an experiment posing "what happens if we double the sunlight?" Finally, experts were consulted to provide categories which led to the expert analysis of data. In order to deal with ecosystems problems, all aspects of the system and their interrelated dynamics must be taken into account.

How Systems Thinking Is Used in Problem Solving

Systems theory and ecosystems ecology share similar roots in their concern about holistic systems, such as ecosystems, the body, and complex machines. Below, some examples of how systems thinking is used in a simulation are described in order to define systems thinking involvement in ecosystems problem solving.

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Systems thinking helps the solver to give explanations and make predictions about the system's future behavior (Salisbury, 1996). So the coding categories involving the tool called systems thinking can make sense of ecosystems. Feedback loops are defined as instances when information about the result of a transformation or an action is sent back to the input of the system in the form of input data (Kim, 1994). Feedback loops are a basic explanation for many dynamics of ecosystems. For example, if one searches the portion of an EDM problem space in which sunlight is input to pond life, one can explain the resulting growth and approach to carrying capacity by invoking the concept of positive feedback. Pond life increases with increased sunlight, and the greater pond life density allows even more growth and reproduction. One could next predict the effects of increasing the initial sunlight. The pond life biomass would increase proportionately to the increase in sunlight because of the behavior of positive feedback.

The above example illustrates some of the most apparent details of systems thinking which can be used by solvers. Appendix A includes all of the biological emergent properties inherent in the EDM problems for this study and the analogous properties of systems thinking which arise within good problem solving. "Emergent" properties are those generally recognized as biological properties, and "arising" properties are those which are not. Procedural knowledge involving the systems thinking components comprise systems thinking heuristics. A major task of the study is to access how many of the possible systems thinking heuristics are used by various solvers, and later to apply the heuristics participants did not use to teaching ecosystems problem solving better.

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Much of the previous research on dynamic modeling has been exploratory and formative (Miller, Luther, & Hendershott, 1993; Schecker, 1995; Stratford et al., 1998), reporting not comparative results but qualitative observations. Other research (e.g., Mandinach & Cline, 1989) has focused on research questions related to curriculum integration and reform, and therefore used methods matched to those questions. The data in this study consisted of think aloud protocols. Most of the methods used in this study were adapted from more general interview, observation, conversation, and artifact analysis methods (Chi, 1997). During earlier work and during data analysis, the researcher developed not only the main analysis categories of content and procedural knowledge, but also sub-categories for each.

Three types of data were collected: transcripts, actions using the simulation, and notes. They were collectively analyzed in artificial units called frames (e.g., Kowalski, 1979). Frames are defined as the data representing all actions associated with a given problem. The frames were then examined for clues to the use of content knowledge and heuristics.

The analysis was evaluated for intercoder reliability. As described in Brewer (1996), using a set of example protocols, the researcher and an associate applied the components expected in a model solution of each problem and compared differences until agreement was reached regarding how each component was to be applied. Subsequently, a second set of example protocols were coded by each coder, compared, and the percent correspondence calculated.

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Set of Meaningful Moves

The meaningful moves are those problems that collectively incorporate all conceptual relationships which are demonstrable in the pond scenario. For examples, meaningful moves are represented in Table 1. The set of meaningful moves which resulted from the expert analysis was conceived as a template for analyzing the think-aloud protocol data. Low values are those which are below the ultimate carrying capacity values for a given problem type. Middle values are equal to the carrying capacity ranges. High values are above carrying capacity ranges. For example, the complete pond problem has consistent middle (carrying capacity) values for each of the entities—pond life, sunfish, bass, and gar—at a given value of sunlight.

There are two overlapping approaches to searching the problem space: (1) a "thorough" approach, which requires the participant to search the full range of each value for each entity, and (2) a "comparison" approach, which requires the participant to keep values constant and compare. Both approaches are required for the ideal pattern of search through the problems. A good example of the thorough approach was:

Chris:

1. 4200 kcalories sun, 10 kg/hectare pond life, 10 kg/hectare sunfish, 10 kg/hectare bass, 10 kg/hectare gar--> 10 kg/hectare pond life, 10 kg/hectare sunfish, 10 kg/hectare bass, 10 kg/hectare gar, ran 18 days.
2. 4200 kcalories sun, 10 kg/hectare pond life, 10 kg/hectare sunfish, 20 kg/hectare bass, 10 kg/hectare gar -->7448 kg/hectare pond life, 15 kg/hectare sunfish, 15 kg/hectare bass, 15 kg/hectare gar, only ran 60 days.

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Table 1

The Set of Meaningful Moves in EDM

	Variable													
	Sun	Sun	Sun	Pond Life	Pond Life	Pond Life	Sun-fish	Sun-fish	Sun-fish	Bass	Bass	Bass	Gar	Gar
Constant	a	b	c	d	e	f	g	h	i	j	k	l	m	n
Sun		2			7		5			9	15	16	15	16
Pond Life	1, 6		3	4			5			9	15	16	15	16
Sunfish	6		3	4	7					9	15	16	15	16
Bass	6				7			8						
Gar														

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8. 2000 kcalories sun, 10 kg/hectare pond life, 40 kg/hectare sunfish, 10 kg/hectare bass, 10 kg/hectare gar --> 3000 kg/hectare pond life, 100 kg/hectare sunfish, 0.01 kg/hectare bass, 0.01 kg/hectare gar, 1440 days.
9. 2000 kcalories sun, 10 kg/hectare pond life, 40 kg/hectare sunfish, 0 kg/hectare bass, 10 kg/hectare gar --> 3037 kg/hectare pond life, 98.5 kg/hectare sunfish, 0.36 kg/hectare gar, 2625 days.

It was thorough because the approach to the problems was systematic through those runs. A good example of the comparison approach was:

Pat:

1. 3000 kcalories sun, 10 kg/hectare pond life, 33 kg/hectare sunfish, kg/hectare bass --> 4545 kg/hectare pond life, 100 kg/hectare sunfish, 15.46 kg/hectare bass, 2916 days.
2. 3000 kcalories sun, 10 kg/hectare pond life, 66 kg/hectare sunfish, 100 kg/hectare bass, 100 kg/hectare gar -->4545 kg/hectare pond life, 100 kg/hectare sunfish, 7.72 kg/hectare bass, 7.72 kg/hectare gar, 3229 days.
3. 3000 kcalories sun, 40 kg/hectare pond life, 66 kg/hectare sunfish, 100 kg/hectare bass, 100 kg/hectare gar --> 4545 kg/hectare pond life, 100 kg/hectare sunfish, 7.72 kg/hectare bass, 7.72 kg/hectare gar, 3229 days.
4. 3000 kcalories sun, 40 kg/hectare pond life, 100 kg/hectare sunfish, 100 kg/hectare bass, 100 kg/hectare gar --> 4545 kg/hectare pond life,

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100 kg/hectare sunfish, 7.72 kg/hectare bass, 7.72 kg/hectare gar, 3099 days.

5. 3500 kcalories sun, 40 kg/hectare pond life, 100 kg/hectare sunfish, 100 kg/hectare bass, 100 kg/hectare gar --> 5303 kg/hectare pond life, 100 kg/hectare sunfish, 11.51 kg/hectare bass, 11.51 kg/hectare gar, 2604 days.
6. 3500 kcalories sun, 200 kg/hectare pond life, 100 kg/hectare sunfish, 100 kg/hectare bass, 100 kg/hectare gar --> 5303 kg/hectare pond life, 100 kg/hectare sunfish, 11.51 kg/hectare bass, 11.51 kg/hectare gar, 3125 days.
7. 3500 kcalories sun, 1000 kg/hectare pond life, 100 kg/hectare sunfish, 100 kg/hectare bass, 100--> 5303 kg/hectare pond life, 100 kg/hectare sunfish, 11.51 kg/hectare bass, 11.51 kg/hectare gar, 3072 days.
8. 3500 kcalories sun, 10000 kg/hectare pond life, 100 kg/hectare sunfish, 100 kg/hectare bass, 100 kg/hectare gar --> 5303 kg/hectare pond life, 100 kg/hectare sunfish, 11.51 kg/hectare bass, 11.51 kg/hectare gar, 2600 days.

It was a comparison approach because it involved changing the same variable each time, and only one at a time. These two examples show the extremes of approaches that are either comparison or thorough. However, Terri used a combination of the thorough and comparison approaches. Terri's problem solving was thorough for two problems and comparative for others.

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As an example of problem posing in Figure 9, the participant might keep pond life constant, and try low, middle, and high values of sunlight influence. Then the participant would keep sunlight at a high value, changing pond life to low, middle, and high. Moves 1 and 2 are in the pond system, 3, 4, and 5 are in the sunfish system, 6 through 9 are in the bass system, and 10 through 16 are in the gar system. The moves represent comparisons, e.g., pond life 1, 2, and 3 is a set of runs, which keep sunlight constant and run three different pond life values in order to see the controlled effect of changing only the pond life. The moves involve the comparative approach, but may also include a relatively thorough explanation approach. The issue of confirming an understanding of the system is dealt with by running comparative runs at a given level. At least three comparative runs are considered necessary to confirm a hypothesis.

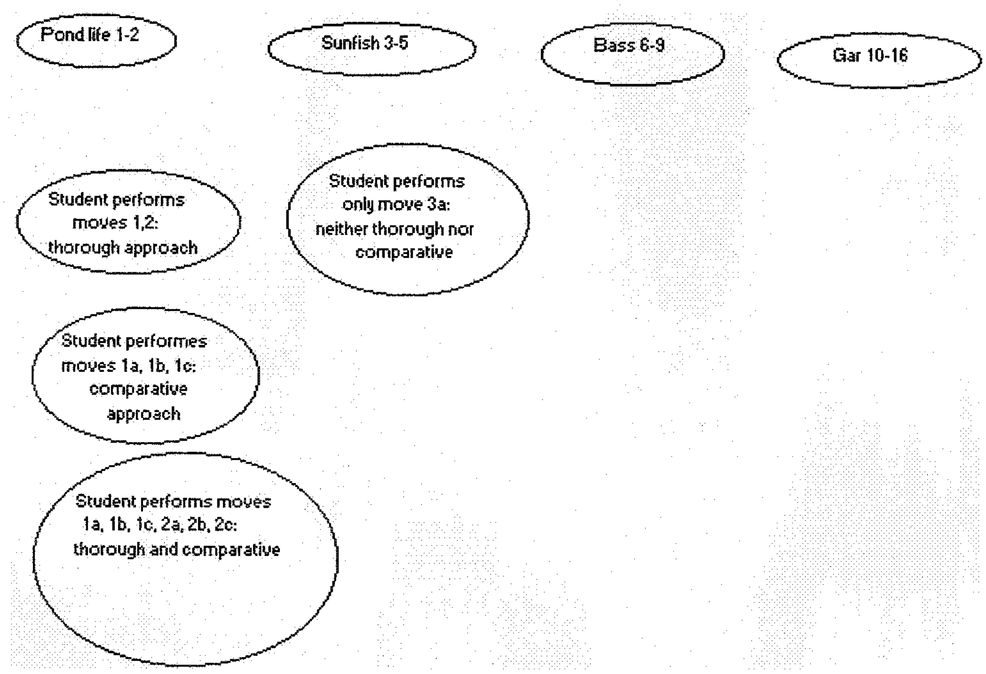

Figure 9. Illustration of a Set of Meaningful Moves.

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CHAPTER IV

RESULTS

The results of the study are presented in two major categories, relating to the research questions: content knowledge, and procedural knowledge. Expert analysis revealed a large amount of content and procedural knowledge. Students pursued a subset of both types of knowledge. Content knowledge in the students was relatively similar in quantity and quality. Procedural knowledge was more variable in terms of moves and heuristics. High-level knowledge was not prevalent. The expert analysis of procedural knowledge in the ecology computer simulation Environmental Decision Making (EDM) used in the study showed that there were many heuristics and moves available in the simulation, and participants used a varying subset. Meaningful moves varied in coverage by students, and in fact, those coverages helped the researcher decide which of the three participants would be analyzed in more depth. The specific heuristics used by students varied and written heuristics varied. Written heuristics in particular were varied, but used by all students.

The number of runs or experiments created by students varied. The time spent with the simulation varied tremendously, in terms of hours, but also in the number of sessions students chose to use to ask all their questions about EDM.

Students used confirming and disconfirming statements to announce when they were supporting or refuting a hypothesis. Those statements helped to determine whether

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students continued to be persistent in using more knowledge after unsatisfactory runs. All students did to one degree or another.

Some analysis of all seven students is given to show their variation in procedural knowledge. However, three students were chosen for in depth presentation. The focus is on only three students because the three showed the most variation in their procedural knowledge. Content knowledge was similar among them, but the analysis of the transcripts showed variation in procedural knowledge.

Content Knowledge

To define the system for the study, ecology experts described the content and procedural knowledge available in EDM, and the researcher analyzed their thoughts. This is called expert analysis. This allowed examination of the knowledge participants used. In this section, examples of student expression of the content knowledge available in EDM will be shown. Content knowledge available in EDM was summarized which represents expert knowledge available in the simulation. Ecology experts and the researcher listed the content knowledge most basic to ecology, and that which is available in EDM. After the expert examples, the content knowledge participants used will be shown.

Expert Analysis of the Content of EDM

Results of expert content analysis (as defined in Chapter III, an exhaustive analysis of the information known by experts) revealed ecology knowledge in the simulation (Figure 8 in Chapter III and Table 2). Seven categories summarize the

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definitions. Expert analysis allowed for the seven chosen categories of definitions, based upon difficulty. The expert definitions allowed for concepts which allowed for connection between concepts and process. For example, the definition of carrying capacity allows for equilibrium among the concept of populations, which allows one to compare predation between those populations. Further, the three levels from the expert knowledge are low-, middle-, and high-level knowledge:

1. Low-level knowledge will be considered that which involves defining objects.

2. Middle-level knowledge will be considered that which involves connecting one definition to another definition.

3. High-level knowledge will be considered that which involves connecting a definition with a complex process.

At the low-level, definitions are available in EDM knowledge. The list of definitions includes statements of ecology knowledge, placed below for the reader's inspection. Definition statements required participants to use the concept correctly in context in a sentence, using noun-verb agreement. Experts used the following ecology definitions, which were used in the analysis:

1. Autotroph: an organism capable of synthesizing organic matter by using radiant energy and inorganic matter (carbon dioxide, water and nutrients). This process is termed photosynthesis. The chemical energy contained in organic matter that is synthesized by autotrophs is subsequently used by them as well as heterotrophs for growth and development, metabolism, reproduction. This process is termed respiration. Examples: the plant portion of the "pond life" in EDM; rapid-cycling Brassicas plants used in biology courses.

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2. Biomass: the total mass of living matter constituting the component(s) of a trophic level within a given habitat. Biomass is a measure of the carrying capacity of a habitat and is inversely proportional to the trophic level (i.e., higher trophic levels in the food chain have less total biomass). In EDM, mostly measured in weight/area (Kilograms of organism/hectare of water or Kg/hectare).

3. Chemical energy: energy in the bonds of organic molecules which autotrophs "fix" and use and which heterotrophs use. Example: C----O bond between the Carbon and the Oxygen produces energy when it is broken. This energy is subsequently used for metabolism, growth and development, reproduction.

4. Community: a grouping of populations (both plant and animal) living and interacting with one another in a specific region under relatively similar environmental conditions; the biotic component of ecosystems which contain several food chains/webs. Example: a pond's organisms, or a field's organisms.

5. Conditions: components of an organism's environment which typically cannot be depleted and thus are not competed for by organisms. Example: water is a condition for aquatic plants.

6. Consumer: a heterotrophic organism that ingests other living organisms (plants or animals) and thus organic matter in a food chain; an example of a community niche.

7. Decomposer: an organism (example, fungi and bacteria) that obtains organic matter and chemical energy by breaking down nonliving organic materials from any source (from organisms at all trophic levels); an example of a community niche.

8. Density: the number of individuals occupying a given habitat; competition increases with increasing density.

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9. Density-dependent factors: regulatory factors that affect the growth of a population as a function of that population's size. For example: both competition within and predation upon a population increase when that population increases.

10. Density-independent factors: regulatory factors that affect the growth of a population that are not a function of the population's size: For example: temperature.

11. Ecosystem: an ecological community together with the abiotic components of its environment functioning as a unit. Example: a pond, forest, or field.

12. Energy exchange: exchange of usable heat or power; of the capacity to do work; of energy flows through food webs. For our purposes, energy can be classified as either radiant or chemical.

13. Environment: environment can be characterized by a number of interacting dualities at any level of the hierarchy: biotic and abiotic components; resources and conditions; matter and energy.

14. Food chain/web: a succession of organisms in an ecological community that constitutes a cycling of matter and a flowing of energy from one organism to another as each consumes a lower member and in turn is preyed upon by a higher member (a food web is a complex, interlocking sequence of food chains in a community).

15. Heterotroph: an organism that must obtain chemical energy and nutrients from the organic matter originally produced and stored in autotrophs (the byproducts of photosynthesis). The process by which heterotrophs break down and utilize organic matter for chemical energy is termed respiration. Examples: sunfish, bass, bacteria, people. Decomposers, carnivores (eat meat), herbivores (eat vegetative matter), and

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omnivores (eat meat and vegetative matter) are all heterotrophs because they obtain and use autotroph energy either directly or indirectly.

16. Inorganic matter: matter involving neither organic life nor the products of organic life; matter used by autotrophs in the production of organic matter: water ($H2O$) carbon dioxide ($CO2$), minerals (magnesium, potassium, phosphorous, nitrogen, etc.), matter produced by autotrophs in the production of organic matter: oxygen ($O2$).

17. Matter: molecules which make up everything in the universe; matter cycles through food webs. Matter can be classified as either inorganic or organic.

18. Niche: the ecological role a species plays in a community. Used expansively, this concept describes a species' trophic level, habitat, time of year for reproduction, and specific type of food. In other words, it describes the multidimensional specific role the species plays in a community.

19. Organic matter: carbon containing molecules (for example, sugars, fats, proteins) which autotrophs produce and use and which heterotrophs use for living processes. Organic matter contains chemical energy in its molecular bonds. For a biologist, "food" is synonymous with organic matter.

20. Organism: an individual living creature, either unicellular or multicellular. Organisms use the chemical energy contained in the molecular bonds of organic matter for such processes as: growth; metabolism; reproduction.

21. Population: a group of individuals of the same species that occupy the same habitat. Example: the sunfish in a single EDM pond are a population.

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22. Producer: an autotrophic organism that produces food for itself and other living organisms (plants or animals) and thus organic matter in a food chain; an example of a community niche.

23. Radiant energy: sunlight which autotrophs utilize (through photosynthesis using chlorophyll) in the production of organic matter. In EDM this is measured in heat in kilocalories, the same unit used to measure calories in food.

24. Resources: components of an organism's environment which can be depleted and thus competed for. Example: oxygen is a resource for aquatic plants because it is limited.

25. Regional biota: large scale groupings of communities occupying a geographic area. Examples: a mountain range, Lake Michigan, etc.

26. Trophic level: successive steps of a food chain/web, each of which has less available energy and biomass than the previous level; the levels are referred to as producers; primary, secondary, tertiary (and higher) levels of consumers.

At the middle level, connections are possible between concepts (objects). Connections made between any of the above concepts were considered in the analysis of students' thinking. At the high level, relations are possible between concepts (above) and processes/states. Examples of processes include: carrying capacity (abbreviated K), competition, density, intraspecific interactions, interspecific interactions, photosynthesis, predation, reproductive rate (abbreviated r), respiration, and symbiosis.

The resulting categories of concept knowledge fit into the seven categories in Table 2, where A is low-level, B is middle-level, and C is high-level.

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Table 2

Categories of Declarative Ecology Knowledge

I. Energy
- A) Changes in energy lead to proportional changes in producer biomass.
- B) All entities depend on sun.
- C) Respiration accounts for the loss of energy as it flows through trophic levels. (Loss of energy results in an inverse relationship between biomass and trophic level.)

II. Trophic levels
- A1) In EDM, a trophic pyramid always results.
- A2) Trophic levels are inversely related to biomass.
- A3) The biomass of a trophic level entity and the direction of change is a function of the difference in relative birth and death rates.
- B1) Population growth responses at higher trophic levels display a time lag.
- B2) At the intermediate population level of the trophic pyramid, growth is a function of components, individually as well as collectively.
- C1) Growth rate changes from above down through the levels are dampened.
- C2) Dampened growth changes are due to the inverse relation between biomass and trophic level.

III. Predator/prey dynamics
- A1) Prey increases births of predator as a function of its biomass.
- A2) Predation, a density-dependent phenomenon, from one trophic level increases death at the next lower level as a function of its biomass.
- A3) The degree of oscillation of the growth rate of prey is a function of starting biomass of the predator.
- A4) Rate of predation depends on the quantity of prey and quantity of predator.
- B1) Time lag is due to bioaccumulation of prey by predator.
- B2) Predation lowers prey carrying capacity to a set level
- B3) The set level of carrying capacity can be independent of starting predator biomass.
- B4) The further from carrying capacity the biomass of the predator, the greater the oscillation.
- B5) Relatively low predator values result in the prey overshooting its carrying capacity.
- B6) Increase in prey leads to temporary increase in predator.
- B7) When carrying capacity is overshot, predator and prey are inversely proportional.
- B8) One predator can win.

