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Rethinking biology instruction: the application of DNR-based instruction to the learning and teaching of biology

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Rethinking Biology Instruction: The Application of DNR-based Instruction to the Learning and Teaching of Biology

A dissertation submitted in partial satisfaction of the requirements for the degree Doctor of Philosophy in Mathematics and Science Education

by

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Professor Alexander Chizhik
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2006
The dissertation of April Lee Maskiewicz is approved, and it is acceptable in quality and form for publication on microfilm:

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University of California, San Diego

San Diego State University

2006
I dedicate this dissertation to my husband, Frank Maskiewicz,
and to my parents, Vincent and Lynn Cramer,
who never wavered in their confidence that I could reach my goals.
Thank you for your endless encouragement.
TABLE OF CONTENTS

Signature Page ..............................................................................................................iii
Dedication .....................................................................................................................iv
Table of Contents ..........................................................................................................v
List of Figures and Tables ............................................................................................ix
Acknowledgements .......................................................................................................x
Vita ..............................................................................................................................xii
Abstract of the Dissertation ........................................................................................xiv

CHAPTER 1: INTRODUCTION ..................................................................................1
The Need to Rethink Biology Instruction ................................................................. 1
Unscientific Reasoning ............................................................................................ 4
Factors that Affect Students’ Learning ................................................................. 8
Summary of the Need to Rethink Biology Instruction .................................. 14
Theoretical Perspective: DNR-based Instruction in Mathematics .................. 17
The Application of Harel’s DNR to Biology ......................................................... 19
Ecology as the Context for the Application of DNR to Biology .................... 21
Overview of the Dissertation .................................................................................... 25

CHAPTER 2: THE DNR INSTRUCTIONAL PRINCIPLES AND BIOLOGY .......29
DNR-based Instruction in Mathematics ................................................................. 30
The Duality Principle ............................................................................................ 30
The Necessity Principle ......................................................................................... 35
Repeated Reasoning .............................................................................................. 37
Summary of the Principles of DNR-based Instruction ........................................ 38
The Relationship of Harel’s DNR to Theories on Learning ....................... 39
Cognitive Theoretical Perspective on Learning ................................................. 40
Social Theoretical Perspective on Learning ......................................................... 41
Summary of the Relationship of Harel’s DNR to Theories on Learning .......... 45
Conclusion: The Application of DNR-based Instruction in Biology ............. 46

CHAPTER 3: REVIEW OF EXISTING RESEARCH ..............................................49
The Research on Ways of Thinking in Biology .................................................... 49
Beliefs Influencing Students’ Interpretations ....................................................... 50
Problem Solving Approaches ............................................................................. 53
Anthropomorphic and Teleological Reasoning ............................................... 67
Summary of the Research on Ways of Thinking in Biology ......................... 69
A Review of the Literature on Students’ Current Ways of Understanding
Ecological Concepts and Processes ................................................................. 70
The Role of Photosynthesis and Respiration in Ecosystems ....................... 71
Matter and Energy in Ecological Systems ......................................................... 75
Summary of the Research on Students’ Ways of Understanding .................. 82
The Research on Problem Solving in Science Education ......................... 84
Well-structured versus Ill-structured Problems .......................................................... 85
Problem-based Learning.............................................................................................. 87
Conclusion................................................................................................................... 90

CHAPTER 4: METHODOLOGY.................................................................................. 93
Methodological Implications of the DNR Framework............................................... 93
Interview and Teaching Experiment Methodology ................................................... 95
Setting......................................................................................................................... 97
Phase 1: Observations and Interviews ...................................................................... 98
  Observations............................................................................................................ 98
  Semi-structured Clinical Interviews ...................................................................... 99
  Teaching Interviews............................................................................................... 101
Phase 2: Primary Teaching Experiment ................................................................ 103
  Participants .......................................................................................................... 104
  Class Format......................................................................................................... 104
  Data Collection..................................................................................................... 105
  Data Analysis........................................................................................................ 105