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Table 2—Continued

	C1)	In a predator system, large oscillation is due to the effects of instability and growth effects of temporary escape of predation.
	C2)	Effect of the rate of change of growth of lowest prey entity on predator is dampened in severity up trophic levels.
	C3)	At a given sunlight, predated sunfish always reach same carrying capacity values.
IV.	Carrying Capacity	
	A1)	Sun and predation lead to pond life carrying capacity.
	A2)	In EDM, all entities eventually stabilize to carrying capacity.
	A3)	Each trophic level entity has a carrying capacity.
	B1)	The time to reach carrying capacity is a function of starting biomass and energy input.
	B2)	In a simple pond life-sun system, pond life carrying capacity is determined by sunlight.
	B3)	Carrying capacity happens as an entity uses up resources.
	B4)	Carrying capacity can be overshot.
	C)	Carrying capacity is ultimately due to available energy and nutrients available from 'below' and, if present, modified by predation from 'above.'
V.	Systems behavior	
causality:		
	A1)	Direct cause occurs here.
	A2)	Linear cause occurs here (Proportional changes lead to proportional results.)
	B1)	Indirect cause occurs here.
	B2)	Dual cause occurs here.
	C1)	Multiple cause exists.
self-stabilization:		
	C2) Cycles of cause and effect can be paired.	
VI.	Competition	
	A1)	Intraspecific competition is density dependent.
	A2)	Interspecific competition is density dependent.
	A3)	Intraspecific competition is a function of death rate times the entity's biomass.
	B1)	Intraspecific competition slows the rate of population growth/decrease (by affecting birth and death).
	B2)	Competition coefficients for one competitor are just a function of the biomass of the other.

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Table 2—Continued

	C1)	Competitors can behave jointly as a single predator, but day-to-day values and results of birth and death rates are different. (At any given time, effects of two competing predators is directly proportional to their cumulative biomass.)
	C2)	Interspecific competitors appear to respond to one another through the level of their shared prey.
VII.	Population growth	
	A1)	Reproduction increases a population.
	A2)	Pond life depends on radiant energy.
	B)	Reproductive rate (r) is an intrinsic property of an entity which is modified by density-dependent factors.
	C)	Reproductive rate is a function of birth rate times the population size of the entity, times the population size of any predator.

Participant Content Knowledge

Next, an example will be given from transcript analysis, to be read with the code standardizing analysis, showing the thoughts which indicate content knowledge and meaningful moves. This provides a clear description of how excerpts from students' transcripts will be presented as evidence for statements. For example, Pat used gar. Her utterance at that time was "...bass population is going to go…level out…minimize this a peak…probably need up to maybe 23ish as the same as the gar...," which translates to "bass population is going to go up to maybe 23ish same as gar." This statement is scored as a use of procedural knowledge (move 10) in which Pat predicted carrying capacity levels of bass and gar (high-level content knowledge of competitors C1—high-level because it connects a definition of carrying capacity (level out) to process of competition

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(bass and gar being competitors for the same food) to be equal and ran a confirming experiment.[1]

This coding explanation provided evidence for how low-, middle-, and high-level concept statements were inferred from students' remarks. Theoretical statements were found in Table 2 and Figure 8, and examples are found in the text of Chapter IV.

Substance of Participant Content Knowledge

As Figures 10–13 show, the frequencies of content knowledge statements across all students were as follows: energy exchange was described four times at the low level, trophic relationships four times, predator/prey dynamics one time, carrying capacity levels three times, systems behavior five times, competitive relationships one time, and population growth one time. Energy exchange was described three times at the middle level, trophic relationships one time, carrying capacity levels two times, and systems behavior one time. Predator/prey dynamics were described two times at the high level, carrying capacity one time, and competitive relationships one time. Below are the statements made by the selected participants.

As in a lecture before a class, where a teacher would oscillate between low-, middle-, and high-level concepts in an hour, students seemed to oscillate between the content categories. At some times, high-level knowledge is possible, and then at others the same student will move to a low level, and perhaps up again.

[1]Critical words are in *italics*. Researcher's interpretations/explanations are in [square brackets]. "Level out [is a verb phrase that states that systems reach carrying capacity.] Minimize [calibration] this [this undefined references to—not relevant to analysis] the peak [is in the diagram, Figure 7 of 2500 kg] probably [speculation] need [to add, important to hypothetical future run.].

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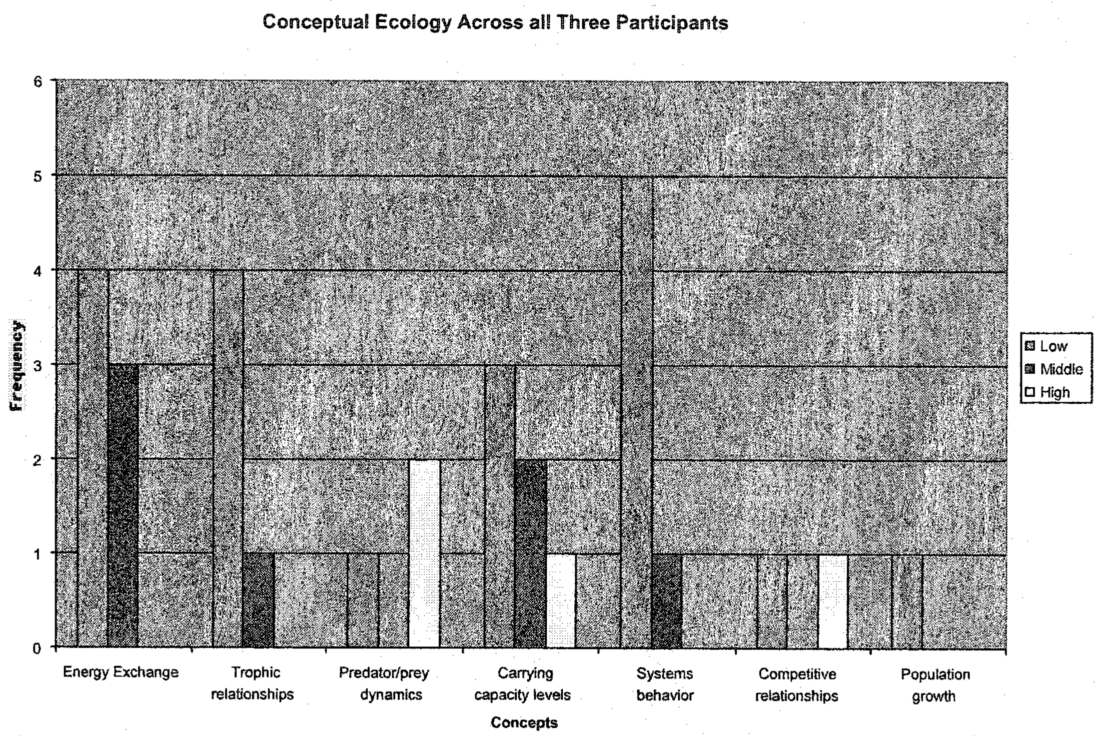

Figure 10. Conceptual Knowledge Across All Three Participants.

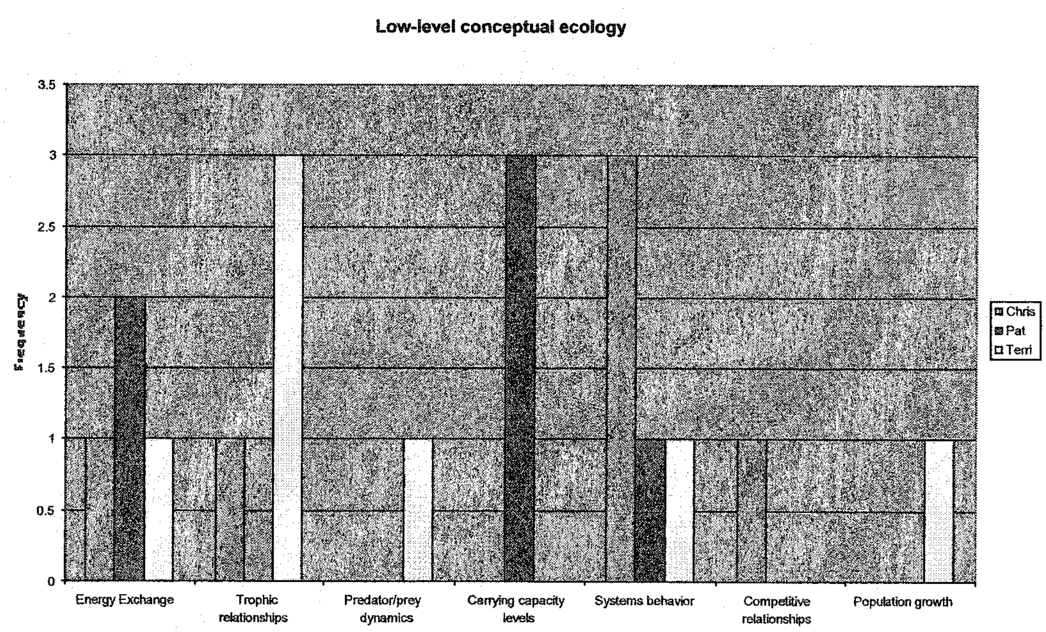

Figure 11. Low-Level Conceptual Knowledge.

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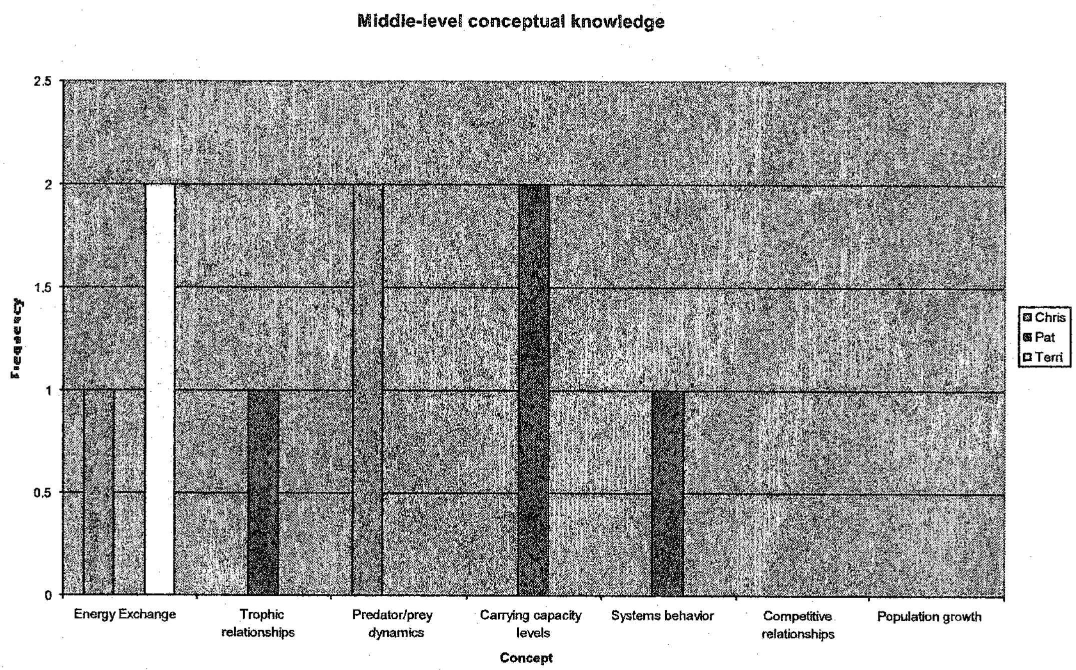

Figure 12. Middle-Level Conceptual Knowledge.

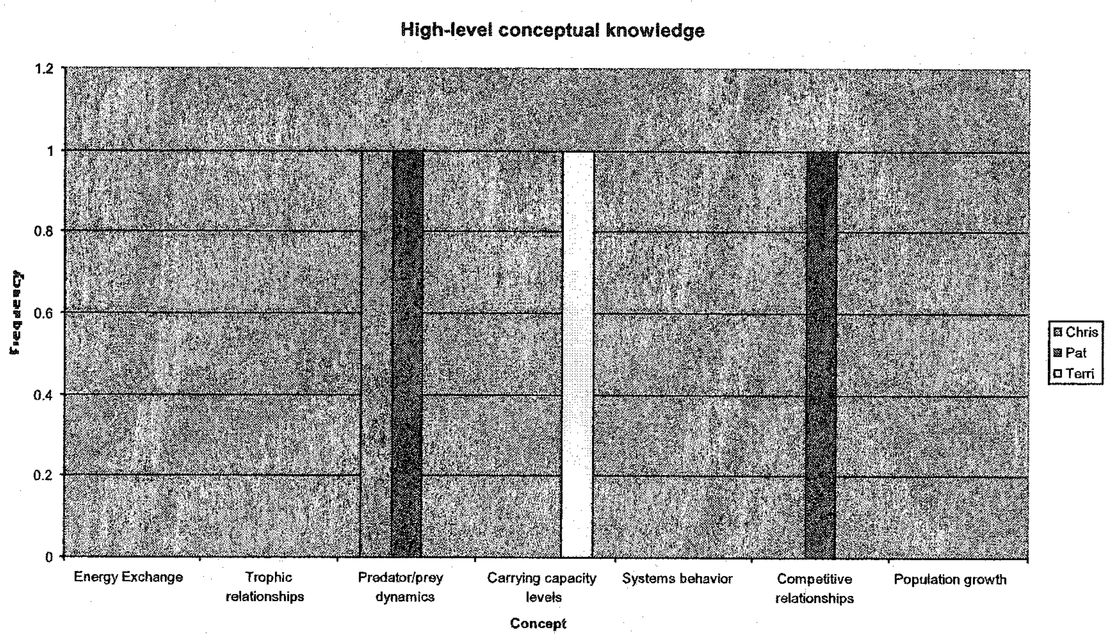

Figure 13. High-Level Conceptual Knowledge.

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Energy Exchange. Chris' statement relating to energy exchange: low-level: "they *have less threat of being consumed* [eaten] *by predators...*"

Pat's statements relating to energy exchange: low-level: (a) "no matter what...*starting* [value] *point is* for pond life...*sunlight* [energy]...*make*[s] *it be a certain amount"*; (b) "*plant* [pond] *life is getting sufficient...sun*...keep a steady graph."

Terri's statements relating to energy exchange: low-level: *"sunlight* [pond life depends] *support less...should keep decreasing* [from lack of sun]"

Chris' statement relating to energy exchange: middle-level: "*sunfish*[carrying capacity]...that's *not going to change because it's dependent* [for energy] *on the sun*"

Terri's statements relating to energy exchange: middle-level: (a) *"3000* [sun energy] *probably has a direct relationship...so...*[sunfish] *won't be higher than* [proportional] *450"*; (b) *"sunlight...*[in] *direct effect on* the *steady state of...sunfish even though pond life stays...same"*; (c) *"sunlight...does dictate...*[equillibrium] *in the* [food] *chain."*

Pat's statement relating to energy exchange: high-level: "[the] *system* [with sun] *can support* [maintain] *a certain amount of a predator* [growth]."

Trophic Relationships. Chris' statement relating to trophic relationships: low-level: "*sunfish* [are consistently] *being consumed by predators*"

Terri's statements relating to trophic relationships: low-level: (a) *"one* is *better* at *catching* [trophic relationship] *sunfish...two* [bass and gar] *at 25 which is still 50* [total], *that the steady state* [steady equillibrium] *will still equal 38* [prediction]"; (b) *"both* [bass and gar] *shared equally on* [eating] *sunfish*"; (c) *"pond life not...huge increase due to the* [one level away] *sunfish...predated on* [by bass two levels away]."

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Pat's statement relating to trophic relationships: middle-level: *"sunfish* [food] *probably about half* [proportional] *the weight of* the *bass* [eater]"

Predator/prey Dynamics. Terri's statements relating to predator/prey dynamics: low-level: *"more sunfish* [predator] *lead to less pond life*[prey] *due to predation"* and "[sunfish predator] *crash...because* it might *not* be *enough* [dependence on prey] *pond life."*

Chris' statements relating to predator/prey dynamics: middle-level: (a) *"pond life...increase half* [direct proportion] *as high...because of the* [predator] *sunfish"*; (b) "[sunfish] *only grow to an amount it's allowed* [carrying capacity]*...given that amount* of *pond life* [prey]*."*

Chris' statement relating to predator/prey dynamics: high-level: "*change... gar...don't think* [prediction] *it will decrease the* [impervious] *sunfish"*

Pat's statement relating to predator/prey dynamics: high-level: "its *death is by the bass* [predator from above]…and…*life is by the pond* [growth from below] population"

Carrying Capacity Levels. Pat's statements relating to carrying capacity levels: low-level: (a) *"pond life is getting sufficient...sun* [causes] *to...keep a steady* [carrying capacity] *graph"*; (b) *"no matter...starting point...for pond life, the sunlight...make it* [causes] be a *certain amount* [carrying capacity]*"*; (c) *"pond life is going to grow until* [carrying capacity] *it doesn't have any more resources."*

Pat's statements relating to carrying capacity levels: middle-level: (a) *"no matter what...pond life...in turn...sunfish...bass and gar...eventually it's going to level out* [carrying capacity] *and keep* a *steady population*[s]"; (b) "*sunlight isn't the determining*

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factor [in carrying capacity] *as much as the fish mixed with the sunlight* [determined by energy plus predator]."

Terri's statement relating to carrying capacity levels: high-level: *"when sunfish* [predator] *are present, pulls* the *pond life* [prey] *down to an* [carrying capacity] *equilibrium."*

Systems Behavior. Chris' statements relating to systems behavior: low-level: (a) "*since* [if] *there are more predators feeding on it* [then].*it's going to* [direct cause] *decrease*"; (b) *"less pond life for the sunfish…less sunfish, and that means…less sunfish for the bass* [linear cause] *and gar"*; (c) *"does delay the increase of the* [time lag] *population curve."*

Pat's statement relating to systems behavior: low-level: *"change…plant life to 40…should make* [direct cause]…*sunfish go higher."*

Terri's statement relating to systems behavior: low-level: *"more sunfish…pull* [paired cycles] *pond life* [population] *down"*

Pat's statement relating to systems behavior: middle-level: *"plants build up a big population then* [time lag] *the sunfish also goes up"*

Competitive Relationships. Chris' statement relating to competitive relationships was low-level: *"with one less predator…*we'll [prediction] *see a larger increase in the sunfish."* Chris' statement is low-level because it gives a definition of predator-prey dynamics.

Pat's statement relating to competitive relationships was high-level: *"bass and gar* [competitors] *both eat the same* [competition coefficients equal] *amount of sunfish."*

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Pat's statement is high-level because she connected the process of predation to mathematical probability. Statements such as these helped refine the categories.

Population Growth. Terri's statement relating to population growth: low-level: *"reproduce…come back up* [populations grow]*…bass were able to survive…leveled out"*

Figure 10 shows the collective conceptual knowledge used by all three participants. This is all the conceptual knowledge used in the following comparisons, which reveals strengths and weaknesses in the knowledge base. For example, carrying capacity knowledge is strong in the sense that it is used at low-, middle- and high-levels, whereas population growth is only used at the low-level.

Next, the content knowledge used by individual students is shown. This knowledge is a subset of all expert knowledge available in the simulation. As described below, Figures 10–13 show the conceptual knowledge at different levels of complexity/depth. Chapter III named the seven categories used in content analysis: energy exchange, trophic relationships, predator/prey dynamics, carrying capacity levels, systems behavior, competitive relationships, and population growth. Again, low, middle- and high-level knowledge is possible, involving definitions, connections to processes, and relations between definitions and processes, respectively. Following the examples, an analysis of what participants' statements meant is shown.

Figures 11, 12, and 13 show the conceptual knowledge at different levels of description of predator population sizes as corresponding to prey population sizes. Low-level knowledge was common. Chris' statement: "*with one less predator we'll* [prediction] *see a larger increase in the sunfish*" is low-level because it gives a definition of competition between predators. Pat's statement relating to energy exchange was low-

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level: "*the system with sun can support* [maintain] *a certain amount of predator* [growth]." Pat's statement is low-level because she defined the effect of sunlight energy. Statements such as these helped refine the categories.

Middle-level knowledge was less common, but still prevalent. Chris used the statement: "*sunfish* [carrying capacity]*…that's not going to change because it's dependent* [for energy] *on the sun*" to show a middle-level statement because she connected the definition of sun as an energy source to sun as the ultimate determiner of carrying capacity. Pat used the statement: "*sunlight isn't the determining factor* [in carrying capacity] *as much as the fish mixed with the sunlight* [determined by energy plus predator]" to show a middle-level statement because she connected the definition of carrying capacity among one population to that of another. Statements such as these showed the diversity in the categories.

High-level knowledge was uncommon as evidenced by the lack of activity in Figure 13. As an example of a higher-level conceptual ecology statement, Chris said "*change…gar…don't think* [prediction] *it will decrease the* [impervious] *sunfish*" because she connected the process of population growth to the complex process of system equilibrium. Pat used the following statement to show a high-level knowledge because she also connected the process of population growth to the complex process of system equilibrium. She stated: "[the] *system* [with sun] *can support* [maintain] *a certain amount of a predator* [growth]." Statements such as these were distinctly high-level statements because they connected definitions to complex processes.

How the participants' content knowledge compared to the expert analysis list (the expert knowledge) is revealed by the open areas in Figure 10. Figure 10 shows much

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more open space than would the expert list, which would have no open spaces. The students described only a portion of all possible content knowledge, with the greatest overall frequency in systems thinking at the low level, energy exchange at the middle level, and predator/prey dynamics at the high level. This correlates to the number of possible statements in each category from expert analysis. All categories were used at the low level. Predator/prey dynamics, competitive relationships, and population growth were not used at the middle level. Energy exchange, trophic relationships, systems behavior, and population growth were not described at the high level. Not surprisingly, it appears that participants were better at using low- and middle-level knowledge than high-level knowledge. Also not surprising, the participants only used a subset of all possible knowledge revealed in the expert's knowledge. In other words, the content knowledge of participants is smaller than the list resulting from expert analysis.

A general model of content knowledge is not possible for this group. However, the above patterns emerge upon inspection of all data: low-level knowledge is used frequently, middle-level knowledge is used less frequently, and high-level knowledge is used rarely. Because it shows the knowledge students used, the collective description of the three selected participants in Figure 10 is a beginning toward a general model.

Procedural Knowledge

In this section, procedural knowledge, including moves and heuristics, are described. Meaningful moves are runs of the simulation which contain content knowledge. Heuristics are the rules of thumb for how to proceed through problems. Expert knowledge was revealed by expert analysis, running through all possible problem

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types and listing the content knowledge and heuristics available, and corroborating with local experts.

Expert Analysis of Procedural Knowledge in EDM

Expert analysis of procedural knowledge in EDM revealed the procedural knowledge available in the simulation. As elaborated below, the moves (Table 1) and heuristics (Table 3) resulting from expert analysis were pursued, in part, by the students. Meaningful moves are those which reveal knowledge, as discovered by expert analysis. Because of the exhaustive number of runs, this is a thorough exposition of expert knowledge, revealed by the author and other writers and local experts. The problems are defined as discussed in Chapter III, and are in appendices. Experts could use the heuristics in the table in general or systems-specific ways, or in specific instances. Some heuristics are called systems-specific heuristics because they are examples of the systems thinking components in Chapter III. Other heuristics are general because they are not examples of systems thinking. For example, "inverse the trophic pyramid…" is a systems-specific heuristic related to emergent properties, while "use written aids" is a general heuristic, unrelated to systems thinking. In combination with the specific instances, the heuristics available are numerous, a total of 33 unique possibilities.

Substance of Procedural Knowledge

No participant pursued all heuristics, but their approaches showed a variety of subsets. The following example involved using equalities in the simulation:

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Table 3

General and Systems-Specific Heuristics and Instances

General and Systems-specific heuristics:

Specific Instances	General Heuristics
Emergent:	
1) Use values that reflect trophic pyramid relationships of decreasing biomass with decreasing levels because they show the stable system.	Decrease biomasses by one decimal place each time. Use realistic proportions in sunfish system. Use realistic proportions in gar system.
2) Inverse the trophic pyramid because you will see the effect [test thresholds].	Change pond, sunfish, bass.
Causality:	
3) Keep extra entities out of explanations because it isolates causality to predation from above or competition from either below or at the level of interest.	a) Start problem solving with a smaller loop or process because it reduces possible effects of competition and predation. b) Explain effects using processes, such as nutrient cycling, which change rates of predation and competition c) Add one entity at a time because it isolates causes such as predation and growth. Add an entity in each new problem from sunfish to gar. Start with sunfish. d) Compare intact simulations/change only one system entity at a time because it exposes consistent causes such as predation and competition. e) Remove a system entity because it isolates cause to predation and competition. Remove sun. Remove pond and bass. Remove bass. Remove gar. f) Compare competitive system entities by alternating their presence; it exposes whether their effects are equal. Compare competitive effects of bass and gar.

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Table 3—Continued

Specific Instances	General Heuristics
4) Use known values as fixed points in systems because they will isolate cause such as predation and competition.	Start with carrying capacity. Fix pond. Fix sunfish. Fix bass and gar.
Inside/outside constraints:	
5) Use constant starting values between sub- and full systems because you can compare the effects of competition and predation with and without additional forces. This heuristic is also associated with emergent properties because each additional entity brings new emergent properties.	Compare pond, sunfish, and bass systems. Compare pond, sunfish, bass, and gar systems. Compare sunfish, bass, and gar systems. Compare sunfish and bass systems. Compare sunfish and gar systems.
Self-stabilization:	
6) Use zero starting value because it tests the system for crashing ability.	Make pond zero. Make sunfish zero. Make bass zero. Make bass and gar zero.
7) Try proportional changes in starting values between runs because curves will expose patterns such as linearity in predation and competition.	Change pond. Change pond, sunfish, bass, and gar. Change sunfish. Change sunfish and bass. Change sunfish and gar. Change bass.
8) Try extremes beyond ecosystem thresholds because they will test effects of births and deaths due to predation and competition.	Extreme values are tried when the entities were given values one order of ten or more away from meaningful values. Try extreme sun. Try extreme pond. Try non-meaningful sun values.
9) Run several (3 or more) simulations holding all entities constant except one because it will allow one to confirm hypotheses.	

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Table 3—Continued

Specific Instances	General Heuristics
10) Explore full ranges (low, middle, high) of an ecosystem's meaningful energy input values because it allows one to see the effects of changing locations on death and growth.	
11) Look at small segments of time because effects may be only visible there.	
12) Use written aids.	a) Write equations to find patterns of predation and reproduction in data. b) Write data for future comparisons because you can compare to similar situations. c) Make a chart to compare values because it exposes patterns. d) Use abbreviations because it will simplify explanations. e) Draw diagrams to represent multiple causes because they simplify things.

Chris used equal starting values of competing predators, allowing testing of their equality. She also used equalities in other starting values, allowing testing for equal effects.

Meaningful Moves

All seven students' meaningful moves are displayed to illustrate the selection of three students for case study in this dissertation. Hereafter, only the three selected students will be discussed in detail.

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Table 4 displays results of analysis of meaningful moves posed by all seven participants. In the table, level of engagement 1 refers to the participant (Terri) who explored the smallest subset of meaningful moves, only 6.25% in explore and constrained (preposed problem) tasks. Level of engagement 6 refers to the participant who explored the largest subset. In the example of Pat, a moderate amount of the problems was explored: she posed problems 11, 12, and 10.

Table 4

Problems Participants Posed During the Explore and Constrained Tasks as a Subset of the Set of Meaningful Moves

Participant #	Explore	Constrained	Level of Engagement
Annie	25%	6.25%	3
Ben	12.5%	0%	2
Chris	43.75%	31.25%	6
Pat	18.75%	12.5%	4
Pete	12.5%	18.75%	4
Mike	18.75%	25%	5
Terri	6.25%	6.25%	1

The three most interesting participants for the purposes of presenting results to question 1 were Chris, Pat and Terri. The level of engagement of the collective data shows that the most thorough problem solver was Chris. The least thorough problem solver was Terri. Although Pat was in the middle levels of engagement (4), she was very thorough in the use of conceptual and procedural knowledge (see Figures 11–13, 19).

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Chris explored the greatest part of the meaningful move set in both sets of problems. Pat consistently explored a greater part of the meaningful move set than Terri, in both sets of problems. This consistency within individual participants' performances may indicate each individual participant's satisfaction with completing problem solving: each is satisfied at a consistent rate in both sets of problems.

Moves are divided into starting values—high, middle, and low. Unrealistic values are defined as values which are not possible in the real world, for example 10,000 kilocalories of sunlight. Although noted and distinguished as unrealistic values, these values were also considered either high or low values, depending upon whether they were above or below carrying capacity. Figure 14 shows the three selected students with moves.

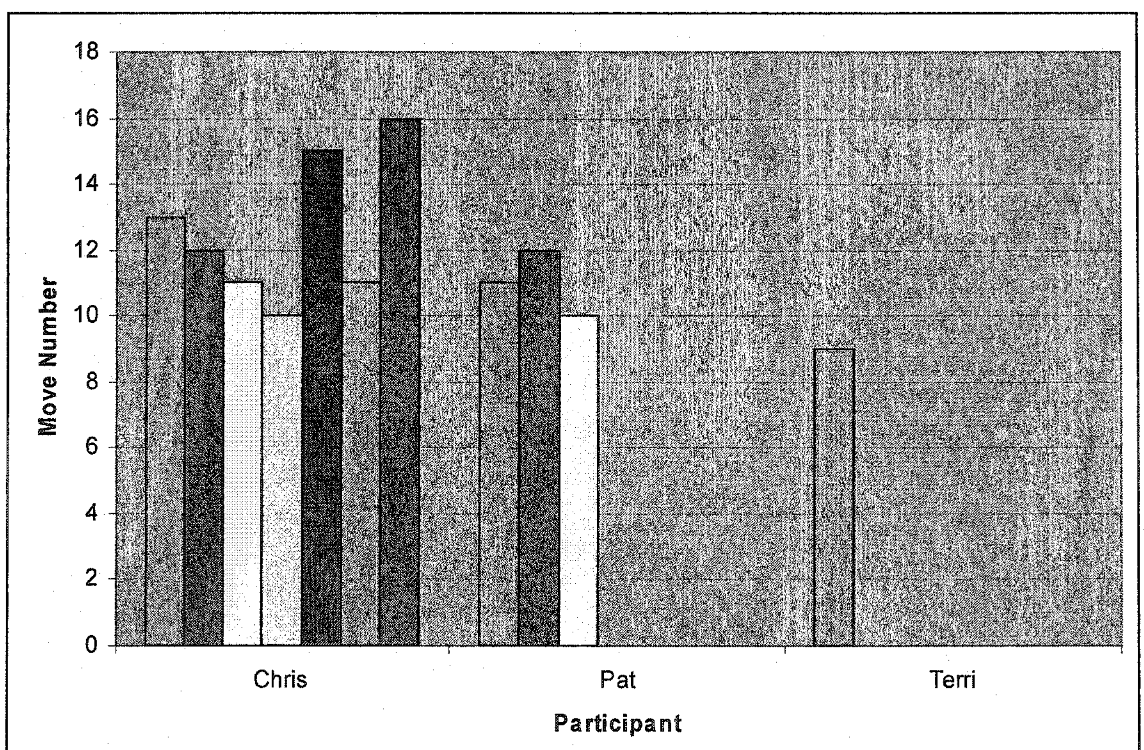

Figure 14. Moves of Chris, Pat, and Terri.

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Middle values were defined as equal to ultimate carrying capacity values, and low and high values were above and below carrying capacity respectively. In order, Chris pursued moves 13, 12, 11, 10, 15, 11 (repeated), and 16 (a total of 6).

Starting values of first runs for Chris:

1. 13: 4200 kcalories sunlight, 10 kg/hectare pond life, 20 kg/hectare sunfish, 20 kg/hectare bass, 10 kg/hectare gar -->5700 kg/ha pond life, 100 kg/hectare sunfish, 30 kg/hectare bass, 6 kg/hectare gar, 950 days; *"leave...10,change* that *to...20."*
2. 12: 2000 kcalories sunlight, 10 kg/hectare pond life, 40 kg/hectare sunfish, 0 kg/hectare bass, 20 kg/hectare gar -->3021 kg/hectare pond life, 100 kg/hectare sunfish, 0 kg/hectare bass, 0.02 kg/hectare gar, 2535 days; *"sunlight...2500."*
3. 11: 2000 kcalories sunlight, 10 kg/hectare pond life, 40 kg/hectare sunfish, 10 kg/hectare bass, 10 kg/hectare gar -->3000 kg/hectare pond life, 100 kg/hectare sunfish, 0.01 kg/hectare bass, 0.01 kg/hectare gar, 1440 days; *"sunlight...2000?"*
4. 10: 2000 kcalories sunlight, 0 kg/hectare pond life, 40 kg/hectare sunfish, 0 kg/hectare bass, 20 kg/hectare gar -->0 kg/hectare pond life, 0 kg/hectare sunfish, 0 kg/hectare bass, 0 kg/hectare gar, 0 days; *"eliminate* the *pond life."*
5. 15: 2000 kcalories sunlight, 10 kg/hectare pond life, 40 kg/hectare sunfish, 10 kg/hectare bass, 20 kg/hectare gar -->3036 kg/hectare pond life, 98.7 kg/hectare sunfish, 0.36 kg/hectare bass, 0 kg/hectare gar, 2978 days; *"put it* [pond life] *back eliminating gar."*

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6. 11: 2000 kcalories sunlight, 10 kg/hectare pond life, 1 kg/hectare sunfish, 10 kg/hectare bass, 20 kg/hectare gar -->3001 kg/hectare pond life, 105.7 kg/hectare sunfish, 0 kg/hectare bass, 0 kg/hectare gar, 2847 days; *"sunfish…1."*
7. 16: 2000 kcalories sunlight, 10 kg/hectare pond life, 10 kg/hectare sunfish, 10 kg/hectare bass, 10 kg/hectare gar -->3010 kg/hectare pond life, 103 kg/hectare sunfish, 0.04 kg/hectare bass, 0.04 kg/hectare gar, 2211 days; *"run everything at 10."*

Some of the starting values in the runs were unrealistic, including at least one starting value that was at least one order of ten different from carrying capacity value. Pat pursued moves 11, 12, and 10 (a total of 3).

Starting values of first runs for Pat:

1. 11: 3000 kcalories sunlight, 10 kg/hectare pond life, 66 kg/hectare sunfish, 100, 100 kg/hectare gar -->4545 kg/hectare pond life, 100 kg/hectare sunfish, 7.72 kg/hectare bass, 7.72 kg/hectare gar, 3329 days; *"double that to 40…plant life."*
2. 12: 3500 kcalories sunlight, 40 kg/hectare pond life, 100 kg/hectare sunfish, 100 kg/hectare bass , 100 kg/hectare gar -->5303 kg/hectare pond life, 100 kg/hectare sunfish, 11.51 kg/hectare bass, 11.51 kg/hectare gar, 2604 days; *"sunlight to…3500."*
3. 10: 2500 kcalories sunlight, 1000 kg/hectare pond life, 100 kg/hectare sunfish, 10 kg/hectare bass, 10 kg/hectare gar -->3787.9 kg/hectare pond life, 100

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kg/hectare sunfish, 3.94 kg/hectare bass, 3.94 kg/hectare gar, 3220 days; *"sunlight...2500."*

Some of the starting values in the runs were unrealistic, including at least one starting value that was at least one order of ten different from carrying capacity value. Terri pursued move 9 only.

Starting values of first runs for Terri:

1. 9: 4500 kcalories sunlight, 3000 kg/hectare pond life, 1500 kg/hectare sunfish, 0 kg/hectare bass, 50 kg/hectare gar -->6818 kg/hectare pond life, 100 kg/hectare sunfish 0 kg/hectare bass, 38.18 kg/hectare gar, 1601 days; *"how about the gar at 50."*

Some of the starting values in the run were unrealistic, including at least one starting value that was at least one order of ten different from carrying capacity value. A word search performed on all three transcripts found no evidence of utterances regarding the realism of the starting values chosen, so it is not known whether students were choosing unrealistic values intentionally.

Chris pursued the largest subset of the meaningful moves set (problems defined in Table 1, as determined during expert analysis). This participant pursued moves 1, 2, and 4, 5 in order. This movement allowed Chris to explore heuristics and conceptual knowledge related to the problem solving, which are specifically detailed below.

Meaningful moves are made within posed problems. Participants made many moves that were not among the meaningful set. This type of exploration is more random and "hit or miss" but is its own heuristic of sorts (Nickles, 1987). The majority of participants, five, explored only the gar problem.

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Some participants appeared to have no pattern of search. However, all three selected participants had a pattern, and others will not be followed or developed into a case for this document. Some participants searched a subset of the idealized pattern. Chris explored problems 13, 12, 11, and 10 in reverse-consecutive order, thus showing some thorough approach pattern (above text and Table 1). This was thorough, because the moves were relatively exhaustive, and pursued in order.

Students used different moves for different reasons, which later revealed content knowledge. For example, move 12 by Pat allowed effects of competing predators to be revealed. Move 9, used by Terri, allowed definition of interspecific competition. (Also see Table 1.)

Chris' exploration of the largest set of meaningful moves was useful because it allowed the opportunity for more content knowledge. However, this opportunity was squandered, and Chris may have done well with a more structured, goal-oriented approach. Pat did well without exploring a larger set of meaningful moves or having a more structured, goal-oriented approach, so students may respond differently.

A general model of procedural knowledge is not possible given this data. However, the sets of heuristics resulting from the idealized pattern and used by the participants display the wide variety of possibilities. Expert analysis provides an ideal model of performance: if a participant were to use all the knowledge revealed by expert analysis, they would be solving ideally. The following aspects of knowledge are part of the problem-solving observed:

1. Levels. The ideal problem solver looks like the solver that would use all 16 problems from expert analysis.

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2. Moves. Moves are within problems explored.

3. Systems thinking. Systems thinking is revealed in the procedural heuristics related to causality and self-stabilization.

Number of Runs

As shown in Figure 15, there was variation in the number of runs performed. Chris had 25 runs, Pat had 23 runs, and Terri had 33 runs. In spite of this diversity, Chris and Terri used two and three heuristics respectively, while Pat used 13. This is a large difference between Pat and the others. The reason is unknown.

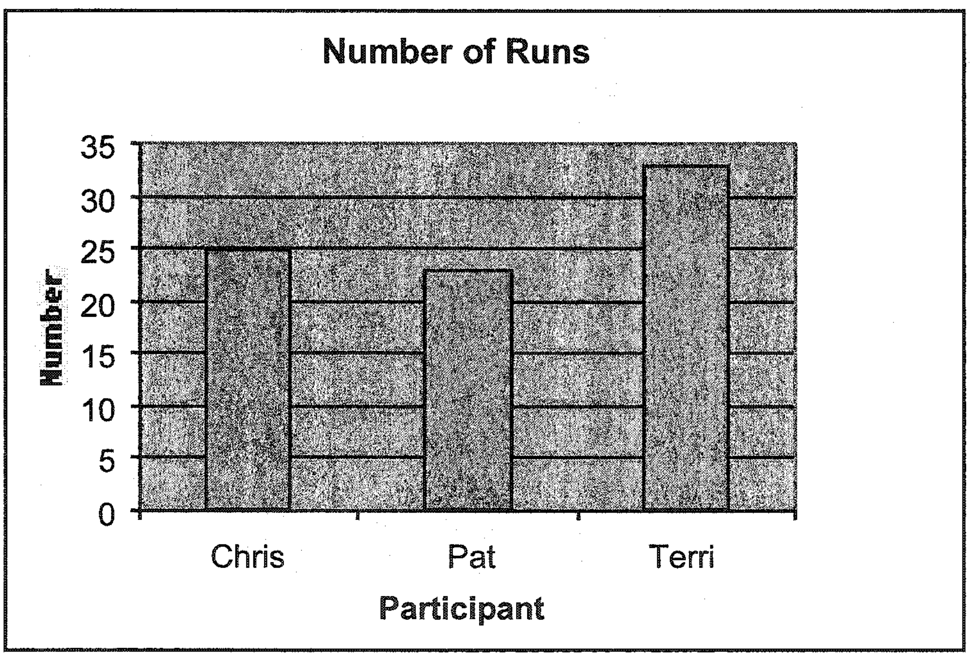

Figure 15. Number of Runs.

Time Spent

There was variation in total time spent for each person. The data collection involved some anecdotal interview questions and additional problems which are not used

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for this study. However, the total problem-solving time comparing the three students is consistent with or without the extra data collection. Figure 16 shows Chris worked for 1.5 hours, Pat worked for 6 hours, and Terri worked for 3 hours. Perhaps because of these time differences, procedural knowledge varied between Pat and the others.

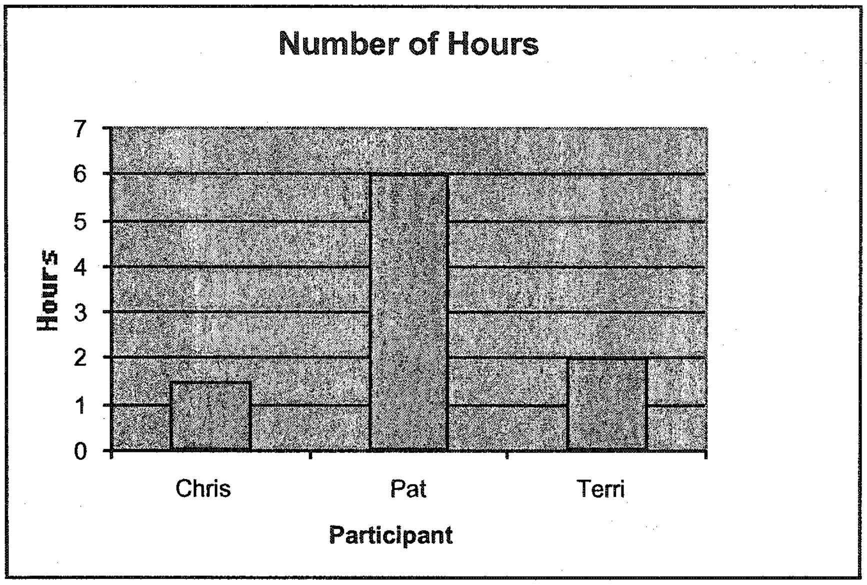

Figure 16. Number of Hours Used.

Number of Sessions

A session with a participant was a maximum of two hours in length. The number of sessions varied for each person, depending upon when felt that they had explored every meaningful move and were satisfied. Figure 17 shows Chris required only one session, Pat required three, and Terri required two.