CHAPTER 5: THE DUALITY AND NECESSITY PRINCIPLE APPLIED TO
ECOLOGY EDUCATION....................................................................................... 110
Mental Act: Accounting for Phenomena................................................................. 110
The Ways of Thinking of Ecologists Associated with the Mental Act of
Accounting for Phenomena...................................................................................... 112
  Stage I: Interconnectedness ................................................................................ 113
  Stage II: Multi-dimensional Relating ................................................................. 115
  Stage III: Expanding Multi-dimensional Relating .............................................. 122
Summary of the Ways of Thinking of Ecologists associated with the Mental
Act of Accounting for Phenomena......................................................................... 137
Models of Students’ Ways of Understanding......................................................... 140
  Transformation of Matter and Energy ................................................................ 141
  Cellular Processes: Photosynthesis and Respiration .......................................... 144
Summary of Students’ Ways of Understanding....................................................... 146
Designing Instruction based on the Necessity Principle ........................................ 149
  Explicating Intellectual Need in Biology ............................................................ 152
Designing Instruction based on Creating Intellectual Need..................................... 153
Hypothetical Learning Trajectory............................................................................. 156

CHAPTER 6: RESULTS ON THE EVOLUTION OF STUDENTS’ WAYS OF
THINKING AND WAYS OF UNDERSTANDING................................................. 160
Student 1: The Evolution of Franjelica’s Ways of Understanding and Thinking 162
  Franjelica’s Initial Ways of Understanding.......................................................... 162
  Franjelica’s Initial Ways of Thinking................................................................... 165
Changes in Franjelica’s Ways of Understanding.................................................... 173
Changes in Franjelica’s Ways of Thinking............................................................. 183
LIST OF FIGURES AND TABLES

Figure 1: Two textbook’s treatment of biology concepts ............................................11
Figure 2: The science education view of the Nature of Science .................................53
Figure 3: Scientific knowledge and practices (from Anderson, 2003)..............................111
Figure 4: Comparison of the complexity of students’ versus ecologists’ diagrams..118
Figure 5: Evolution of my understanding of ecologists’ ways of thinking ...............122
Figure 6: Characteristics of students’ accounts of phenomena .................................127
Figure 7: Evolution of my understanding of ecologists’ ways of thinking - 2 .........137
Figure 9: Diagram of application of Duality Principle to biology instruction .........148
Figure 10: Cognitive objective for instruction and interdependent ways of understanding ............................................................................................................150
Figure 11: Duality Principle applied to learning in ecology ........................................161
Figure 12: Franjelica’s initial ways of understanding and thinking .........................173
Figure 13: Franjelica’s ways of understanding before and after instruction ............183
Figure 14: Changes in Franjelica’s ways of understanding and thinking ..............191
Figure 15: Austin’s initial ways of understanding and thinking .............................200
Figure 16: Austin’s ways of understanding before and after instruction ...............203
Figure 17: Changes in Austin’s ways of understanding and thinking ...................208
Figure 18: Rachel’s initial ways of understanding and thinking .............................217
Figure 19: Rachel’s ways of understanding before and after instruction ...............223
Figure 20: Changes in Rachel’s ways of understanding and thinking .................228
Figure 21: Problem statement 1B .................................................................234
Figure 22: Problem statement 1C .......................................................................236
Figure 23: Problem statement 1D .......................................................................248
Figure 24: Problem statement 1E .......................................................................252
Figure 25: Problem statement 1E supplemental .....................................................253
Figure 26: Problem statement 3A – The Dead Zone ............................................259
Figure 27: Information sheet accompanying Problem 3A.................................259

Table 1: Description of student participants ..............................................................108
Table 2: Modified explication of Model-based Reasoning .......................................131
Table 3: Ecosphere water composition data .............................................................237
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# VITA

## EDUCATION

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<td>1992</td>
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<td>University of California, San Diego</td>
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<td>2000</td>
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<td>2006</td>
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## RESEARCH EXPERIENCE

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<td>2002</td>
<td>Research Assistant</td>
<td>Dr. Kathleen Fisher, P.I. San Diego State University Biology Education</td>
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<tr>
<td>2001-2003</td>
<td>Research Assistant</td>
<td>Dr. Fred Goldberg, P.I. San Diego State University Physics Education and Teacher Professional Development</td>
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<tr>
<td>2004 Winter</td>
<td>Research Assistant</td>
<td>Dr. Guershon Harel P.I. University of California, San Diego Mathematics Education</td>
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<tr>
<td>2005–2006</td>
<td>Research Assistant</td>
<td>Dr. Guershon Harel and Dr. Barbara Sawrey, Co-P.I.’s University of California, San Diego Biology Teacher Professional Development</td>
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## COLLEGIATE TEACHING EXPERIENCES