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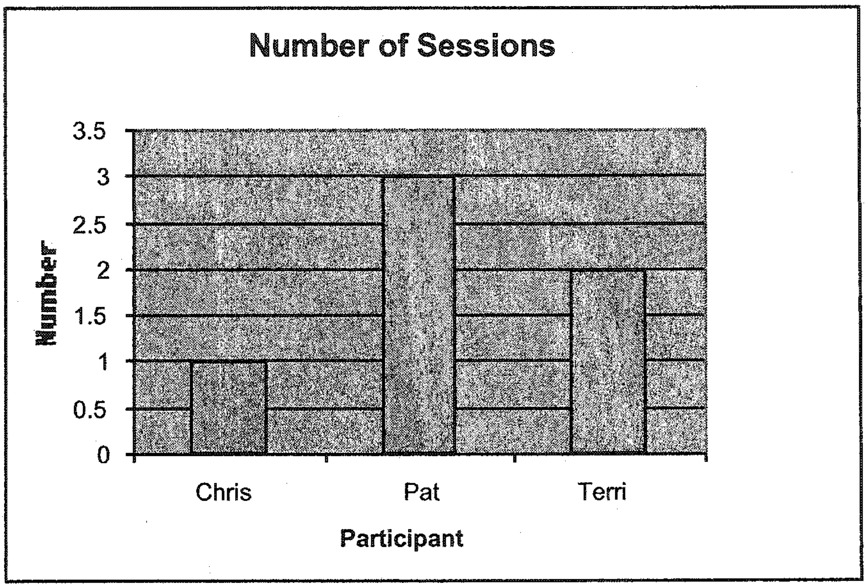

Figure 17. Number of Sessions Used.

Heuristics

In this section there is a discussion of the specific heuristics used by the three selected participants. Heuristics are rules of thumb for how to solve problems. This is an exposition of expert knowledge, revealed by the author and other writers and local experts. The problems are defined as discussed in Chapter III, and are in appendices.

Figure 18 indicates all heuristics used by all participants. This is to give an overview of all possibilities that were explored, before detailing the three selected participants.

The types of heuristic categories (grouped) with frequencies are listed in Table 5. There are written behaviors, behaviors about starting values, behaviors the number of pond components, and behaviors about changing views of graphs.

Chris used one written heuristic and two starting values heuristics. Pat used five written heuristics, five starting values heuristics, two changing number of components

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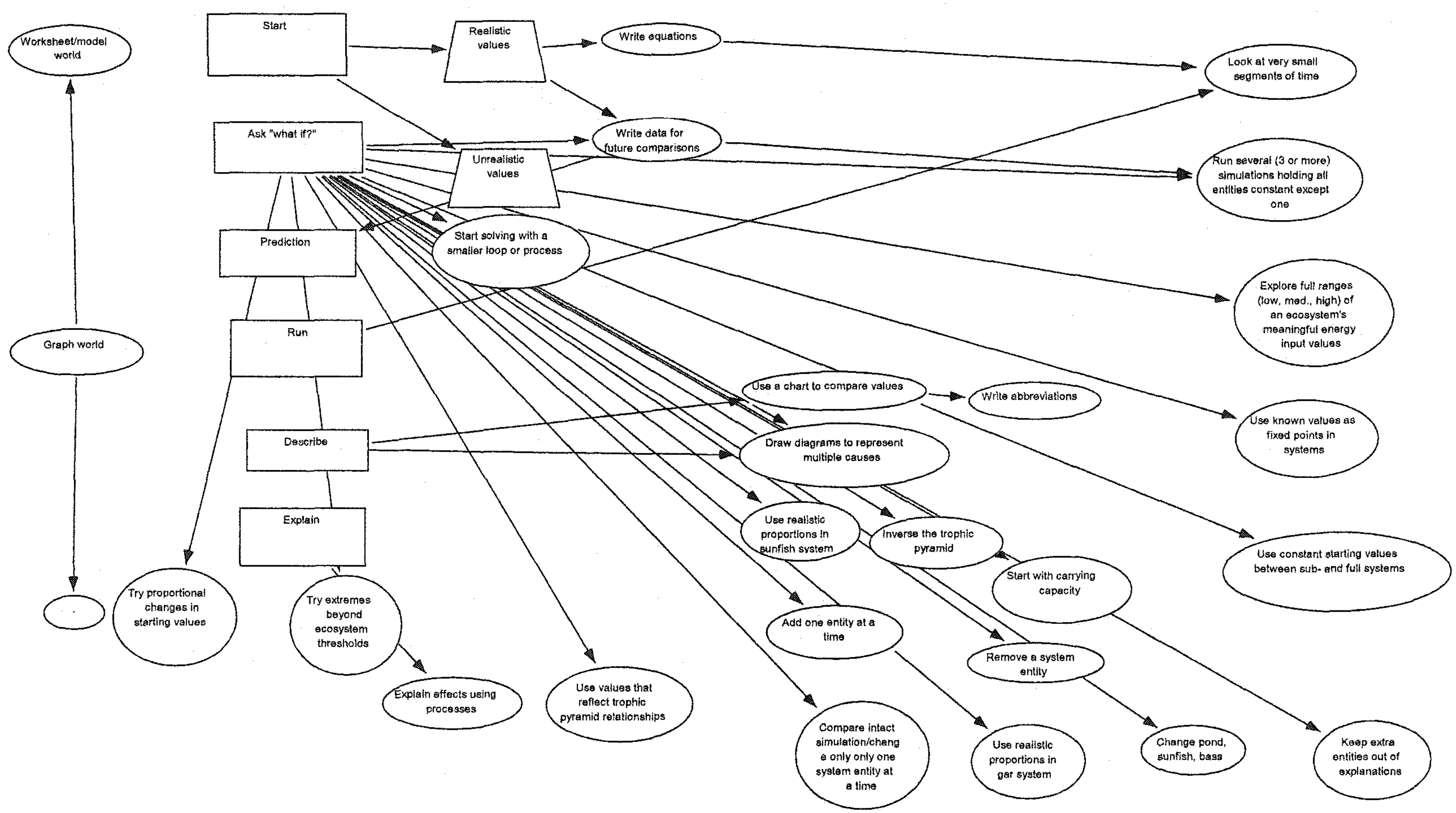

Figure 18. All Heuristics Used by All Participants.

Table 5

Frequencies of Types of Heuristics Used by Selected Participants

	Chris	Pat	Terri
Heuristic type			
Written	1	5	1
Write equations	1	1	1
Write data for future comparisons		1	
Make chart		1	
Use abbreviations		1	
Use diagrams		1	
Starting values	2	5	1
Number of components		2	
Views		1	

heuristics, and one view-changing heuristic. Terri used one written heuristic and one starting values heuristic. Finally, the ways their procedural knowledge compared to expert analysis (the full list of expert knowledge) are shown.

The heuristics used, in order and the meaningful moves associated with the search, are listed by participant in Table 6. Pat used most of the heuristics possible, providing the numbering system below. Pat used numbers 1–13, while Chris added unique heuristics 14–15. Others used a subset of Pat's list.

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Table 6

Heuristics Used by Each Participant

Heuristics	Annie, Moves: 5,12,14,11	Ben, Moves: 11, 12	Chris, Moves: 13, 12, 11, 10, 15, 16	Pat, Moves: 11, 12, 10	Pete, Moves: 10, 12	Mike, Moves: 13, 14, 15	Terri, Moves: 9
1.				X			
2.				X	X		X
3.		X		X		X	
4.	X			X			
5.				X			
6.	X			X	X		
7.				X			
8.				X		X	
9.			X	X			
10.	X			X			
11.				X			
12.				X			
13.	X			X			X
14.							
15.							

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The key to the number of heuristics is as follows:

1. Use values that reflect trophic pyramid relationships. Use realistic proportions.
2. Compare intact simulations/change only one system entity at a time.
3. Remove a system entity.
4. Start with carrying capacity.
5. Use constant starting values between sub- and full systems.
6. Try proportional changes in starting values between runs.
7. Run several (3 or more) simulations holding all entities constant except one.
8. Look at small segments of time.
9. Write equations.
10. Write data for future comparisons.
11. Make a chart to compare values.
12. Use abbreviations.
13. Draw diagrams to represent multiple causes.
14. Look for equalities as starting values to test for equal effects.
15. Try equal amounts of competing predators.

The pattern of heuristics used by all participants (Figure 18), is followed by the subset used by Pat and Terri (Figures 19 and 20). Since Chris and Terri only used one of the heuristics, only one participant, Terri, is pictured. It is easy to see that there were a greater number of uses of heuristics by Pat. Again, Pat had a superior use of knowledge to the students at the highest and lowest levels of engagement. Chris was the participant with superior problem-posing, but it did not translate to superior content knowledge or use of heuristics. In other words, she knew how to ask good questions with the simulation, but not how to get or interpret good answers.

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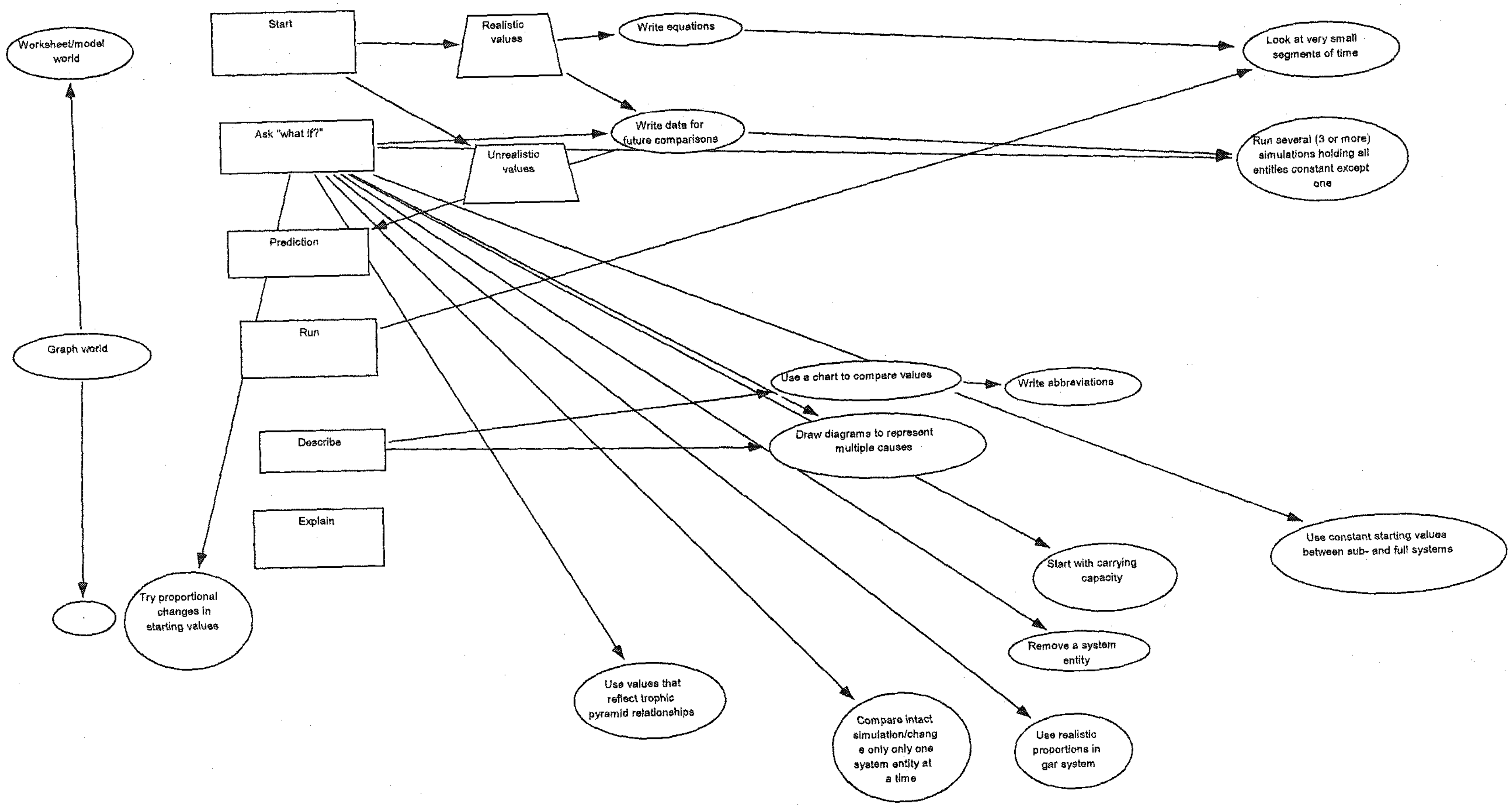

Figure 19. All Heuristics Used by Pat.

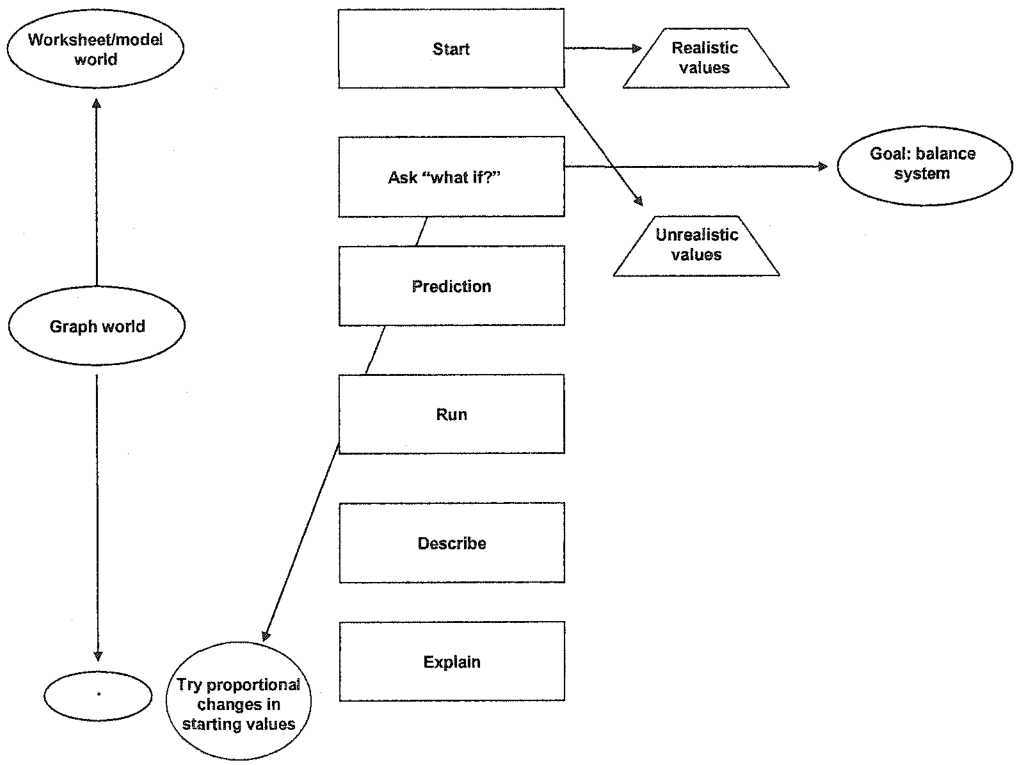

Figure 20. All Heuristics Used by Terri.

Three Selected Participants' Heuristics Used

Here, the specific heuristics used by each of the three selected participants, in order is given. The numbered lists indicate the heuristics used, which are followed by evidence from data analysis which indicate how the heuristic was used. Statements given by participants are examples of the use of the specific heuristic. Figures under statements give the graphs created during the run, when relevant, and written notes given by the participants are [underlined, in brackets]. The data are presented in order of moves.

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Chris' Heuristics Used

Chris used only three heuristics with her seven moves. This indicates that she was one of the less thorough participants, in terms of heuristics.

1. Look for equalities as starting values to test for equal effects. Start with sunfish plus gar system.

> Um, so I'd like to go back just to see a graph just to see what happens [testing hypothesis] and *eliminate the pond life* all together...*there will be nothing* at all. *[Starting values: 2000 kcalories sun, none of pond life, 40 kg/hectare sunfish, none of bass, 20 kg/hectare gar --> 0 kg/hectare pond life, 0 kg/hectare sunfish, 0 kg/hectare bass, 0 kg/hectare gar, 0 days].*

As the quote shows, she was testing for equal effects because she changed pond life to zero, holding other values constant and compared it to the previous problem (see starting values). The equal effects are shown by her statement that it was exactly as she thought.

2. Try equal amounts of competing predators. Fix bass and gar.

> Maybe it'll, it *should increase instantly* [compared with previous problem] [testing hypothesis] as a matter of fact. So [mumble] it looks like that's what [confirming] *it did* (see Figure 21).

The quote and graph illustrate that she held things constant over the previous problem. As seen in the quote, she confirmed that it would increase instantly.

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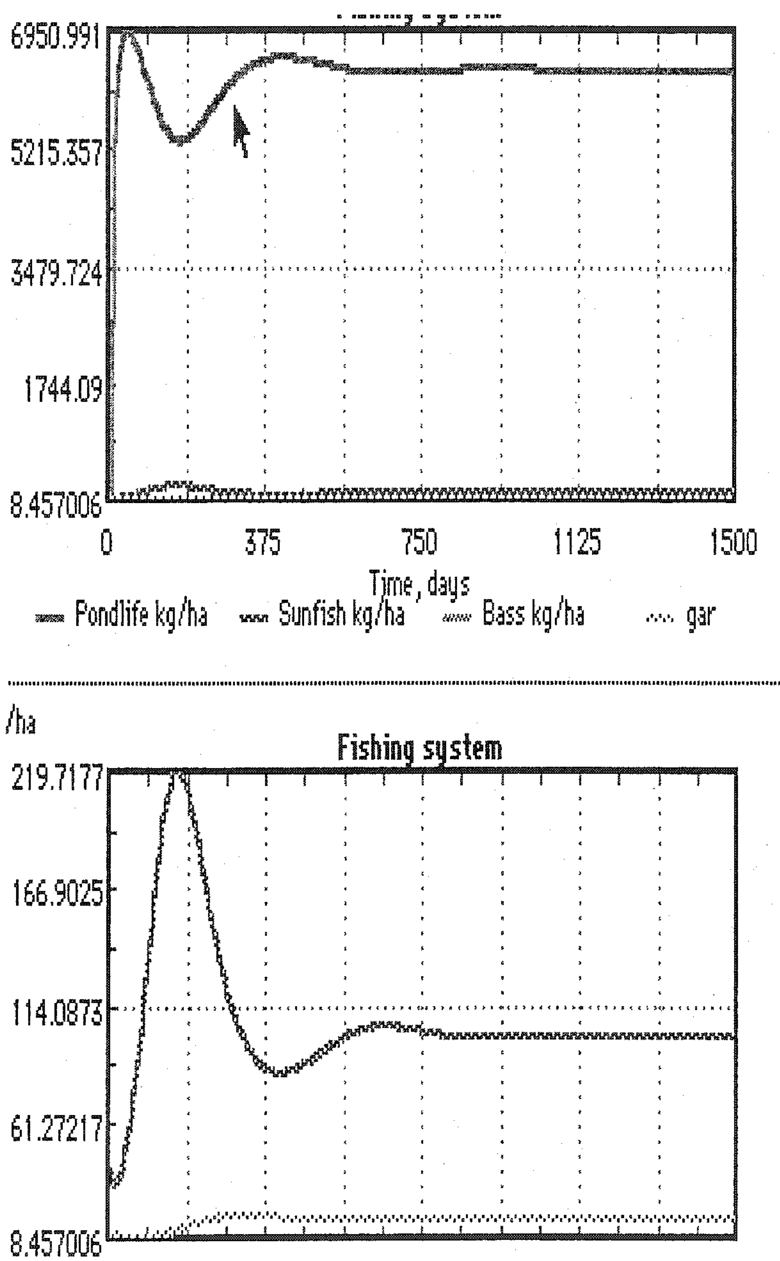

2500, 10, 40, 10, 10--> 5800, 100, 10, 10, 1450.

Figure 21. Chris' Second Problem.

3. Write equations.

The only other thing I could do would be to go back and *change sunlight* to about...2000 and bring the sunfish back up even with the pond life to 10

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and I think [hypothesis] the, it's going to do *exactly the same thing except everything is going* [wrote 105, 90%] Yeah, it's about 105 [confirmed]. Cutting the sunlight in half it cut the pond life in half but it cut the sunfish by like about 90 or 80 percent so way over half.

As the quote and writing illustrate, the heuristic allowed her to keep track of numbers between problems. These were the only three heuristics used by Chris. They allowed her to predict results before running experiments, test interspecific competition to confirm that coefficients vary, and keep track of numbers. This was useful for Chris, but is not equated to relatively good success at exploring meaningful moves or the nine conceptual ecology statements made because she was less successful at these.

Pat's Heuristics Used

Pat's heuristics used were shown in Figure 19. Because she used so many heuristics, she was, by far, the most thorough of all participants.

1. Use values that reflect trophic pyramid relationships. Use realistic proportions in gar system.

I *have pond life at?* [checking hypothesis]

M: *5750.*

S: And then *sunfish* was at?

M: *100.*

S: 100, and bass and the gar [trophically related]...that's *where* they all *leveled out* [equilibrium] at. And that was *minimum to maintain*

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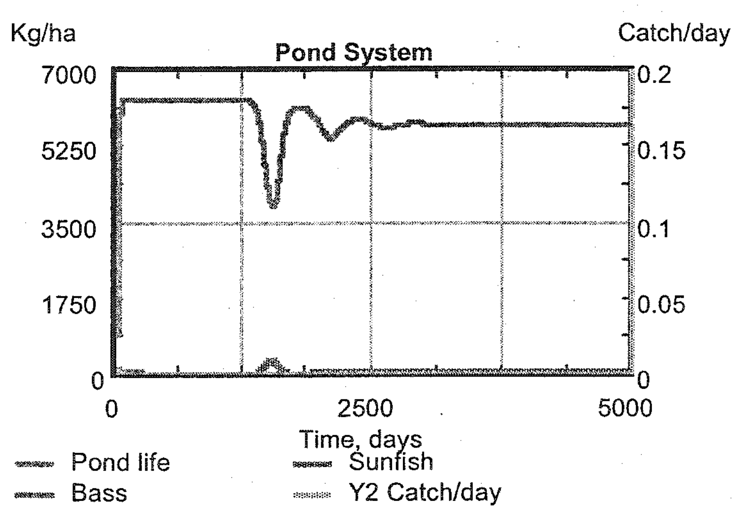
the populations [relative sizes to one another]" (see Figures 22–24).

The quote illustrates that the use of trophic relationships was helpful to Pat because they consist of decreasing biomass with decreasing levels which shows the stable system. This heuristic is emergent because a trophic pyramid is an inherent property observed in biological systems at the ecosystem level.

2. <u>Compare intact simulations/change only one system entity at a time.</u>

"...So the others *should be double* and it should look almost the same [hypothesis] as the others.

Okay, it doesn't look like it changed too much at all. That *didn't do much.*"



3500, 200, 100, 100, 100-->5303, 100, 11.51, 11.51, 3125 days

Figure 22. Pat's First Problem.

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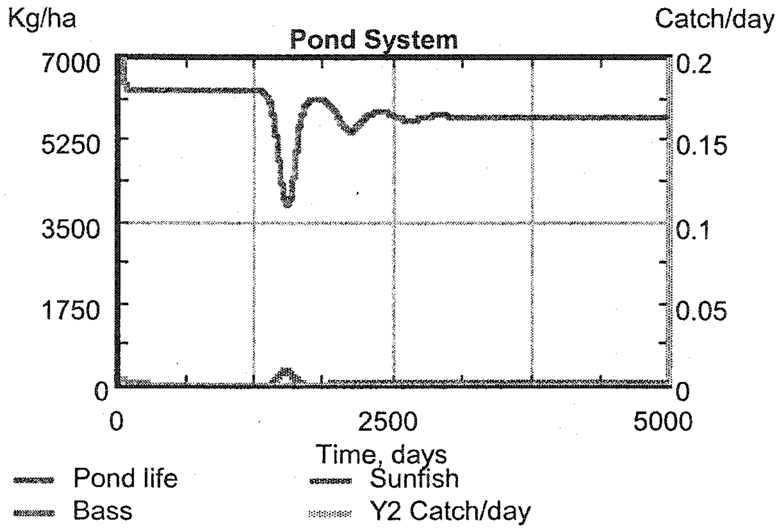
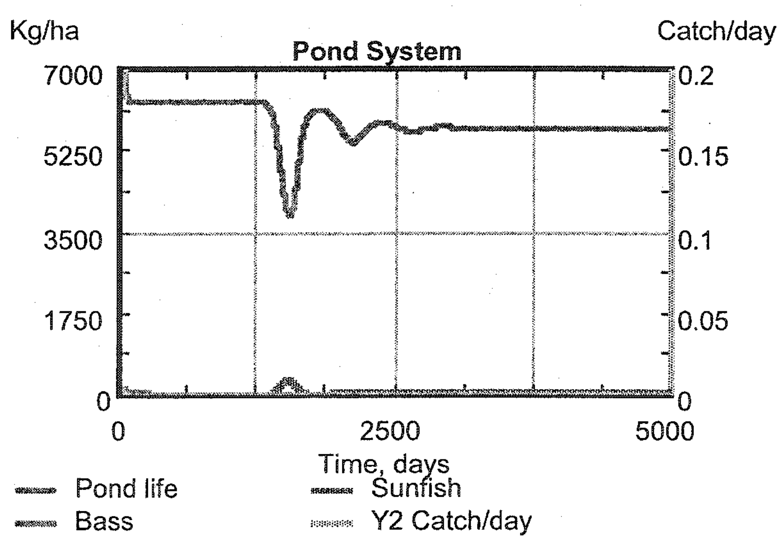


3500, 1000, 100, 100, 100-->5303, 100, 11.51, 11.51, 3072 days

Figure 23. Pat's Second Problem.



3500, 10000, 100, 100, 100-->5302, 100, 11.52, 11.52, 2578 days

Figure 24. Pat's Third Problem.

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"All right. I think that the change was so minimal that it's [changing competitive value] not really going to make a bit of difference [in this case] [new hypothesis]. *Not much change* [mumble]."

As the quote illustrates, this heuristic exposed consistent causes such as predation and competition. This instance of the heuristic was not combined with others.

4. Remove a system entity.

"Well basically what I *want to* try to see is the [perturbations] *fluctuation differences, comparing them*...[competitor and predator to prey]...Because *it's* pretty much *doing the same thing* either way...Okay, so I'm looking at one where the *pond life is going to be 7500* [prediction] and then the other one is going to be 3700."

Pat removed gar. As the quote illustrates, cause was isolated to competition regardless of gar.

5. Start with carrying capacity.

"...Yeah the *bass* [predator] *and the gar* [competitor] *eat, obviously eat equal amount* [fixed points] because their *population change was right on time of each other* with the amount of sunfish present.

[then compares] *It doesn't look any different.* So, basically there's...if I was...giving them that much of an increase didn't change the population of the bass or gar."

As the quote illustrates, used with predators at known values as fixed points was helpful to Pat. She fixed sunfish at carrying capacity values. Pat made a statement

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relating this instance to the fact that carrying capacity is determined by sunlight and competition with others.

6. Use constant starting values between sub- and full systems.

"Okay.

M: Pond life given this much sun.

S: [if] *Pond life given this much sun*, so it sounds like it's [then] *going to have way too much sun* to support the pond life so at first, it's starting at 1,000 it's going to be like, it's going to go way up and then *level off* [equilibrium]...Cause what happens in the beginning really is that it's just quick to balance out since..."

Pat compared pond, sunfish, and bass systems. As the quote illustrates, this heuristic allowed Pat to compare the effects of competition with and without additional forces—here there was too much sun to "support pond life" given the sunfish predator. Constant starting values are related to inside/outside constraints because they allow participants to test the similarity of subsystems that build on one another. This heuristic is also associated with emergent properties because each additional entity in larger and larger systems brings new properties.

7. Try proportional changes in starting values between runs.

"Is about, it goes *way down in the beginning*. [wrote In Mich 3000kcal sun ---> 1/3 plant life. [linear growth]] It looks like they *don't have enough sunfish* to start off with [not near carrying capacity]. The sunfish go way up, okay."

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(+ Transcript from "Compare intact simulations/change only one system entity at a time" above.)

"...So the others *should be double* and it should look almost the same as the others."

Pat changed the value of pond life. As the quote illustrates, she found that the benefit of using this heuristic is that curves expose the pattern of linearity in predation. Proportional changes are related to self-stabilization because they later allowed her to make comparisons of relative stability between runs.

8. Run several (3 or more) simulations holding all entities constant except one.

"All right, let's see, what if we, um, what if we decreased, *increased pond life*, pond life would be, *initially way more* than what it is now, *then* I'm thinking we might get *less* of a little *fluctuation* there [hypothesis] *so* can we *try* just pond life changing to being, what is it now, 40? Make it like *200*. See if it'll. Oh, this one was 10,000."

While Pat did not make relevant statements to running several (3 or more) simulations holding all entities constant except one, she used the heuristic. As the quote illustrates, it allowed her to confirm the hypothesis that increasing pond life would slow fluctuation. The graphs show the first two sets of values used.

9. Look at small segments of time. (Transcript for this problem same as "Use values that reflect trophic pyramid relationships. Use realistic proportions in gar system.")

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Pat took small segments of time into account to compare the segments of the curve, noting its sloping approach to carrying capacity. As the quote illustrates, she noted that ultimately "it levels out."

Writing and drawing were actions Pat utilized extensively. In physics education literature, the use of representations such as writing and drawings has been touted as the mark of the expert (Chi et al., 1988). The writing was associated with nearly every run created. As evidenced by the fact that Pat kept going long after the other participants quit, drawings helped this participant to visualize and further model what the pond was doing.

For example, the following quote came after the above drawing: "...So the others *should be double* and it should look almost the same as the others."

10. Write equations. (Transcript same as "Start with carrying capacity.")

As the quote illustrates, this use of written equations allowed Pat to seek decreases in entities due to predation. The benefit of this heuristic was that writing equations was useful for finding the pattern of predation in data.

11. Write data for future comparisons. (Transcript same as "Try proportional changes in starting values between runs.")

(+ Transcript from "Compare intact simulations/change only one system entity at a time" above.)

As illustrated in the quote, the benefit of this heuristic was that Pat could compare a run to similar situations. She did so in later problem solving (see heuristic 8).

12. Make a chart to compare values.

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[wrote 2x/ 100/ 7500/22] So, if you just do 2 times whatever it is, like if you want…Okay, yeah. So, the *sunfish did go to 100,* [confirmed hypothesis] I got that one right, and *7,500 for the pond life*, 22 yep [trophic pyramid numbers], exactly the same for those two. Okay, so basically *I was right* and that's the same thing as last time...

Pat compared pond life, sunfish, bass, and gar. As the quote illustrates, the benefit of this heuristic was that she exposed trophic patterns in the data of 100, 7500, and 22 in the entities' ending values.

13. Use abbreviations.

...so, now my bass population at that time in the beginning [mumble] [wrote 55/2=5000/200] that's not what I wanted. There we go [confirm hypothesis], *bass was at 55*

As the quote illustrates, Pat wrote abbreviations in this problem. Pat used this heuristic extensively, starting with a gar problem. The benefit of this heuristic is that it simplified her explanations into single-page representations.

14. Draw diagrams to represent multiple causes.

[drew: sun-->pond-->sunfish-->bass-->sunfish-->pond gar-->bass-->gar-->sunfish-->gar]

As the drawing illustrates, the representation is much smaller than one that incorporates data or a worksheet diagram. Pat used these to make small figures throughout. The benefit of this heuristic is that diagrams simplify work (Chi et al., 1981), keeping it all in one place.

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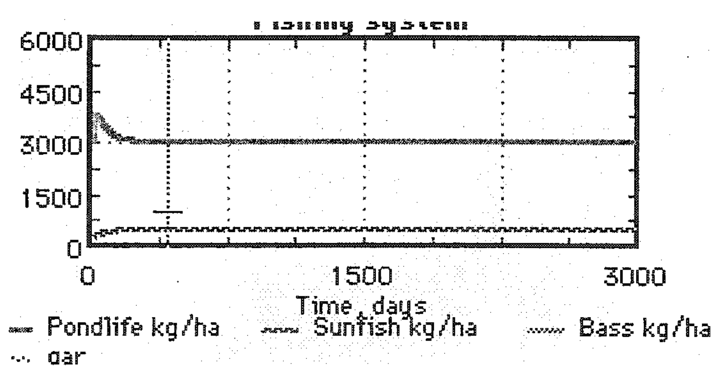
Terri's Heuristics Used.

Terri used only two heuristics in two moves. Figure 20 shows how small a subset this was, compared with Pat.

1. Look for equalities as starting values to test for equal effects. Fix pond.

2. Write equations. [wrote: *3200, 3000, 250, 3000, 468, 453*]

As the graphs illustrate, equalities were used. As the quote illustrates, writing was used. Figures 25 and 26 represent the only heuristics used by Terri. The two heuristics allowed Terri to predict results before running experiments as written, and to keep track of numbers all in one place. This success at keeping track of numbers was not connected to Terri's relative lack of exploration of meaningful moves because there was not much exploration, but may explain Terri's relative success at making conceptual ecology statements.



3200, 3000, 250 ---> 3000, 469, 451 days

3200 kalories sun, 3000 kg/hectare pond life, 250 kg/hectare sunfish ---> 3000 kg/hectare pond life, 469 kg/hectare sunfish, 451 days.

Figure 25. Terri's First Problem.

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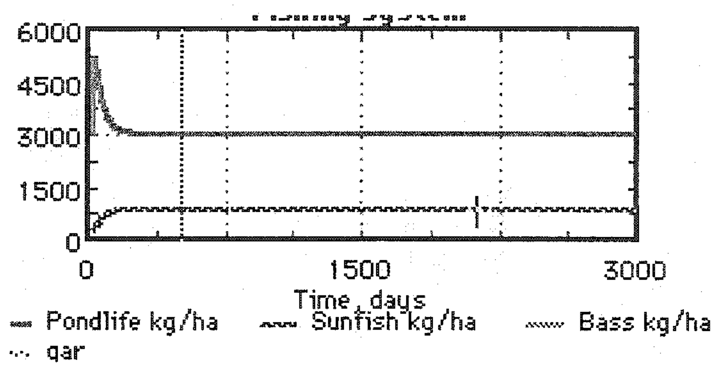

4500, 3000, 250 ---> 3000, 863, 393 days

4500 kalories sun, 3000 kg/hectare pond life, 250 kg/hectare sunfish ---> 3000 kg/hectare pond life, 863 kg/hectare sunfish, 393 days.

Figure 26. Terri's Second Problem.

The three case studies examined show the knowledge and problem solving of students with relatively similar amounts of conceptual knowledge (Figures 11–13). However, their procedural knowledge is not similar. Examples of content knowledge used include defining predators and connecting predation to competition. One participant utilized a wide variety of heuristics, while the other two used the same conceptual knowledge, using only a couple of heuristics. The participant who used a wide variety of heuristics explored an average amount of the problem space, in that it was in the middle of all participants. The moves performed by participants through the set of meaningful moves during the explore task were recorded and analyzed (Table 1). Of the 16 meaningful moves through the problems, no participant explored the entire set. The range of percentage of meaningful moves explored ranged from 6.25% to 43.75%. Participants did not take a systematic approach to exploring the moves in the explore task. They did, however, explore a variety of moves.

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The ways students went about their work was not always in a predictable order or the order predicted by expert analysis of an ideal pattern of exploration. An ideal pattern of using heuristics is not clear. The order of use of the heuristics was given above. The significance of these patterns is unclear. Each participant used each heuristic only once except: write equations (all participants), use abbreviations (Pat). Then, students explored runs without apparent use of principled heuristics.

The ideal number of problems explored refers to the set of meaningful moves resulting from expert analysis (Table 1). This set of problems reflects the moves which must be posed to reveal the conceptual knowledge contained in EDM, also assessed by expert analysis (Appendix C). How each person did, compared to this ideal state of exploring meaningful moves, is summarized by Table 4. The other participants explored problems in various patterns, but these patterns are not worth mentioning because they don't display any commonality or significance, except in terms of picking three case studies.

The following trends were found: all three students used equations, which is not surprising given literature on expertise (for example, Chi, et al., 1988). Chi, et al. (1988) observed that experts use written representations as they solve (physics) problems. They used equations in somewhat different basic ways. The ideal pattern requires they write starting values and made predictions about carrying capacity results and time to carrying capacity. Pat used all three values and the others only noted starting values. This may reflect their levels of use of this expert strategy: prediction as well as explanation is possible when each whole equation is both recorded and used. It is not possible at this

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time to determine whether equations are consistently used. The results of the use of this heuristic may be different because the students varied in most other uses of knowledge.

Confirmations and Disconfirmations

Confirmations are defined as those where the participant saw what was predicted in the problem, and disconfirmations are defined as those where the participant did not see what was predicted in the problem initially, and they continued to reason toward an explanation. That is, confirmation is what made them stop the run. As described in this section, a word search performed on all three transcripts revealed consistent patterns of utterances within each participant about the satisfaction level within runs.

Disconfirmations are what happens when people were surprised or their predictions were not confirmed. The researcher tracks this in terms of content knowledge, moves, and heuristics.

Table 7 shows instances indicating either change in direction or disconfirmation. Chris stopped her solving several times to utter “wow” or “for some reason,” disconfirming her initial hypotheses. This interacted with procedural knowledge because, each time, she persisted and continued to search for an explanation. In each case, she was ultimately satisfied and moved to another run. For example, during run three, immediately after she had defined direct cause, she said “wow,” disconfirming a hypothesis that pond life would grow large. Soon after, she said that in fact, it was “like I said,” after she looked through the rest of the graph, then went on to run again by increasing pond life. Again, after run four, she said “for some reason” again pond life was not as high as expected, and went on to try a new run, which confirmed the proper

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Table 7

Instances Indicating Either Change in Direction or Disconfirmation

Participant	Chris	Pat	Terri
Confirmation	"Wow" pond life grows large--> increase pond life	"Wow"---> ended up balancing--->start at carrying capacity ---> connect carrying capacity to reduced resources--->relate bass and gar competition as equal ---> write equations.	"I have no idea" ---> sun is proportional to biomass--->write equations.
	"For some reason"---> pond life not high as expected--->connect new run carrying capacity to sun---> try equal amounts of competing predators.	"oops/whoops"---> define direct cause---> start with carrying capacity.	

level of pond life. Chris concluded that they "affect sunfish." Next, she went on to "increase sunfish," and start another run. Next, she used middle-level conceptual knowledge as she connected carrying capacity to sun's energy, and she used a heuristic of: Try equal amounts of competing predators.

During run eight, Pat said "wow, going very high," but before run nine, concluded it "ended up balancing," and was satisfied. During run eight, she used the heuristic: Start at carrying capacity, and by run 11, she connected carrying capacity to the reduction of resources. Later, in run 21, she said "wow…big value…sunlight back to 5,000, that's what I really wanted." This occurred immediately after she had related bass and gar

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competition as equal, and while she was making move 10 of the meaningful moves, and using the heuristic: Use abbreviations. In spite of her missteps, Pat kept going on to the next run, using the information she had gained. She went on to say "oops" in run six when she misspoke, and redirected with conceptual knowledge by defining direct cause, and procedural knowledge in run eight by using the heuristic: Start with carrying capacity. She went on to say "whoops" or "oops" a full 10 times more without questioning her hypothesis. Pat changed her mind frequently after misspeaking, saying "no." She used "no" four times, for example "no just 500 I'm sorry," to indicate misspeaking. She also used "for some reason" to pause, without redirecting. For example, "for some reason I'm just not counting right." She simply seemed to lack confidence.

Terri used the phrase "oops" once, but it appeared to be in the context of misspeaking. She said "oops, 870, not pond life, sunfish." Terri often used the phrase "I have no idea" during the prediction phase to indicate her lack of knowledge of what carrying capacities would be reached specifically. For example, she predicted run seven would "decrease the steady state for sunfish and I have no idea how much though." This was immediately after she defined sun as proportional to biomass, and two runs after using the heuristic: "Write equations." So Terri did not ultimately appear to have unsatisfactory runs.

Conclusions

In all three cases, the participants reinvested in their problem solving after being surprised by some information. In the cases of Chris and Pat, the surprises were about

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results of runs. They then went to draw on different knowledge, both conceptual and procedural.

Conceptual and procedural knowledge overlap somewhat, naturally because participants are using ecology knowledge in both cases. While Terri was the problem searcher at the lowest level of engagement, she had the same basic pattern with middle-level and high-level conceptual knowledge as Chris, the problem searcher at the highest level of engagement. Both were consistent through both explore and constrained problems. Pat, on the other hand, a problem searcher at the middle-level of engagement, used the high-level concept knowledge the most. Pat's use of heuristics was also thorough, compared to Terri's and Chris'.

The data show the total number and average level of difficulty of conceptual ecology statements used by Chris, Pat, and Terri. They show that the total number of concepts across these three students is comparable. The researcher calculated the average level of difficulty by dividing the total number of conceptual statements by the difficulty levels used in each. Chris made 9 statements, with an average difficulty level of 1.5; Pat made 12 statements, with an average difficulty level of 1.67; and Terri made 11 statements, with an average difficulty level of 1.54.

In summary, the patterns in content and procedural knowledge reveal similarities and differences. In spite of similarities in conceptual knowledge and variation in moves, all three students used new knowledge when faced with disconfirmation. Utterances indicating disconfirmation were quickly answered with confirmation in the form of uses of content and procedural knowledge.

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All three students used writing as a type of heuristic. The type of writing was also similar across the three selected students. This occurred in spite of directions which lacked guidance on what to write.

However, Pat excelled in the number of total moves and number of heuristics. These differences did not seem to bear heavily on students' use of content knowledge, which was a subset of all possible content knowledge. In overview, the results, given what is going on in each category, show that content and procedural knowledge are revealed chronologically together, and they may inform one another.

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CHAPTER V

DISCUSSION

This chapter provides discussion of the results and practical implications for high school and college teachers. Analysis involved searching for patterns and sorting data into categories of knowledge. The sections in this discussion address the main implications of the analysis. Implications for problem solving indicate how the student performances with the ecology computer simulation Environmental Decision Making (EDM) might influence learning with problem solving. The section on pedagogical implications indicates how the student performances with EDM might influence teaching. The limitations section describes concerns remaining about the study and their implications. The section on areas for future research indicates diverse directions in which this type of research might go in the future.

Chi et al. (1981) suggest what good problem solvers need: representations of the problem, i.e., drawings. Students also may need to use writing of words and numbers as another way to document their thoughts. This is what experts tend to use in solving problems. This phenomenon of making representations was also found in the present study. This is helpful, but it is also useful to look at other behaviors with the creation of representations. The basic results are in two areas: content knowledge and procedural knowledge (both meaningful moves and heuristics). Content knowledge was similar across three selected participants. Meaningful moves varied, allowing the selection of

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three diverse students for more detailed analysis. Heuristics varied, although all three selected participants used writing.

Implications for Problem Solving

Through the analysis of data, several lessons are pertinent about the open-ended problem solving. This kind of problem solving, while open-ended, leads students into specific conceptual and procedural knowledge. From examining the student quotes such as those used in the content analysis examples, the researcher suspects that some learning was taking place. Whether that knowledge is already known or new learning is not known at this time. The major lessons learned about problem solving by doing this study are described next.