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<td>Adolescent Development and Education (Education Studies) Biodiversity (Biology Dept.) Introductory upper division Ecology (Biology Dept) Evolution, Behavior and Ecology (Biology Dept) University of California, San Diego</td>
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K-12 TEACHING EXPERIENCE

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<td>Rancho Buena Vista High School</td>
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PRESENTATIONS AND PAPERS


ABSTRACT OF THE DISSERTATION

Rethinking Biology Instruction: The Application of DNR-based Instruction to the Learning and Teaching of Biology

by

April Lee Maskiewicz

Doctor of Philosophy in Mathematics and Science Education

University of California, San Diego, 2006

San Diego State University, 2006

Professor Guershon Harel, Co-chair
Professor Gabriele Wienhausen, Co-chair

Educational studies report that secondary and college level students have developed only limited understandings of the most basic biological processes and their interrelationships from typical classroom experiences. Furthermore, students have developed undesirable reasoning schemes and beliefs that directly affect how they make sense of and account for biological phenomena. For these reasons, there exists a need to rethink instructional practices in biology.

This dissertation discusses how the principles of Harel’s (1998, 2001) DNR-based instruction in mathematics could be applied to the teaching and learning of biology. DNR is an acronym for the three foundational principles of the system:
Duality, Necessity, and Repeated-reasoning. This study examines the application of these three principles to ecology instruction. Through clinical and teaching interviews, I developed models of students’ existing ways of understanding in ecology and inferred their ways of thinking. From these models a hypothetical learning trajectory was developed for 16 college level freshmen enrolled in a 10-week ecology teaching experiment. Through cyclical, interpretive analysis I documented and analyzed the evolution of the participants’ progress.

The results provide empirical evidence to support the claim that the DNR principles are applicable to ecology instruction. With respect to the Duality Principle, helping students develop specific ways of understanding led to the development of model-based reasoning—a way of thinking and the cognitive objective guiding instruction. Through carefully structured problem solving tasks, the students developed a biological understanding of the relationship between matter cycling, energy flow, and cellular processes such as photosynthesis and respiration, and used this understanding to account for observable phenomena in nature.

In the case of intellectual necessity, the results illuminate how problem situations can be developed for biology learners that create cognitive disequilibrium-equilibrium phases and thus lead to modification or refinement of existing schemes. Elements that contributed to creating intellectual need include (a) problem tasks that built on students’ existing knowledge; (b) problem tasks that challenged students; (c) a routine in which students presented their group’s solution to the class; and (d) the didactical contract (Brousseau, 1997) established in the classroom.
CHAPTER 1: INTRODUCTION

The Need to Rethink Biology Instruction

From my observations of high school biology teachers, experience teaching biology at the secondary and college level, and recent participation in over a half dozen biology courses at the university level, biology classroom instructional practices are consistent with the “transmission” model of instruction: students primarily listen, watch, read and restate information for instructors. Although a variety of alternate strategies have been developed for science instruction (Albanese and Mitchell, 1993; Christianson and Fisher, 1999; Lotan, Cohen, and Holthuis, 1994; Tanner and Allen, 2004), these approaches are not widely used. Instead, the traditional pedagogical setting of teacher-centred instruction dominates the biology classroom. The NAEP results (Henke, Chen, and Goldman, 1999) confirm my own experience that current curricula and teaching methods impart facts and rote skills to most students through “lecture, textbook reading and routine exercises” (p. 67). This instructional approach has not proved to be effective. It is well documented in science education research that after instruction, many students continue to harbor unscientific conceptions for a variety of biology concepts¹ and processes. (Carlsson, 2002a,b; Driver, Squires, Rushworth, and Wood-Robinson, 1994; Leach, Driver, Scott, and Wood-Robinson, 1995, 1996a,b; Lumpe and Staver, 1995; Songer and Mintzes, 1994). In fact, several studies have examined the effect of prerequisite courses on student success and found that the number of previous classes students had completed was not an accurate

Studies conducted as part of the research for this dissertation revealed similar findings. The undergraduate college students interviewed in this study did not reveal a biological understanding of many basic biology concepts regardless of the number of previous high school or lower division biology classes the students had completed. Consider, for example, the following responses to questions about the needs of plants from a college level freshman biology major. This student completed two years of high school biology, passed the AP Biology exam (allowing her to test out of two required lower division biology courses offered at the university level) and was concurrently enrolled in the last of three required lower division chemistry courses.