As predicted by Stewart (1988), open-ended tasks generate several problem-solving strategies: making moves through the simulation, writing, drawing, and trying starting values which reflect on conceptual ecology knowledge and proportions. Specifically, in terms of moves, one of the selected students was in the middle, one was thorough and one was poor. In terms of heuristics, the diversity was remarkable, especially represented by the best problem solver. In terms of conceptual knowledge, all three were relatively consistent.

Chi, et al. (1981) would recommend that novice problem solvers use drawings like experts, to increase their problem-solving success. In this study, problem solving in ecology does not appear to generate wide student experimentation in moves or heuristics. The one heuristic in common among the participants was "write equations." The equations were also the same in form. While this resembles the recommendation of Chi,

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et al. (1981), it is expected that students would use this heuristic. The writing of equations is reinforced in the ecology course which each of the students took, and recommended by math and science teachers all through school and college (L. Beauving, personal communication, November 15, 2000). It is possible that participants were transferring the knowledge of writing equations to the EDM situation. This could mean that problem solving in ecology needs to be taught explicitly, particularly the importance of the proper forms of equations. It is also possible that students are too tied to equations and do not think creatively very far beyond them. The biggest concern among instructors is that the student will memorize or consider understanding the equations to be understanding the ecology (S. Malcolm, personal communication, December 4, 1998).

There was some consistency in content knowledge during problem solving, used by students. Ecology problem solving appears in this study to involve different content knowledge for different students, although the amounts used are similar. The consistency in content knowledge may come out of the common ecology course that all participants have taken. Their other coursework and instructors are also similar (L. Beauving, personal communication, November 15, 2000). Students seem to draw consistently on low-level knowledge and hesitate to use high-level knowledge. This is not surprising, considering that definition statements are commonly contained in basic ecology learning (S. Malcolm, personal communication, December 4, 1998). According to the list of expert knowledge such as content knowledge (Table 2), this knowledge could have been obtained from using EDM. EDM helps establish high-level content knowledge if students come to the simulation without such knowledge. This researcher's experience teaching Life Science for Elementary Education (SCI 170) has shown that students raise

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their levels of knowledge in many cases from low-level understandings to middle- and high-level ones with EDM. The ways to use the simulation better include using a highly-structured manual such as the one created for Life Science for Elementary Education, a scaffolded cognitive apprentice-style learning environment (Collins, et al., 1989) where students learn expert strategies and model them gradually more and more on their own, and limits on the open-endedness of EDM, as discussed below.

Connecting concepts and relating concepts to processes is probably more challenging and complex, something students do last. They might go to this knowledge because it is safer to explore without being incorrect.

Problem solving can help students achieve high-level knowledge. This is helpful to teachers, according to Stewart (1988). Teachers, at least in the high school and elementary world, are always trying to get students to be "critical thinkers," "creative problem solvers" who can "synthesize," and are perplexed at how to do so (Adsit, 1999).

The lack of high-level and even middle-level knowledge may make it more difficult for them to become more successful problem solvers. As seen in the data analysis of content knowledge, systems thinking is revealed in the content emergence and causality statements. The lack of data in systems thinking content knowledge may suggest that there is no reason to logically expect trends. However, the use of systems thinking heuristics may indicate that systems thinking is used more with procedural knowledge here than with content knowledge. This may be dysfunctional for problem solving in ecology, because the content itself involves systems thinking.

Also seen in the data analysis, the reinvestment in problem solving after an unsatisfactory run may indicate that the type of inquiry used in EDM may allow students

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to go to deeper and further levels of understanding. After hitting a road block, participants kept going and redirected.

In summary, the lessons for ecology problem solving show concerns for teachers. In spite of efforts to give a structured introduction to EDM, students do not fully use content and procedural knowledge. Students perform in varied ways. Teachers might learn from these problems, as described below.

Pedagogical Implications

This dissertation could aid in potential revision and improvement of limited computer based ecosystems simulation programs. The researcher addresses concerns over how we can increase and improve problem-solving behaviors of students. The ideas include the following:

Use of the lists of conceptual and procedural knowledge available in EDM can be used directly in classrooms. When teachers are aware of the explicit expert conceptual and procedural knowledge, they can better convey it to students. This could help teachers focus only on the most basic, important information about ecology. While teachers have themselves successfully learned from textbooks, they may not be able to envision the most important information at their fingertips. There is so much ancillary curriculum material about sideroads in ecology and the environment that teachers at Western Michigan University, for example, have found it difficult to choose subject matter. Use of the analysis has already improved the development of problem-solving modules in Life Science for Elementary Education at Western Michigan University. The lists of definitions, instruction manual, and instructors' manuals have all been informed by this

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dissertation. EDM is used in a more structured way than suggested in Odum, Odum and Peterson's (1991) manual. The improved structure has involved giving students specific problems to solve, which provides a goal end-state. Additionally, students are given spreadsheets with constraints on the objects used in problem solving.

Knowing the typical road blocks participants had might help teachers warn students about unproductive work and strategies. Teachers can teach the best procedural knowledge of experts, in order to get their students to learn the best conceptual knowledge.

This study suggests some limitations of EDM (listed in Chapter II) of which teachers should be aware so that they can make the best use of the simulation. These limitations have a one-to-one correspondence to the limitations of models uttered by participants. It is important for teachers to teach the limitations of the model not only so that students realize the model does not exactly map to the real world, but also so that students see the benefits of using false models (Wimsatt, 1987). False models allow a problem-solver to set up a "straw man," a model that is known to be faulty, in order to compare and contrast and better understand their own model. Teachers can use the limitations of EDM to teach students about false models.

Teachers could also use concept mapping, integrated with the use of problem solving. Concept mapping in Life Science for Elementary Education makes content knowledge visual, explicit, and connected. With connected content knowledge, students might be better able to integrate procedural knowledge. The above list of types of limitations of EDM of which teachers should be aware provides suggestions. The various methodologies in which teachers are oriented can be flexibly used to teach these

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limitations to students about false models. In Life Science for Elementary Education, the technique might be more discovery-oriented, but there is no reason to believe that it could not work in a more lecture-oriented classroom.

Additional simulations and problem solving activities might also be useful for teachers. In Life Science for Elementary Education, a simulation is used called Ecobeaker (Meir, 2002). This simulation, like EDM, focuses on predator/prey relationships and competition, but the visual interface is a more explicit and realistic view of individual organisms. The combination of EDM with Ecobeaker seems to work best.

Limitations

In this section, the researcher discusses limitations of the study. The study had flaws, and can point ways toward improvements.

Students used values which were not realistic in real ponds. Since students used them with some regularity and no pattern, it is not known which of the unrealistic values students used were intentional. If a student were intentionally setting up a false model (Nickles, 1987) in order to test a stronger model, this may have been a purposeful strategy. If, on the other hand, the student was not aware that the values were realistic, they might be searching more randomly. This is a limitation because students should have been constrained to more realistic values. For example, although it was not apparent during design, it would have helped to tell students that sunlight over 6,000 kilocalories is unrealistic. This would have saved effort, because many fewer fruitless moves would have been performed.

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It is possible that students' thinking changed between sessions. Those students who came back for a second or even third session may have changed their minds or their thinking about how to approach the simulation, or what knowledge to pursue. This is a limitation because there is no way to determine whether the same knowledge would have been revealed in one long session compared with what was revealed in several smaller sessions.

The analysis was problematic in some ways. Chi's model is a general description of what is used, and "frames" as described by the model referenced (Kowalski, 1979). This analysis may have been limited. For instance, the kinds of data were so varied that analyses are difficult to compare. Content knowledge is seen in quotes, procedural is seen in moves and sometimes quotes. The diversity of different kinds of data made the analysis exceptionally difficult. This analysis may also have been limited. Two of the selected students simply used less heuristics, while one student used considerably more. Their lack of engagement limited my study and analysis because there was not much data from them.

Suggestions for Future Research

In this section, the researcher provides suggestions that might help influence future research. Due to the flaws in this dissertation, a number of suggestions have become clear.

Future research needs to be done with more structured tasks to determine whether the kind of knowledge used by students is truly consistent. The reason there are few trends is unclear. Learning research (e.g., Piaget, et al., 1980) shows substantial trends

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both within and between learners. Although the present study is not a learning study, these trends were relatively undetectable with the methods used. The similarities in knowledge may have "passed under the radar screen" of the analysis—that is, the expert analysis may not have provided categories which include the most basic knowledge that is held in common by these students. Additionally, the lack of structure provided to students for their exploration may contribute to this problem. This lack of trends may be due also to the EDM environment which is so open-ended compared to many simulations researched (e.g., Hafner and Stewart, 1994; K. Schram, personal communication, October 5, 1997). Without providing an open-ended opportunity, the researcher felt it would be too "guided" an experience to reveal knowledge that was truly constructed by the student.

One way that future research may be better guided with the simulation is to use a supplementary program. Such programs could expand our knowledge of problem solving because the data collected would not be so varied. One such program is Supportive Inquiry-Based Learning Environments (SIBLE) (Loh and Lugowski, 2000). They:

> are developing a software tool to help students acquire the skills of reflective inquiry as they work with computer-based investigation environments such as data visualizers, simulations, and web-based explorations. The software tool, called the Progress Portfolio, is an inquiry-support environment that provides tools for students to record, annotate and organize their work...Together these tools inscribe the process of doing inquiry with investigation environments (e.g., documenting, analyzing, and explaining) into explicit and concrete artifacts, providing students with tools to think about and talk about the

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> process of doing inquiry, and teachers with a stage for diagnosis, assistance, and assessment of student inquiry work. (p. 1)

Horwitz (1999) also suggests a tool that may have been useful to my participants. He states that there is:

> a new paradigm for educational technology—the hypermodel—that seeks to use the computer to bridge the gap between a model and the physical world the model represents, between the "facts and figures" offered us by the natural world and the mental associations we construct to explain them. In the traditional textbook approach to teaching science the goal is primarily to give students information. The hypermodel uses a computer to help them turn that information into knowledge...To illustrate genetic phenomena the GenScope program starts with a fictitious species-dragons. (p. 5)

Future research might benefit from use of the expert analysis tool. Expert analysis provides us with an optimal way to use the simulation when viewed as a whole collection of content and procedural knowledge. With the above suggestions and use of expert analysis, future research might obtain more consistent data across students.

Future studies should be done in which pre- and post-tests are used to measure students' learning. If participant knowledge were assessed ahead of time, the changes in post-test would presumably represent knowledge learned during problem solving. A pre- and post-test format might have made claims about learning possible. Students may be adopting a "hit and miss" or trial and error approach (Mayer, 1983). EDM may in fact encourage this type of strategy by its open-endedness.

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One area for future study is determining what other content knowledge students use with EDM. It is helpful to have described the principles of ecology knowledge embedded in EDM. The next stages of research should probe deeper into the content knowledge actually used by students. This exploration will help to complete the model of novice performance. The content knowledge used in conjunction with the procedural knowledge will provide insight into the interplay between the two.

Expert interpretation of ecosystems simulation is another area of questioning that could be further explored. How simulations are evaluated, interpreted, and used by experts could corroborate and extend much of what is described in this study. It would be useful to research what content and procedural knowledge experts use in ecosystems problem solving. It would also be useful to determine what ideas both novices and experts have about the nature of science with respect to models. Finally, it would be useful to know whether novices and experts pay attention to the limitations of models when using ecosystems simulation. It would be good to find which aspects of the model they notice in particular and whether that affects the experts' uses of the model. The comparison of expert performance with novice performance can provide better models of both, which will in turn provide better models of teaching and learning. Many questions lie ahead for continued research in this area. Additional areas of research follow. Studies of students' initial conceptions of ecosystems and of expert performance could also inform the teaching of ecosystems problem solving.

A model of expert performance should be created in the future. It can then be compared with a model of novice performance to illustrate specific points that instruction could address to help students improve their problem solving. Meaningful learning in

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science occurs when students come to realize their own conceptions and their limitations, and they seek to replace those conceptions with scientific conceptions (Posner & Gertzog, 1982). Some conceptions held by students are resistant to instruction. In spite of our best pedagogy, students hold dearly to some misconceptions that work to explain their understanding of the world. Understanding the conceptions held by students can provide insight into potential problem areas.

This research project provides new insight into the nature of ecosystems problem solving with computer simulation. The relevant concepts in the simulation have been defined and student use was observed which told the researcher what knowledge students have used by running the simulation.

This study will inform the construction of problem sets for classroom use that encompasses the full range of ecosystems phenomena. The procedural model of ecosystems problem solving adds to the knowledge of problem-solving research and can inform desired performance for students; the descriptions of heuristics provide methods for implementing the model in a variety of classroom scenarios.

The results of this research will inform the creation of curricula that address the teaching of ecology and thus create a foundation for subsequent research in ecology problem-solving, and it will inform computer program designers in designing new and improved models that take into account these findings.

This study has raised a number of questions that would be of interest for future study. These questions both clarify issues within ecosystems problem solving and have evolved from topics that address the practice and use of relevant procedural knowledge. In addition, addressing these questions can provide further connections between the study

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of problem solving in ecology and other areas, such as genetics and evolution because these areas involve biological prediction and explanation.

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Appendix A

Typology of Research Problems with Their Emergent and Arising Properties

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Typology of Research Problems with Their Emergent and Arising Properties

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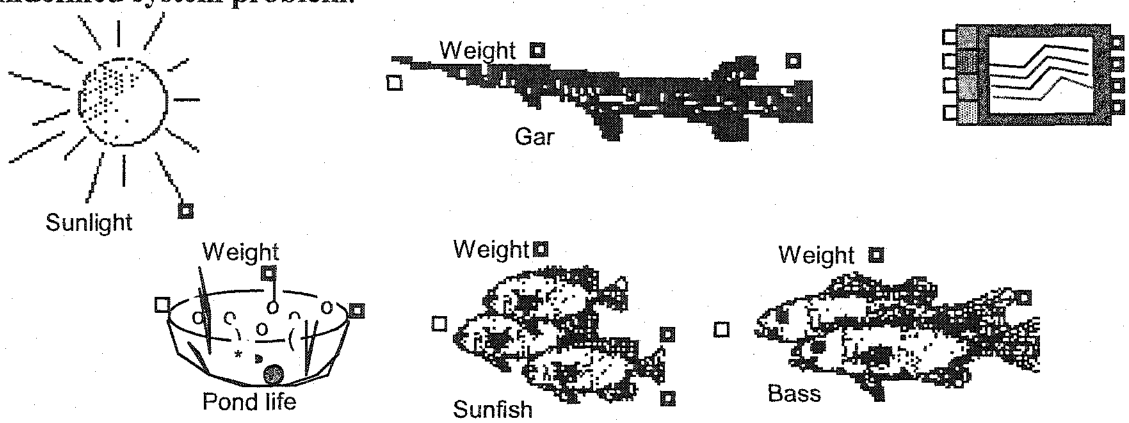
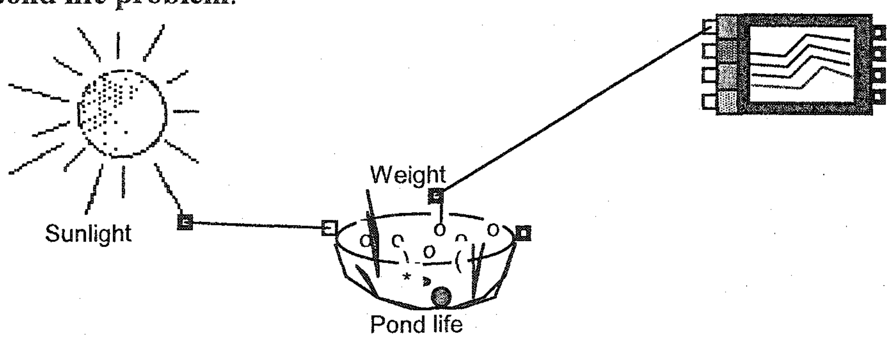
undefined system problem:



Biological emergent properties and systems components which arise:
all system components available in the pond system are available, thus all emergent and arising properties below are possible.

---

pond life problem:



Biological emergent properties:

Single Carrying Capacity is emergent at the level of pond life because it behaves like a population, and by definition, it is the biomass a habitat can support of a population.

Overshoot of Carrying Capacity is emergent because it is first possible here.

Limits of Radiant Energy on Growth are emergent because only one entity is necessary for observing the limiting force of sun.

Overshoot Carrying Capacity is emergent here because it is the only place where it is isolated to one population.

Reproduction, Growth and Death are emergent because they are both apparent as explanations of simulation behavior.

Unrealistic biomass is emergent because it is possible to allow the pond life to be low if insufficient sunlight is given.

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Systems components which arise:

Direct and Single Causality arises because the simulation is linear here.

Positive Feedback Loop arises because pond life grows from sunlight exposure and the dead pond life facilitate the new growth.

The concept of Closed System arises here because it is apparent that realistic entities that affect pond life are missing.

Systems component combinations which arise:

negative feedback, single cause, positive feedback, direct cause, outside sun, inside constraints, dynamic self-stabilization, single carrying capacity, closed system.

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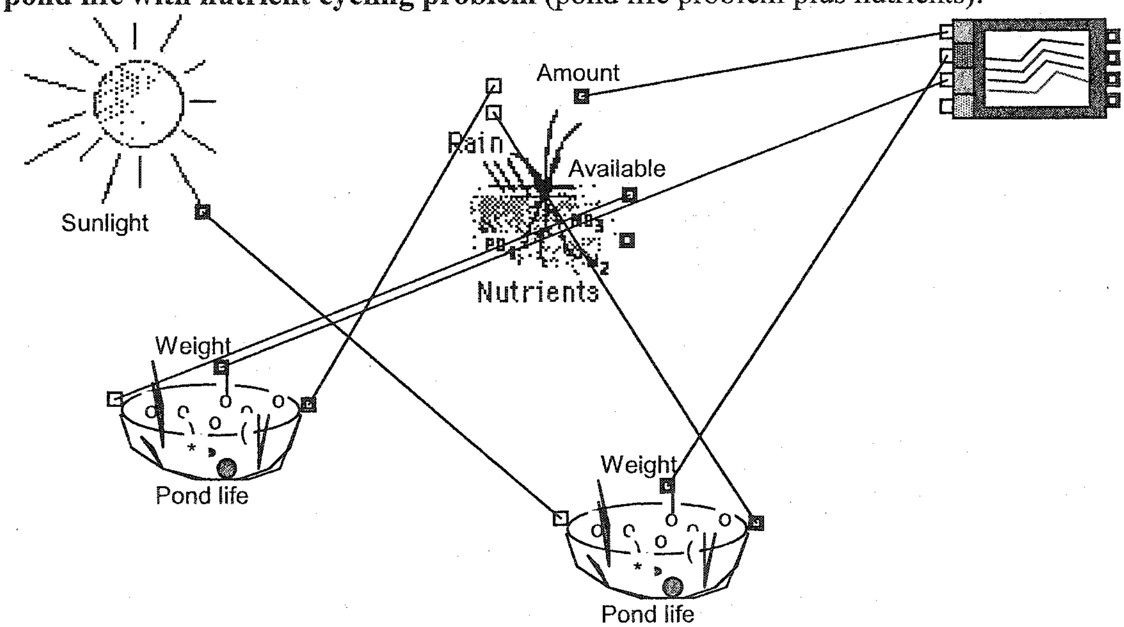
pond life with nutrient cycling problem (pond life problem plus nutrients):



Systems component combinations which arise:

outside sun, nutrients, dynamic self-stabilization, positive feedback, plural carrying capacity, negative feedback, direct cause, indirect cause.

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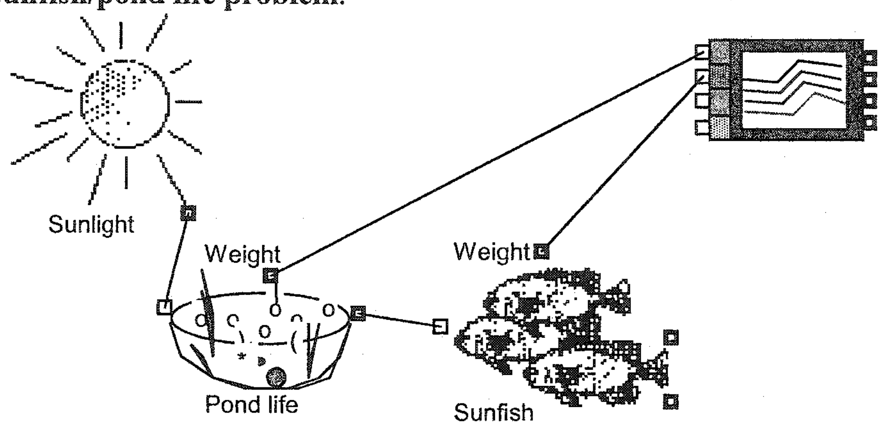
sunfish/pond life problem:



Biological emergent properties:

Time Lag Due to Reproductive Rate and Predation is emergent because two entities are necessary to exhibit time lag. The predator accumulates prey biomass until it can reach the limits of its oscillation.

Community Equilibrium is emergent because two entities are necessary to exhibit it.

Oscillation Around Carrying Capacity is emergent because the behavior of a sensitive system is displayed with two populations.

Intraspecific Competition is emergent because two populations are being explicitly modeled and competition is a reasonable explanation for the effects produced.

Limit of Radiant Energy on Community Growth is emergent because this is where a community is first explicit, and sunlight limits both entities.

Systems components which arise:

Indirect Causality arises because sunlight can affect the quantity of sunfish.

Systems component combinations which arise:

dual cause, negative feedback, multiple cause, direct, dynamic self-stabilization, plural carrying capacity, paired cycles, inside constraint, outside sun, nutrients, closed system, single cause, direct cause

sunfish with pond life nutrients problem (sunfish problem plus nutrients):

Systems component combinations which arise:

nutrients, multiple cause, dynamic self-stabilization, plural carrying capacity, dual cause, paired cycles.

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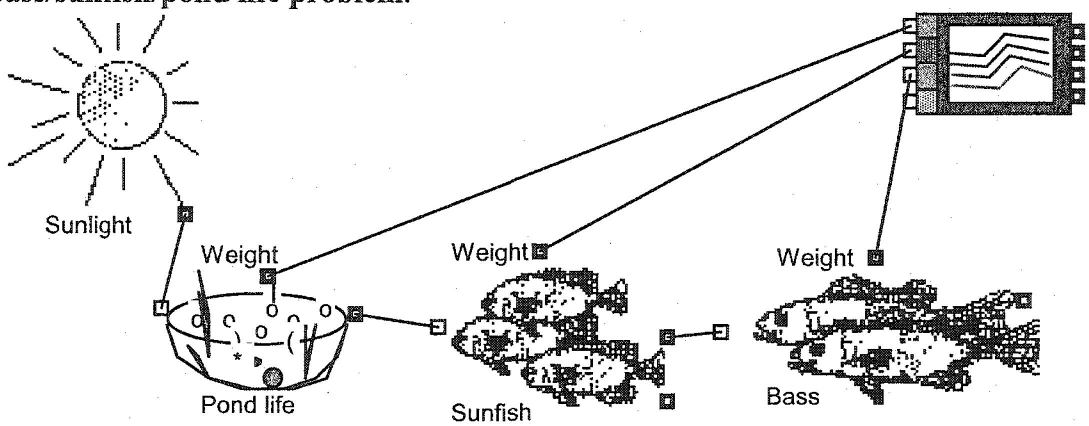
bass/sunfish/pond life problem:



Biological emergent properties:

Trophic Pyramid is emergent because several trophic levels and their pyramid-shaped proportions become explicit in the simulation.

Systems components which arise:

Negative Feedback Loops arise because decreases in sunlight cause decreases in all other entities.

Dual Causality arises, because bass and sunlight can simultaneously cause changes in sunfish.

Systems component combinations which arise:

negative feedback, indirect cause, positive feedback, single cause, paired cycles, plural carrying capacity, inside constraints, dual cause, closed system, multiple cause.

bass with pond life nutrients problem (bass problem plus nutrients):

Systems component combinations which arise:

multiple cause, paired cycles, indirect cause, closed sun.

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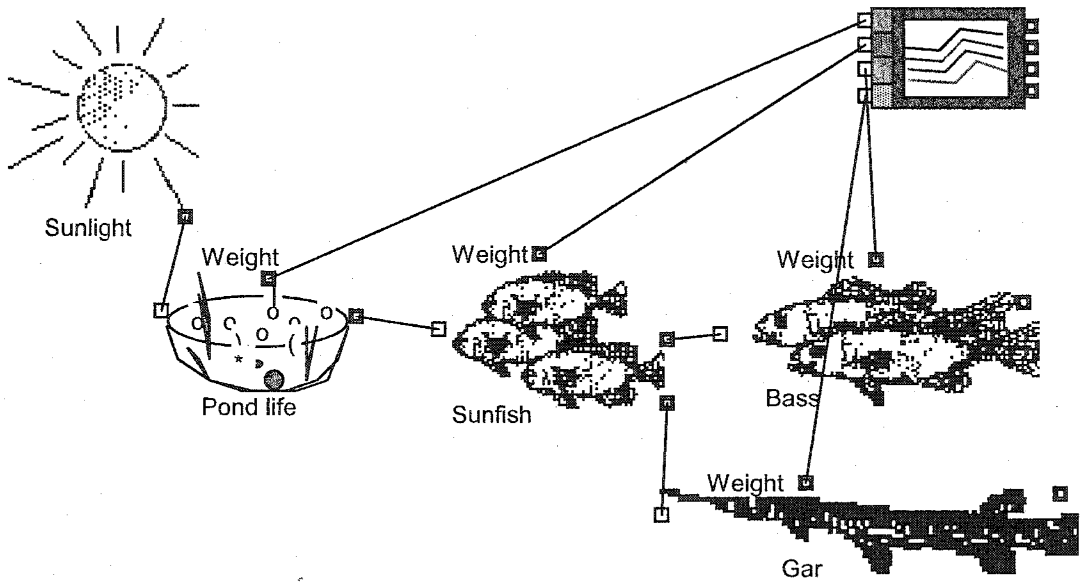
gar/bass/sunfish/pond life problem:



Biological emergent properties:

Interspecific Competition is emergent because it is not explicit until the two competing populations of gar and bass are present.

Systems components which arise:

Multiple Causality arises because gar and bass are causing changes in sunfish at the same time as pond life.

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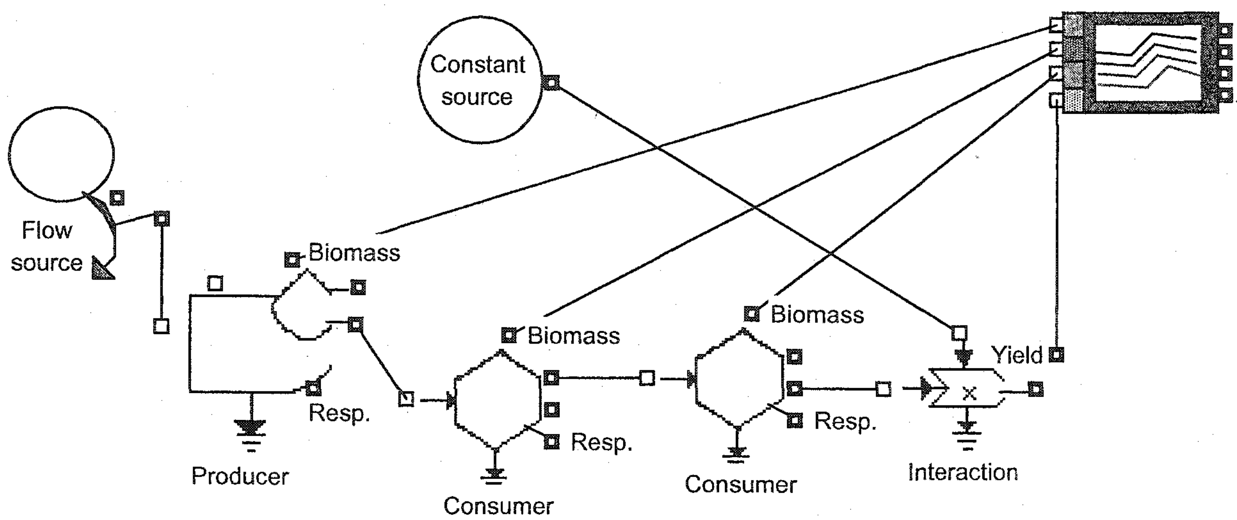
pond general symbols problem: sun, producer, consumer, consumer



Biological emergent properties:

Producer externally limited source flow is emergent because pond life is limited in its absorption of sunlight.

Producer transformity is emergent because pond life is inefficient at transforming sunlight into biomass.

Matter flow is emergent because it is first made explicit here.

Systems component combinations which arise:

negative, indirect, positive, single, multiple, plural carrying capacity, inside constraint, dual cause, multiple cause, and closed sun.

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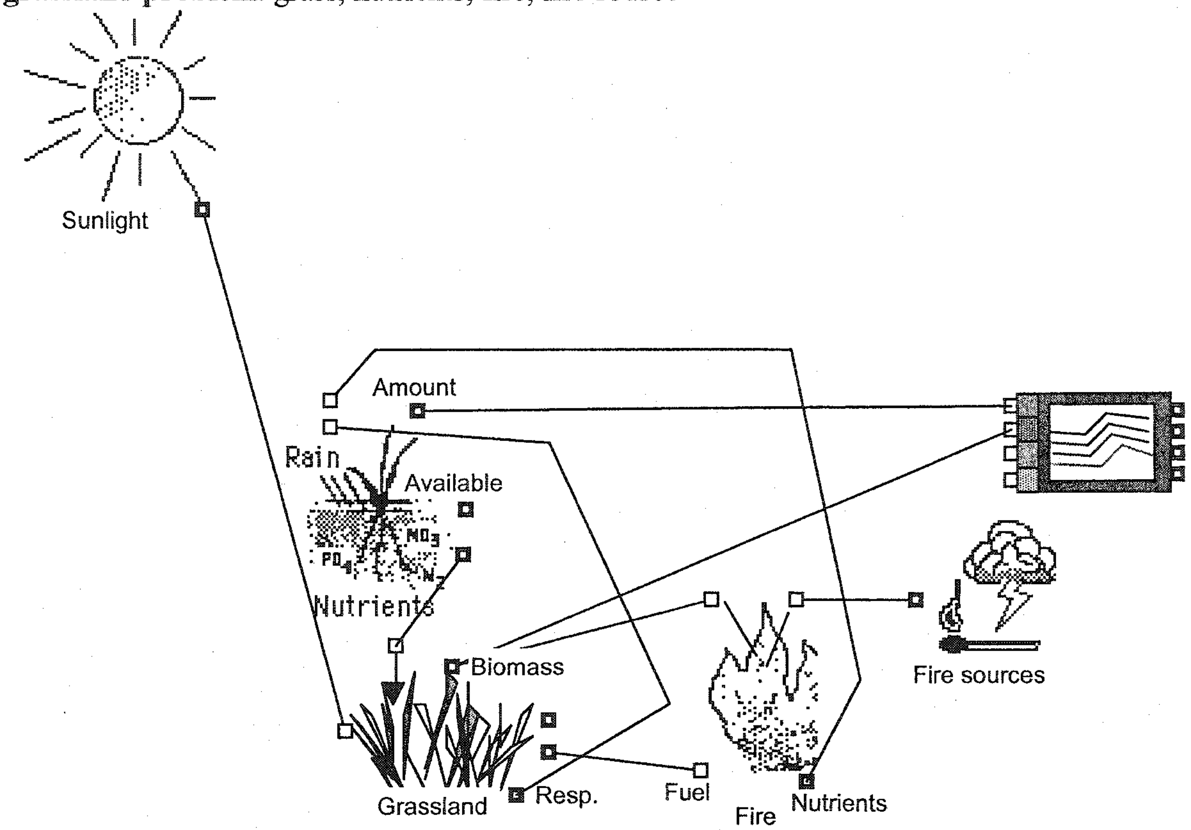
grassland problem: grass, nutrients, fire, fire source



Biological emergent properties:

Starting [nutrient] is emergent it is the first starting mass that is not energy-based.

Systems components which arise:

Frequency and source of ignition arises because fire is uniquely ignited (biomass is consumed) on a rhythmic basis determined by a manager's perception of threshold biomass or on a rhythm determined by flammability by lightning of the threshold.

Systems component combinations which arise:

inside constraints, nutrients, ignition frequency, outside sun, closed, single carrying capacity, plural carrying capacity, dynamic self-stabilization, paired cycles, direct cause, single cause, positive, and negative feedback.

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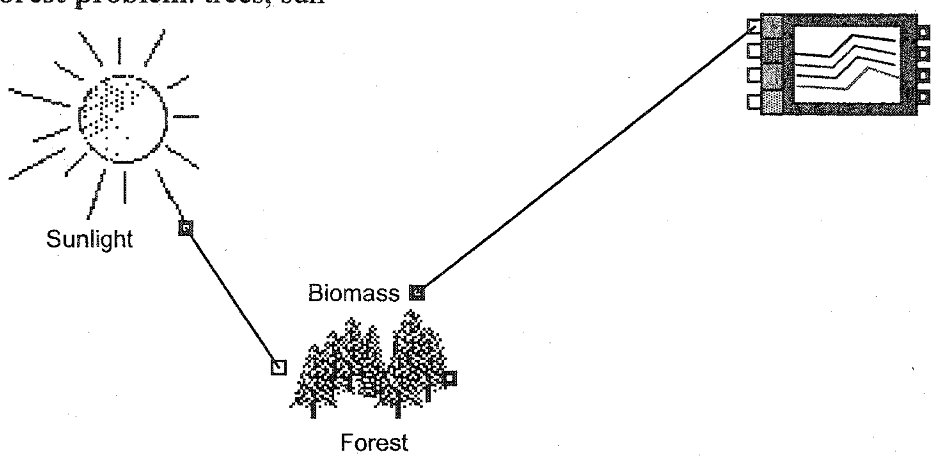
forest problem: trees, sun



Systems components which arise:

Storage arises because it is explicit here that biomass accumulates in wood.

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Appendix B

Heuristics Used by Participants

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Heuristics Used by Participants
Procedural Ecology Knowledge Used by Participants Chris, Pat, and Terri

Chris:	**Pat:**	**Terri:**
Look for equalities as starting values to test for equal effects.	Use values that reflect pyramid relationships.	Try proportional changes in starting values between runs.
Try equal amounts of competing predators.	Use realistic proportions in gar system.	Write equations.
Write equations.	Compare intact simulation/change only one system entity at a time.	
	Remove a system entity.	
	Start with carrying capacity.	
	Use constant starting values between sub- and full-systems.	
	Try proportional changes in starting values between runs.	
	Write equations.	
	Write data for future comparisons.	
	Make a chart to compare values.	
	Use abbreviations.	

Appendix C

Coding Explanation

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Coding Explanation

This appendix provides evidence for why theoretical statements are inferred from students' remarks. Theoretical statements are found in Table 2 and Figure 8, and examples are found in the text of Chapter IV. Noun-verb agreement clauses constituted a definition statement.

Meaningful moves are defined as moves which involve conceptual ecology knowledge. For example, using gar involves a meaningful move, because it was posed within a problem involving gar, bass, sunfish, pond life.

Low Level Responses: give definition statement of an ecology concept.

Middle Level Responses: relates ecology concept to others.

High Level Responses: connect ecology concept to complex ecological processes.

Code	Type—participant	Code	Reason
Low	Chris	conceptual	defined energy exchange between sun and prey
Low	Chris	conceptual	defined trophic pyramid
Low	Chris	conceptual	defined direct cause
Low	Chris	conceptual	defined single cause
Low	Chris	conceptual	defined multiple cause
Medium	Chris	conceptual	connected energy to population size
Medium	Chris	conceptual	connected predator size to prey dynamics
Medium	Chris	conceptual	connected prey size to predator dynamics
High	Chris	conceptual	related predator-prey dynamics to the process of time lag
Low	Pat	conceptual	defined energy exchange between sun and prey
Low	Pat	conceptual	defined energy exchange between predator and sun
Low	Pat	conceptual	defined carrying capacity as related to sun
Low	Pat	conceptual	defined carrying capacity as related to population size
Low	Pat	conceptual	defined carrying capacity as limited
Low	Pat	conceptual	defined direct cause
Medium	Pat	conceptual	connected trophic relationships to population size

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Code	Type—participant	Code	Reason
Medium	Pat	conceptual	connected carrying capacity to population growth
Medium	Pat	conceptual	connected carrying capacity to to competitor's growth
Medium	Pat	conceptual	connected direct cause to multiple cause
High	Pat	conceptual	related predator-prey dynamics to the process of time lag
High	Pat	conceptual	related competitive relationships to the process of feeding on prey
Low	Terri	conceptual	defined energy exchange
Low	Terri	conceptual	defined trophic pyramid
Low	Terri	conceptual	defined trophic pyramid as related to prey
Low	Terri	conceptual	defined trophic pyramid as related to predator
Low	Terri	conceptual	defined predation
Low	Terri	conceptual	defined direct cause
Low	Terri	conceptual	defined relative population growth
Medium	Terri	conceptual	connected energy to carrying capacity
Medium	Terri	conceptual	connected energy to population size
High	Terri	conceptual	related population growth to carrying capacity
Problem 5	Annie	procedural: move	allowed starvation of predator to be revealed
Problem 12	Annie	procedural: move	allowed direct cause to be revealed
Problem 14	Annie	procedural: move	allowed crashing of population to be revealed
Problem 11	Annie	procedural: move	allowed definition of trophic pyramid
Problem 13	Chris	procedural: move	allowed direct cause to be revealed
Problem 12	Chris	procedural: move	allowed carrying capacity of population's dependence on sun to be revealed
Problem 11	Chris	procedural: move	allowed predation escape to be revealed
Problem 10	Chris	procedural: move	allowed dependence of predator on prey to be revealed
Problem 10	Pat	procedural: move	showed satisfaction with problem space exploration
Problem 12	Pat	procedural: move	allowed effects of competing predators to be revealed
Problem 9	Terri	procedural: move	allowed definition of interspecific competition
Heuristic	Chris	procedural: heuristic	equalities allowed testing for equal effects
Heuristic	Chris	procedural: heuristic	equal competing predators allowed testing their equality
Heuristic	Chris	procedural: heuristic	writing equations allowed view of

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Code	Type—participant	Code	Reason
			whole picture
Heuristic	Pat	procedural: heuristic	using trophic relationships allowed view of inversely related sizes
Heuristic	Pat	procedural: heuristic	comparing intact simulations allowed viewing of consistent causes
Heuristic	Pat	procedural: heuristic	removing an entity isolated causes
Heuristic	Pat	procedural: heuristic	starting with carrying capacity allowed testing of stable values
Heuristic	Pat	procedural: heuristic	using constant starting values allowed comparison of effects
Heuristic	Pat	procedural: heuristic	trying proportional changes allowed pattern detection
Heuristic	Pat	procedural: heuristic	running several experimental simulations allowed hypothesis confirmation
Heuristic	Pat	procedural: heuristic	looking at small segments allowed views of all effects
Heuristic	Pat	procedural: heuristic	writing equations allowed view of whole picture
Heuristic	Pat	procedural: heuristic	writing data allowed comparisons between problems
Heuristic	Pat	procedural: heuristic	making a chart allowed comparisons between values in problems
Heuristic	Pat	procedural: heuristic	using abbreviations simplified explanations
Heuristic	Pat	procedural: heuristic	drawing diagrams summarized work
Heuristic	Terri	procedural: heuristic	equalities allowed testing for equal effects
Heuristic	Terri	procedural: heuristic	writing equations allowed view of whole picture
Interview	Pat	fallibility	stated reproductive rate invariable
	Pat	fallibility	stated external factors not present
	Pat	fallibility	stated that sun is not constrained
	Pat	fallibility	stated that pond cannot be moved

Results of rational analysis:

A. Definitions are possible:

Autotroph: an organism capable of synthesizing organic matter by using radiant energy and inorganic matter (carbon dioxide, water and nutrients). This process is termed photosynthesis. The chemical energy contained in organic matter that is synthesized by autotrophs is subsequently used by them as well as heterotrophs for growth and development, metabolism, reproduction. This process is termed respiration. Examples: the plant portion of the "pond life" in EDM; rapid-cycling Brassicas.

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Biomass: the total mass of living matter constituting the component(s) of a trophic level within a given habitat. Biomass is a measure of the carrying capacity of a habitat and is inversely proportional to the trophic level (ie., higher trophic levels in the food chain have less total biomass). In EDM, mostly measured in weight/area (Kilograms/hectare or Kg/ha).

Carrying capacity (K): the optimal number of individuals (density) that a habitat can support. In EDM, the carrying capacity is measured in Kg/ha of biomass.

Chemical energy: energy in the bonds of organic molecules which autotrophs "fix" and use and which heterotrophs use. Example: C----O bond between the Carbon and the Oxygen produces energy when it is broken. This energy is subsequently used for metabolism, growth and development, reproduction.

Community: a grouping of populations (both plant and animal) living and interacting with one another in a specific region under relatively similar environmental conditions; the biotic component of ecosystems which contain several food chains/webs. Example: a pond's organisms, or a field's organisms.

Competition: the simultaneous demand by two or more organisms of the same species or between two species for limited environmental resources, such as nutrients, living space or light. Competition occurs within species at the level of populations or between species at the level of communities.

Conditions: components of an organism's environment which typically cannot be depleted and thus are not competed for by organisms. Example: water is a condition for aquatic plants.

Consumer: a heterotrophic organism that ingests other living organisms (plants or animals) and thus organic matter in a food chain; an example of a community niche.

Decomposer: an organism (ex., fungi and bacteria) that obtains organic matter and chemical energy by breaking down nonliving organic materials from any source (from organisms at all trophic levels); an example of a community niche.

Density: the number of individuals occupying a given habitat; competition increases with increasing density.

Density-dependent factors: regulatory factors that affect the growth of a population as a function of that population's size. For example: both competiton within, and predation upon, a population increase when that population increases.

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Density-independent factors: regulatory factors that affect the growth of a population that are not a function of the population's size: For example: temperature.

Ecosystem: an ecological community together with the abiotic components of its environment functioning as a unit. Example: a pond, forest or field.

Energy: usable heat or power; the capacity to do work; energy flows through food webs. For our purposes, energy can be classified as either radiant or chemical.

Environment: environment can be characterized by a number of interacting dualities at any level of the hierarchy: biotic and abiotic components; resources and conditions; matter and energy.

Food chain/web: a succession of organisms in an ecological community that constitutes a cycling of matter and a flowing of energy from one organism to another as each consumes a lower member and in turn is preyed upon by a higher member (a food web is a complex, interlocking sequence of food chains in a community).