Yet, when asked a simple question about the needs of plants she revealed limited and fragmented knowledge.

Interviewer: Okay…So what do your plants need to survive? (Asked within the context of growing plants on a space station.)
Student: I guess whatever they need to survive on earth is, ah, sun would be important.

…
Student: Um, they need..god (sigh), I really want to say nitrogen fixing bacteria but, I don't really know.
Interviewer: Do you know what that means when you say it?
Student: Yeah, I mean, I thou-ght so- well sort of. Let’s see, I learned this last year so I should remember it.

…
Student: I mean, I guess you need something to get the nutrients to them or whatever. I'm only remembering like vague words from-
Interviewer: What class was it?
Student: AP bio.

…
Student: Yeah, I can't remember.
Interviewer: So somehow they need this kind of bacteria for doing something but we are not sure what.
Student: Yeah.
Interviewer: Okay, that's fine.
Student: Then gravity cause they needed to grow because of the xylem and phloem. Ooh, I remember that. But yeah, okay.
Interviewer: So we've got sun, we've got gravity, we've got some kind of bacteria that does something for its nutrients you said.
Student: Yeah. And water.
Interviewer: Water, okay.
Student: I suppose fertilizer, because I guess that is part of nutrients.
Interviewer: Okay,
Student: Um (pause) I can't think of what else they would need, or I just can't remember.

This student relied on memorized knowledge from her course work when trying to list what plants need to survive. In her responses, she mentioned nitrifying bacteria—although she did not know why the plants would need them—and gravity for xylem and phloem, yet, later in the interview it became clear that the student did not know the functional roles of xylem and phloem. Noticeably absent from her list of “needs” was carbon dioxide, a requirement commonly omitted by most of the students interviewed. The students associated carbon dioxide with plants only within the context of discussing the gas exchange between plants and animals. They understood photosynthesis as the process by which a plant uses sunlight as energy to convert carbon dioxide into oxygen, as opposed to a process by which carbohydrates are synthesized from carbon dioxide and water using light as an energy source. With her background in biology, this student should have been able to provide a scientific response to this relatively simple question. Instead, she revealed fragmented memorized knowledge.
Interview data collected during the pilot study and this present study reveal similar findings. Of the fourteen college level students interviewed, thirteen held naïve understandings of some of the more fundamental concepts underlying biological systems, including plant and animal composition, needs, and interdependencies. I use the term naïve here to refer to either an unscientific understanding or an understanding associated with a memorized definition. In most cases, the students tried to draw on information they had memorized in previous biology courses, but were often unsuccessful. Furthermore, they struggled to describe the relationships among various biological processes such as photosynthesis, respiration and decomposition. When asked to consider the relationship between organisms and the abiotic factors that comprise a community, none of the students discussed ideas of energy transformation and few mentioned ideas associated with matter cycling. In fact, students often confounded ideas about matter and energy, a common error among students of all ages (Anderson, Mohan and Sharma, 2005). These findings support the existing research that suggests that although a student can memorize and reiterate definitions on an exam, this does not necessarily translate into developing ways of understanding biological concepts and processes that are shared among the community of biologists (Adeniyi, 1985; Carlsson, 2002a,b; Leach, Driver, Scott, and Wood-Robinson, 1995a; National Research Council, 1999; Songer and Mintzes, 1994).

Unscientific Reasoning

The interviews conducted in this study further revealed that these college level students had developed unscientific ways of reasoning about relationships in natural
systems. For instance, students searched for simple linear causal relations between entities in an organic system and often applied teleological reasoning when trying to account for ecological phenomena. Various studies investigating students’ reasoning as they try to account for an observation reveals that students have undesirable ways of thinking about causal relationships in complex systems (Driver, Squires, Rushworth, and Wood-Robinson, 1994; Grotzer and Perkins, 2000; Grotzer and Basca, 2003; White, 2000). To better understand the nature of reasoning for students at the university level, I presented situations in my pilot study interviews that were intended to cause students to engage in identifying relationships, as well as try to account for phenomena. Susan’s interview responses given below provide a representative example of the characteristics of most of the students’ causal reasoning.

Example One. Each pilot interview began with the student discussing the relationships between various components of an intertidal ecosystem (see Appendix 1 for pilot study protocol). The student was then asked about the effects of changes to various components of the intertidal system (for example, an invasive species and/or a change in the ocean temperature). When Susan was asked about the effect of a new species migrating to an existing intertidal ecosystem, she identified the effect by focusing on a linear food chain relationship:

Like its probably going to most immediately affect the mollusk but then that’s going to affect the barnacles which is going to affect the microfauna. So it’s going to change the system… There would be more of them- more of the microfauna. Because there is less barnacles to eat them.
Susan focused on the prey that each organism in the chain ate. She did not mention that other organisms at each level would be affected by these changes, nor did she discuss the change in species at a level above the mollusk. From a scientific viewpoint, at each level in the food chain, when one organism is affected, all organisms within the chain and outside the immediate chain can be affected.

Similarly, when Susan was trying to identify possible causes for the numerical data that she was given, she again described simple linear cause-effect relationships:

Susan: Okay, and then the barnacles eat the microfauna…. The microfauna eat the algae, so…okay somehow they [the snails] are affecting the barnacles.
Interviewer: Which one? [Mexicanthina or native.]
Susan: Both. ‘Cause this guy coming in affects this guy going out. It’s gonna affect the barnacles which is in turn gonna affect the microfauna. So maybe we are finding more, no less of the microfauna.

Here Susan was searching for direct relationships between each organism in the system. She did not consider a branching or ripple effect, but rather, described a domino type of cause-effect relationship. The distinction here lies in the pattern of effects. Susan imposed a simple linear pattern to make sense of the causal relations and explain their effects. She traced the route of the perturbation through a linear chain of cause-effect relations. In natural systems, there are a multitude of organisms that are indirectly affected. A perturbation often spreads out in a branching pattern to affect many organisms. Alternately, a domino pattern of causality describes a linear chain of cause-effect relations. As with most of the students, the general approach to account for a change in a biological system was to search for direct feeding relationships.

Furthermore, none of the students mentioned the more passive events of matter
cycling and energy flow. They focused on the active event of who eats whom.
Conversely, the ecologist interviewed in the pilot study considered multiple possible causes for changes in the intertidal ecosystem presented to her; she considered changes at time scales both short and long term; and she considered indirect as well as direct relationships as possible causes.

Teleological Reasoning. In the process of identifying the character of the connections students made between organisms and entities in the ecosystem, I identified another type of reasoning that the literature in biology education describes as anthropomorphic and teleological reasoning. With anthropomorphic reasoning, when a person considers relationships or connections, he or she ascribes human motivation, characteristics, or behavior to inanimate objects, animals, or natural phenomena. With teleological reasoning, a component of anthropomorphic reasoning, a person attributes conscious purpose to something within a simple physical or natural phenomenon.

Example Two. When Susan considered the possible effect of an increase in water temperature she stated that the organisms living in the water would be most affected:

It’s going to change things for the guy who lives in the water. Some of them. For some of them it’s probably, okay, fine, I’ll deal with it. But for some of them it might be more difficult to live.

Here Susan attributed a consciousness to the actions of the “guy” living in the water. This “guy” will “deal with” the change in water temperature.
Similarly, another student, Maria, attributed conscious purpose to an organism’s dispersal when considering the possible effects of a water temperature increase on the intertidal community:

Um, well, certain organisms usually go to, or live in a climate, or habitat where they can survive and are most, where they flourish the most.

Here Maria implied that organisms choose to move or relocate rather than adapt over time to an area or migrating slowly over time. Later, as she discussed the possible cause of an increase in the mexicanthina snails in the environment, she again revealed teleological reasoning:

And maybe they don’t like the new type of snail; they don’t prey on it as much so that could be an increase in the new snail. They are not used to it. It’s not part of their original area.

In these instances, Maria was attributing conscious purpose to the organisms to explain an ecological phenomenon.

Teleology often plays a role in students’ understanding of biology (Preece and Janvier, 1992; Tamir and Zohar, 1991). Thinking teleologically about the nature of biological processes can hinder students’ development of the scientific way of understanding, and can ultimately affect how they reason about causal relations. Explaining biological phenomena in terms of purposes and intentions does not account for the causes by which these processes are brought about. For this reason, teleological reasoning is undesirable from a science educator perspective.

Factors that Affect Students’ Learning

Instructional approaches in biology can help to explain why students may not be developing the scientific understandings and reasoning patterns that are reflective
of the community of biologists. Biology instruction at both the college level and high school level tend to focus on biological facts, definitions, and processes while ignoring the broader conceptual tools that govern students’ understandings of the subject matter (such as scientific reasoning). Quite often students can respond correctly to test questions on specific concepts; however, research studies reveal that students may have only limited understanding of these concepts and their relation to other biological concepts (Leach, Driver, Scott, and Wood-Robinson, 1995; Carlsson, 2002a). Looking more closely at the structure of the field of biology can provide insight into how this structure has influenced the current instructional approaches to biology.