Habitat: the area or type of environment occupied by a population of organisms. Example: Goldenrod flowers; shoreline of a pond.

Heterotroph: an organism that must obtain chemical energy and nutrients from the organic matter originally produced and stored in autotrophs (the byproducts of photosynthesis). The process by which heterotrophs break down and utilize organic matter for chemical energy is termed respiration. Examples: sunfish, bass, bacteria, people. Decomposers, carnivores (eat meat), herbivores (eat vegetative matter), and omnivores (eat meat and vegetative matter) are all heterotrophs because they obtain and use autotroph energy either directly or indirectly.

Inorganic matter: matter involving neither organic life nor the products of organic life; matter <u>used</u> by autotrophs in the production of organic matter: water (H2O) carbon dioxide (CO2), minerals (magnesium, potassium, phosphorous, nitrogen, etc.) matter <u>produced</u> by autotrophs in the production of organic matter: oxygen (O2)

Intraspecific interactions: interactions between individuals of the same population. Example: competition.

Interspecific interactions: interactions between populations of different species. Example: competition; predation; symbiosis.

Matter: molecules which make up everything in the universe; matter cycles through food webs. Matter can be classified as either inorganic or organic.

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Niche: the ecological role a species plays in a community. Used expansively, this concept describes a species' trophic level, habitat, time of year for reproduction, and specific type of food. In other words, it describes the multidimensional specific role the species plays in a community.

Organic matter: carbon containing molecules (for example, sugars, fats, proteins) which autotrophs produce and use and which heterotrophs use for living processes. Organic matter contains chemical energy in its molecular bonds. For a biologist, "food" is synonymous with organic matter.

Organism: an individual living creature, either unicellular or multicellular. Organisms use the chemical energy contained in the molecular bonds of organic matter for such processes as: growth; metabolism; reproduction.

Photosynthesis: the process by which autotrophs use radiant energy, carbon dioxide and water to produce oxygen and glucose (a form of organic matter) which contains chemical energy within its molecular bonds.

Population: a group of individuals of the same species that occupy the same habitat. Example: the sunfish in a single EDM pond are a population.

Predation: A feeding relationship where one organism gains and the other loses. Includes carnivory and herbivory.

Producer: an autotrophic organism that produces food for itself and other <u>living</u> organisms (plants or animals) and thus organic matter in a food chain; an example of a community niche.

Radiant energy: sunlight which autotrophs utilize (through photosynthesis using chlorophyll) in the production of organic matter. In EDM this is measured in heat in kilocalories, the same unit used to measure calories in food.

Regional biota: large scale groupings of communities occupying a geographic area. Examples: a mountain range, Lake Michigan, etc.

Reproductive rate [r]: rate of population grow when there are no constraints or lack of resources.

Resources: components of an organisms environment which <u>can</u> be depleted and thus competed for. Example: oxygen is a resource for aquatic plants because it is limited.

Respiration: the process by which both autotrophs and heterotrophs utilize oxygen to break down organic matter releasing water, carbon dioxide and chemical

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energy which is subsequently used for growth and development, metabolism, reproduction.

Succession: the developmental change in the member species of a community over time.

Symbiosis: a close association between organisms of different species which: is mutually advantageous for both (for example, the Brassica plant and the honey bee); benefits one not at the expense of the other (for example, an epiphyte living in the branch of a tree); or benefits one at the expense of another (for example, tape worms living and feeding in the intestines of a mammal).

Trophic level: successive steps of a food chain/web, each of which has less available energy and biomass than the previous level; the levels are referred to as producers; primary, secondary, tertiary (and higher) levels of consumers.

Definition statement required student to use the concept correctly in context in a sentence.

probs.
B. Connections are possible between concepts (objects):

Autotroph Biomass Chemical energy Community Conditions Consumer Decomposer Density-dependent factors Density-independent factors Ecosystem Energy Environment Food chain/web Heterotroph Inorganic matter Matter Niche Organic matter Organism Population Producer Radiant energy Resources Trophic level Regional biota

C. Connections are possible between concepts (above) and processes/states:

Carrying capacity (K) Competition Density Intraspecific interactions Interspecific interactions Photosynthesis Predation Reproductive rate [r] Respiration Symbiosis

D. Heuristics are possible (see Table 3).

E. Moves are possible (see Table 1).

F. Falliblity knowledge is possible.

Realism matters and models should display it.

This system always self-stabilizes/No absolute zero possible if entity has energy.

Unrealistic results are an error in the simulation.

Model allows organisms to live unrealistically long without energy.

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Simulation behaves as though it accounts for environmental conditions such as nutrient cycling.

Simulation simplifies reality by using only basic assumptions.

A highly dynamic equilibrium is missing from model.

Things not shown are represented: r is variable here but not visible.

Things not shown are represented: r is variable here but not visible.

External factors such as disease may be here.

Sun realistically is not constrained to one value.

You can't move a pond.

Things not shown are represented.

Exponential explosions are possible here.

It is possible here to have so much sun that entities should realistically burn.

There are entities that are here which are not shown.

Pond life's sheer numbers should be able suffocate fish.

System can crash.

Unrepresented interactions exist.

Canopy penetration should affect producer growth.

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Appendix D

Description of Genetics Construction Kit (GCK)

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Description of Genetics Construction Kit (GCK)

Students solving genetics problems with GCK (Jungck & Calley, 1994) can engage in real-world problem solving. GCK requires students to reason from effects (phenotypes) to causes (genotypes and models of inheritance). In order for a geneticist to determine the model of inheritance relevant to a particular trait, she/he must perform crosses (like those simulated in GCK), use the same sorts of reasoning GCK requires, draw conclusions, and persuade peers of his/her findings (like in GCK). With GCK, students solve problems through a whole unit of study, and make observations and generalizations about the models in a discipline.

Students working with well-structured, effects-to-causes genetics problems with GCK can also gain insight into the biological hierarchy. They can see the effects of phenomena that occur on an organismal level of the biological hierarchy and below, such as Mendelian genetics phenomena. Although merely a hypothesis at this time, it appears that students may experience similar outcomes from working with the relatively ill-defined, effects-to-causes problems in ecosystems simulation that they gain working with genetic problems with GCK.

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Appendix E

Letter of Recruitment

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Letter of Recruitment

I am looking for students to participate in a study I am conducting for my dissertation. I hope to improve the teaching of ecology by having students solve realistic problems of ecosystems. My study, which examines how students solve these problems, will be useful for developing curricula and instructional materials. If you agree to participate, I will ask you to volunteer about 2-3 hours of your time to become familiar with the software I am using and to solve a series of problems using situations I will pose to you, as well as situations you create yourself.

Although I can't offer any direct compensation, you may find that working with these problems will help you in your future biology studies. In addition, this may be an opportunity for you to think about your studies in a way you haven't considered before. We think that this project has the potential to be a powerful tool for learning and teaching ecology.

To find out more and/or volunteer, I will be passing around a sign-up sheet in class, or you may call me (372-1834) or send me some e-mail melissa.howse@wmich.edu.

Sincerely,

Melissa Howse

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Appendix F

Ecology (Biology 301) Syllabus

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Ecology (Biology 301) Syllabus

Course Schedule

<u>BIOS 301: ECOLOGY</u>

Fall Semester 2001

Dr Stephen Malcolm, 3151 Wood Hall
Department of Biological Sciences,
Western Michigan University

Ecology is arguably the most important, the most intuitively appealing and the most difficult of the natural sciences because processes that generate observable patterns in nature are so complex and vary so much in scale. In this course we will deal explicitly with habitat characteristics and three levels of biological hierarchy, from individual organisms, through populations of organisms, to communities of populations and their organization into ecosystems. Although we will consider the hierarchy in this order, ecology is the scientific study of the interactions between organisms and their habitat. The hierarchy is thus a convenient simplification and we will try to understand how various ecological processes structure populations into communities. 'Hands-on' field and laboratory exercises using natural ecosystems will be used to illustrate lecture material.

"Interaction" is the keyword for the course so that we can stress the interconnectedness of nature and emphasize Hutchinson's famous metaphor of the "ecological theater" on which the "evolutionary play" is performed.

The course meets with 2 lecture classes and 1 laboratory class (3 sections) each week. Lectures will be held in room 1001 Wood Hall on Monday and Wednesday at 1:00-1:50 p.m. and laboratory classes will meet in room 1106 Wood Hall each week in three sections on either, Thursday at 1:00-4:50 pm, or Friday at 8:00-11:50 am, or Friday at 1:00-4:50 pm.

The required textbook is:

Begon. M., Harper, J.L., and Townsend, C.R. 1996. *Ecology: Individuals, Populations and Communities.* Blackwell Science, 1068 pp. 3rd edition.
(ISBN 0-632-04393-8 book with CD)

All course material will be taken from the required text, but will be supplemented with material from other texts and published papers as acknowledged during the course. Text readings and laboratory exercises are listed for each class on the course schedule. Exams will anticipate that you have read this material and listened to material given in

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lectures. Please bring the textbook to all lectures and lab meetings. In addition, bring a calculator to all lab meetings and exams as well as a number 2 pencil and pen for exams.

Course assessment:

Lecture points:		
	3, one hour exams at 100 each	300
	1 term paper	100
	1 final exam at 200	200
	Total	600
Laboratory points:		
	10 out of 12 quizzes at 10 each	100
	10 laboratory exercises at 30 each	300
	Total	400
	Overall total	**1000**

Grading scale:

A = >90%	BA = >85%
B = >80%	CB = >75%
C = >70%	DC = >65%
D = >60%	E = <60%

Lecture exams and term paper:

The 3, one hour exams and the final exam will be a mixture of single or multiple questions that will require either single sentence answers, graphical answers, occasional equations and calculations, or short essays.

The term paper will be a review of an ecological topic of your choice in the style and format of review articles published in the *Annual Review of Ecology and Systematics* (on shelf QH 540.A53 in the Waldo Science Library). The term paper topic will be chosen at the start of the course and the final paper will be handed in for assessment no later than the lecture meeting on 12 November 2001. Further information about the paper will be handed out in class.

There will also be opportunities to earn bonus points during the course.

Laboratory assessment:

(Teaching Assistants: Stephanie Swart (Thurs., Fri. p.m.) & Derrick Townsend (Fri. a.m.))

Five of the 12 lab meetings will be in the laboratory (including computer sessions) and 5 will be in the field. The first lab session is for hands-on library orientation in the Waldo library and the last meeting is a review session for the whole course. The 12 lab meetings will start with a short quiz. The 10 best of the 12 quizzes will be used for assessment.

The laboratory classes cover topics timed to complement the lectures. The rationale, methods and results for each of these exercises should be described in writing by each student and handed to the TA on the week following the relevant lab. The 10 best of these reports will be used for assessment.

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Academic dishonesty:

Cheating, fabrication and plagiarism will result in a score of zero for the relevant assessment activity and will be treated as described under "Student rights and responsibilities" in the Undergraduate Catalog.

Office hours: Dr Stephen Malcolm

Room 3151 Wood Hall

Tuesday, Thursday: 2:00-4:00 p.m.

Tel:	(616) 387-5604
E-mail:	steve.malcolm@wmich.edu
Fax:	(616) 387-5609)

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Fall 2001 schedule for BIOS 301 – ECOLOGY

Date	*Class*	*Topic*	Text reading[1]	*Lab exercise*
Aug 29	lecture 1	Habitat: Conditions & constraints	ch 2	
30/31	*lab 1*	*Literature research - Waldo library*		*Library*
Sep 3		***Labor Day Recess***		
5	lecture 2	Habitat: Resources	ch 3	
6/7	*lab 2*	*Acclimation to temperature*		*lab*
10	lecture 3	Birth and death	ch 4	
12	lecture 4	Distribution and movement	ch 5	
13/14	*lab 3*	*Life tables*		*Lab computer*
17	lecture 5	Processes: Intraspecific competition	ch 6	
19	lecture 6	Processes: Interspecific competition	ch 7	
20/21	*lab 4*	*Mark and recapture*		*field*
24	**EXAM 1**	**lectures 1 - 6**		
26	lecture 7	Processes: Predation	ch 8	
27/28	*lab 5*	*Competition*		*Lab computer*
Oct. 1	lecture 8	Predator foraging & prey defense	ch 9	
3	lecture 9	Dynamics of predation	ch 10	
4/5	***No lab***	***Spirit day recess***		
8	lecture 10	Processes: Parasitism & disease	ch 12	
10	lecture 11	Processes: Herbivory	ch 8 & 12	
11/12	*lab 6*	*Lotka-Volterra and the logistic equation*		*Lab computer*
15	lecture 12	Processes: Decomposition & detritivory	ch 11	
17	**EXAM 2**	**lectures 7 - 12**		
18/19	*Lab 7*	*Goldenrod gall density*		*field*
22	lecture 13	Processes: Symbiosis & mutualism	ch 13	
24	lecture 14	Life histories	ch 14	
25/26	*lab 8*	*Goldenrod galls: testing hypotheses*		*lab*
29	lecture 15	Abundance & metapopulations	ch 15	
31	lecture 16	Manipulating abundance	ch 16	
Nov 1/2	*lab 9*	*Dispersion analysis*		*field*
5	lecture 17	Communities	ch 17	
7	lecture 18	Community matter and energy flux	ch 18 & 19	
8/9	*lab 10*	*Metapopulation dynamics*		*field*
12	lecture 19	Community structure & competition	ch 20	
14	lecture 20	Community structure & predation	ch 21	
15/16	*lab 11*	*Stream diversity*		*field*
19	**EXAM 3**	**lectures 13 - 20**		
21	**No lecture**	***Thanksgiving recess (21-25 Nov)***		
22/23	***No lab***	Thanksgiving recess (21-25 Nov)		
26	lects 21 & 22	Food webs & Island biogeography	ch 22 & 23	
28	lecture 23	Patterns of biodiversity & Conservation	ch 24	
29/30	*lab 12*	*Review*		*Course review*
Dec. 6	**FINAL EXAM**	**Thursday, December 6, 2:45 – 4:45 p.m. Room 1001, Wood Hall**		

[1]Begon *et al.* (1996)

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Appendix G

Letter of Consent

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Letter of Consent

Western Michigan University Department of Science Studies

Principal Investigator: Robert Hafner

Research Associate: Melissa A. Howse

I have been invited to participate in a research project entitled "Students' Ecological Problem Solving Using Computer Simulation." I understand that this research is intended to study how students use and learn from simulated ecological scenarios with a computer simulation program. I further understand that this project is Melissa Howse's dissertation project. My consent to participate in this project indicates that I will be asked to attend up to four, one-to-one and a half hour private sessions with Melissa Howse. I will be asked to meet Melissa Howse for these sessions at 1025 Trimpe Hall, Western Michigan University. The sessions will involve learning how to use a computer program called Environmental Decision Making (EDM), and posing and solving ecosystems problems using the program. I will be asked to think aloud while solving problems. After each problem, the researcher may ask clarifying questions.

I am aware that while I am solving these problems, the researcher will be recording the actions I take in the computer environment. I understand that my think-aloud protocol will be tape-recorded.

I understand that no risks, hazards, or discomforts are foreseen as a consequence of this study. As in all research, there may be unforeseen risks to the participant. If an accidental injury occurs, appropriate emergency measures will be taken; however, no compensation or treatment will be made available to me except as otherwise specified in this consent form.

Some ways in which I may benefit from this activity are having the chance to learn about ecology and biology, as well as how to use EDM. I also understand that knowledge gained from this study may contribute to improving instructional materials for teaching ecology. Also, I will be given $30 if I complete the problems by going to all the sessions, and $5 if I complete part of the sessions.

I understand that, although no sensitive information is being recorded, all the information collected from me is confidential: my name will not appear on any papers on which this information is recorded. Participants will be identified with a coded reference and a master list that shows corresponding names of subjects will be kept separately from the data. Once the data are collected and analyzed, the master list will be destroyed. All other forms and the tapes will be retained for three years in a locked file in the principle investigator's office.

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I understand that I may refuse to participate or quit at any time during the study without prejudice or penalty. If I have any questions or concerns about this study, I may contact either Melissa Howse at 616-387-5338 or Robert Hafner at 616-387-5844. I may also contact the Chair of Human Subjects Institutional Review Board at 387-8293 or The Vice President for Research at 387-8398 with any concerns that I have. My signature below indicates that I understand the purpose and requirements of the study and that I agree to participate.

Signature

Date

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Appendix H

Research Checklist

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Research Checklist

Set up Computer

Set up Tape Recorder

Sign Letter of Consent

Read Directions:

Throughout this exercise I will be most interested in hearing you reflect out loud everything you are thinking as you pose and solve problems. My goal in having you do this is to find out what you're thinking while you're working with these problems. Try to simply speak the words that are passing through your mind as you solve the problems. You don't need to say anything special or to clarify your thinking. Just work as you normally would. Some people say that they mumble to themselves while they are solving problems. If that's what you do, then just mumble louder. Don't worry if you feel you're being repetitive. This is not a problem. In any case, try to talk constantly. Say what you are thinking and doing even if it doesn't make sense. I will give you some paper, if you wish to take any notes or make drawings during the session. If at any time you want to stop for any reason, just let me know. Please feel free to ask questions at any time. Thank you for volunteering to participate. While solving the practice problems, and for the problems that follow them, follow this procedure:

In the pond simulation (point), "Pond life" (insects and plants in the pond) directly uses sunlight, sunfish eat only pond life, and gar and bass eat only sunfish. The icons for sun, pond life, sunfish, bass and gar are connected to the input/output plotter. The plotter will draw a graph based upon the above mentioned interactions among those icons. The line represents biomass (on the Y axes) over time (on the X axis). The colored buttons (demonstrate) correspond to the color of line the plotter draws for a given icon. The sun is connected to pond; the pond is input to sunfish and output to the plotter; the sunfish is output to the plotter and input to bass and gar; the bass and gar are output to the plotter. Pond life is a **community** of **populations** of plant and insect species, and the fish are populations of only one species each.

In the simulation, tell me any moves you want to make with the mouse or keyboard, and I'll do them for you, so that you don't need to worry about the actual mechanics of performing commands. By double-clicking the icons, you can change the starting values of sunfish (kilocalories (energy)/square m/ day) or any of the living things (biomass/hectare (an area about the size of a football field). (Demonstrate how to pose grassland system problems by describing, but not explaining the line the graph draws.) You can first pose your own problems by creating your own model. When you pose a problem, I want you to predict what will happen with the starting values you give, **before** running the simulation, even if you're not totally sure what will happen.

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I'll press "command R" to run the simulation when you've made the connections and are ready to begin. The computer will make a graph. If the graph isn't very readable, I'll click on the starting and ending values of biomass, and change them to make the line "fit" better. (For example, the line should not go off the graph, on the original, and the graph should start at 0,0.) I also want you to use an ending time, in simulation setup (show), that fits the curve well. I will do this on your suggestion. I will then "take a picture" of your graph for you, and for my records.

After you've had some time to read and interpret the graph, I want you to give me a biological **explanation** for what you saw, whether it agrees with your prediction or not. After you've read and interpreted the graph as thoroughly as you can, I want you to go back to the worksheet with the icons (toggle function is under Window), and tell me how to "tweak" the model and repeat the process, by changing icons' values, until you have tried making **every meaningful change you can think of**. Make the most complete exploration of the simulation you can. Is that clear? Later, for the pre-posed problems, I will run the simulation and ask you to interpret what you see.

Construct: You will be connecting icons that will be pictured before you from the pond simulation. Don't use anything more than once. I want you, at some point to end up exploring the "big picture," that is, problems which involve all the entities connected at once. Deconstruct: You can connect and disconnect the icons pictured before you by drawing lines from outputs of energy to inputs (demonstrate). You cannot add anything to the model that is not here. I want you at some point to end up exploring the "big picture," that is, problems which involve all the entities connected at once.

Any questions?

Start Taping

Start Practice Problems: "Mentally walk me through your house, and describe for me the number and location of windows in your house." (Gobert & Clement, 1999)

Start Deconstruct and Explore Problems, followed by Open-Ended Research Problems

During Interview:

Can you say what you're thinking?
That's very clear
Please tell me what you're thinking
Mmmm.
OK

Assign closed-ended problems

Take snapshots of problems, when complete (repeat as necessary).

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After the problem solving, show participants the closed-ended gar problem with its associated graph, and ask these questions:

What kinds of models do you think are involved in this simulation?

For representing the world, what are some positive aspects or advantages of this simulation?

For representing the world, what are some negative aspects or disadvantages of this simulation?

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Appendix I

Human Subjects Institutional Review Board Approval Letter

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Human Subjects Institutional Review Board

Kalamazoo, Michigan 49008-3899

WESTERN MICHIGAN UNIVERSITY

Date: 4 June 1997

To: Robert Hafner, Principal Investigator
Melissa Howse, Student Investigator

From: Richard Wright, Chair

Re: Changes to HSIRB Project Number 97-03-22

This letter will serve as confirmation that the changes to your research project "Students' Ecological Problem Solving Using a Computer Simulation Program" received 27 May 1997 have been approved by the Human Subjects Institutional Review Board.

The conditions and the duration of this approval are specified in the Policies of Western Michigan University.

Please note that you may **only** conduct this research exactly in the form it was approved. You must seek specific board approval for any changes in this project. You must also seek reapproval if the project extends beyond the termination date noted below. In addition if there are any unanticipated adverse reactions or unanticipated events associated with the conduct of this research, you should immediately suspend the project and contact the Chair of the HSIRB for consultation.

The Board wishes you success in the pursuit of your research goals.

Approval Termination: 5 April 1998

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