The Compartmentalization of Biology

Over the past century, the field of biology has differentiated into a collection of separate domains. For example, college biology departments are typically separated into at least two academic sections, one focusing on molecular and cellular biology (including developmental and neurological biology) and the other focusing on organismal biology (including ecology and evolution). Within these academic sections, there is often further division into specific specializations: anatomy, biochemistry, biotechnology, botany, developmental biology, evolution, genetics, immunology, ecology, marine biology, neurology, mycology, zoology, and so forth. Biology research journals are also differentiated across these same areas of specialization. The separation of biology into distinct domains results from a need to specialize and focus on a manageable amount of information at one time in order to advance the field.
Biology education has conformed to this same compartmentalized approach. For example, at the university level, students enroll in courses focusing on each separate domain of biology: cellular biology, molecular biology, developmental biology, and so on. Accordingly, many biology textbooks present information segregated into separate domains. Each chapter or group of chapters within the text is often represented as an independent domain. For example, two secondary level biology textbooks, *Biology, The Study of Life*, published by Prentice Hall (1999) and *Modern Biology*, published by Holt, Rinehart, and Winston (1999) are organized into the following biology domains: cells, genetics, evolution, ecology, microorganisms, plants, invertebrates, vertebrates, and humans. Within each text, three to five chapters are offered for each of these divisions.

One of the drawbacks of this compartmentalized approach to biology in textbooks is that it limits students’ ability to develop an intellectual appreciation for interrelationships among biological phenomena and the related concepts and processes. For example, there is an integral relationship between matter and energy concepts and biological processes such as cellular respiration, photosynthesis, and the sustainment of ecosystems. In textbooks however, each of these biological processes is taught independently. Each of the biology concepts involved in matter and energy transformations (cellular metabolism, cycles of matter and flow of energy in ecosystems, and metabolic activities of multicellular organisms such as digestion and circulation) is separated into different units of the text with no clear connection between their relationship and dependence on each other (see Figure 1). Thus, it is not
surprising that students lack a coherent understanding of the role of matter and energy in cells, organs, bodily systems, organisms, or ecosystems.

Prentice Hall (1999) - Biology: The Study of Life:
Ecology is the first section of the text. In this section the text briefly states that energy and matter flow through ecosystems are necessary to sustain life. The text then introduces flow of energy through the ecosystem by discussing food webs and trophic levels. This is followed by a discussion of the cycles of matter (eg. water cycle, carbon cycle…). The next unit in the text focuses on cells. Chapters are titled: Cell Structure and Function, Photosynthesis, Cell Respiration, and Cell Growth and Division. In the photosynthesis and cell respiration chapters, energy is briefly introduced but not related to the previous unit on ecosystems. Body systems such as digestion and circulation comprise the last set of chapters in the book with one chapter for each system. No relationship is made between cellular processes and body systems, nor body systems and organisms within an ecosystem.

Holt, Rinehart, and Winston (1999) – Modern Biology:
The text begins with one chapter on chemistry and one on biochemistry. A few statements address the energy in chemical reactions. The text explains that oxidation and reduction reactions involve the transfer of electrons. The next unit in the text covers cell concepts: Structure and Function of Cells, Photosynthesis, and Cellular Respiration. Little reference is made to the relation between energy concepts discussed in chemical reactions and energy concepts in cellular processes. Just as in Prentice Hall, the systems of the body are the last group of chapters at the end of the text. Digestion is not presented as related to cellular metabolism or biological levels of organization.

Figure 1: Two textbook’s treatment of biology concepts related to matter and energy transformations

Concepts Presented in Isolation

At the high school level science teachers often rely on textbooks for decisions about how to best organize instruction for students (Lloyd, 1993). Therefore, teachers organize their courses into units that perpetuate the division of biology into separate domains. This approach to biology instruction compartmentalizes biology in such a way that few if any connections are made between the different units of instruction. Students are presented with biological facts and processes in isolation and are
expected to learn them in a given sequence without developing a way of understanding the relationships among these concepts. As a result, students develop a belief that biology is an assemblage of unrelated facts that must be memorized.

Although students may perform competently on exam questions focused on the different domains in biology (for example, cells, ecosystems, the digestive and circulatory system) their knowledge is often superficial; that is, students do not understand the relationship between a specific concept and the related biological phenomena (Anderson, Mohan, and Sharma, 2005; Leach, Driver, Scott, and Wood-Robinson, 1995, 1996a; Lumpe and Staver, 1995; Songer and Mintzes, 1994). Instead, they have only memorized knowledge. Schoenfeld (1988) revealed an example of this type of superficial learning through the study of one mathematics teacher whose students consistently scored high on statewide examinations in geometry. The math teacher attributed the high scores to the students’ memorization of a number of geometry proofs that typically appeared on the exams. Schoenfeld found, however, that those same students could not apply their knowledge to problems that were not identical to the problems they had practiced. Although students did well on standardized tests, they did not understand what they were doing, and often could not answer questions that required a deeper understanding of the relevant mathematics.

This type of superficial knowledge is not restricted to mathematics learning. The research in biology education reveals that biology students often do not develop meaningful connections among concepts, but rather they learn to memorize information and reproduce that information as presented (Okebukola, 1990; Leach,

My pilot interviews provide an example of this type of superficial understanding. For instance, when one student was asked how matter was related to any of the intertidal ecosystem components presented on the cards provided (see Appendix 1), she relied on a memorized definition for matter: “Matter is anything that has mass and occupies space.” When asked, however, to describe any connections between matter and the various components of an intertidal ecosystem that were already presented, she became confused: “What is that? Matter is, is it matter is not-no it’s energy. I’m thinking of energy. Energy is neither created nor destroyed.” This student’s understanding of matter and energy was likely developed from a physical science experience, and it appeared that she had not yet considered the relationship between matter and energy and biological organisms, processes, or phenomena. Instead, she had developed memorized definitions and laws related to the terms “matter” and “energy.”

These experiences of learning biology by memorizing not only leads to superficial or shallow understandings, but can also result in developing unscientific beliefs about the nature of biology—that biology is a compilation of facts that are independent of each other. This belief about biology can then influence students’ interpretations of new information. Rather than trying to identify connections and
relationships among biological concepts being learned, students are content to simply memorize facts and engage in rote learning. Thus, a student’s way of understanding specific concepts and ideas in biology leads to a belief about the nature of biology that ultimately affects his or her future understanding of biological concepts. Biology instruction needs to help students develop the perspective that biology is not about memorizing facts, but rather, is about making sense of observations and patterns in nature and building and applying intellectual models that attempt to represent the realities of nature.

Summary of the Need to Rethink Biology Instruction

Typical biology classroom learning situations result in students memorizing information rather than reasoning about it and developing biological understandings. The research in biology education confirms that many students are not currently recognizing the complex relationships in ecological systems (Anderson, Mohan, and Sharma, 2005; Leach, Driver, Scott, and Wood-Robinson, 1996a; Lin and Hu, 2003). Students have limited understandings of basic biological concepts and processes underlying the functioning of an organic system (Anderson, Sheldon, and Dubay, 1986; Anderson, Sheldon, and Dubay, 1990; Carlsson, 2002a, 2002b; Leach, Konicek, and Shapiro, 1992; Leach, Driver, Scott, and Wood-Robinson, 1995, 1996a, 1996b; Roth and Anderson, 1987). Furthermore, students’ undesirablereasoning schemes and beliefs directly affect how they make sense of, and account for biological phenomena (Grotzer and Basca, 2003; Keselman, 2003; White, 2000).
Biologists, on the other hand, understand the interrelationships and interdependencies of the concepts and processes in various domains of biology. For example, ecologists understand that macro-level properties emerge in organic systems as a result of micro-level interactions, and view the net effects of all ecological system relationships as interacting simultaneously (Picket, Kolasa, and Jones, 1994). Ecologists account for biological phenomena by drawing on their understanding of photosynthesis, respiration, and decomposition as biologically mediating processes that facilitate the transformation of matter and energy within ecosystems, and they understand the interrelationships among these processes. The students interviewed for this study, when trying to make connections between objects to explain a phenomenon, often claimed, “All things are connected.” This claim, however, usually represented only organismal level connections. Although the students recognized that objects in a system interacted and affected each other, they did not extend this view beyond local phenomena, nor did they consider the underlying processes that resulted in the observed phenomena.

Students’ fragmented and unscientific knowledge may be the result of instructional practices that deny students an opportunity to reason about relationships in organic systems. For example, in the case of simple linear reasoning, Grotzer and Basca (2003) suggest that because instruction relies on simple linear models, students develop this type of reasoning. It is common for students to be presented with information about the cycling of elements in nature and at a later time told about natural phenomena that involve the cycling of matter. Students are not provided with
an opportunity to consider the nonlinear relationships in ecological contexts. It may also be that developing nonlinear ways of thinking about relationships is a more difficult obstacle to overcome. In either case, our existing knowledge about students’ thinking can and should be used to begin to reconsider cognitive goals for instruction so that students can develop scientific understandings and reasoning that reflects those of biologists.

Within the field of biology education, little foundation exists for developing cognitive objectives for instruction based on these overarching broad conceptual tools institutionalized in the field. Many research studies focus instead on students’ concept knowledge in the same way that instruction does. The purpose of my dissertation research is to contribute to the development of theory for reconceptualizing biology instruction to consider both the subject matter content and the broader overarching conceptions of students. How can we foster students’ construction of biological ways of thinking and understanding that took the community of biologists centuries to develop? An instructional principle is needed in biology education that considers both the subject matter content and the broader overarching conceptions so that students can develop the intellectual tools that define biological thinking. This theoretical perspective must consider how the learners’ existing knowledge influences their future learning. Finally, the instructional framework must be based on a scientific understanding of student learning and the influence of classroom situations.
Theoretical Perspective: DNR-based Instruction in Mathematics

Harel’s (1998; 2001) DNR-based instruction in mathematics is an instructional principle that combines the views of the learner with the way the learner understands the content. DNR is an acronym for the three foundational principles of the system: Duality, Necessity, and Repeated-reasoning. The DNR instructional principles are empirical inferences about the effects of teaching actions on students’ learning within the domain of mathematics. This instructional framework can be interpreted as being grounded in and unifying two theories on learning—the constructivist theories (Steffe, 1991; Steffe and Thompson, 2000; von Glasersfeld, 1995) and the sociocultural theories (Cobb and Yackel, 1996; John-Steiner and Mahn, 1996) on learning. Accordingly, this theoretically grounded instructional system consists of elements that appear to be both practical and applicable for the transformation of biology instruction. The DNR perspective is discussed in detail in chapter 2; however, I include a brief introduction here.

**Duality Principle.** Harel (1998) identifies two categories of knowledge that affect mathematical reasoning: “ways of thinking” and “ways of understanding.” “Ways of understanding” is defined as the particular product of a mental act carried out by an individual, such as interpretations, solutions, and justifications. The characteristics of one’s mental acts are his or her “ways of thinking,” and include problem-solving approaches, proof schemes, and beliefs about mathematics. Ways of thinking govern one’s ways of understanding (Harel, 1998, 2001).
A developmental interdependency exists between one’s ways of understanding and ways of thinking: “a change in ways of thinking brings about a change in ways of understanding, and vice versa” (Harel, in press, p.18). Harel (2001) labeled this the Duality Principle. According to Harel, reciprocity exists between what students produce and the character of their mental acts—between their ways of understanding and their ways of thinking—and both types of knowledge must be considered in developing cognitive instructional goals.

**The Necessity Principle.** This principle states that students are more likely to learn when they see a genuine need (intellectual, not necessarily social or economic). “The term intellectual need,” explains Harel (in press), “refers to a behavior that manifests itself internally with learners when they encounter an intrinsic problem—a problem they understand and appreciate” (p.18). This principle is grounded in the Piagetian theory of equilibration. Students’ existing knowledge provides a contrast to the new knowledge thus facilitating the acquisition of the new knowledge. According to the necessity principle, “problem solving is not just a goal but also the means—the only means—for learning mathematics” (Harel, in press, p.21).

**Repeated Reasoning.** The Repeating Reasoning principle posits that students must practice reasoning in order to internalize specific ways of thinking and ways of understanding (Harel, 1998; 2001). The Repeated Reasoning principle complements the other two principles because it aims for students to internalize what they have learned through the application of the Duality and Necessity Principles.
In summary, the DNR perspective calls attention to the reflexive relationship between subject matter and conceptual tools; one’s ways of understanding and ways of thinking. As such, it advocates that instruction should focus on both types of knowledge, with conceptual objectives for instruction formed in terms of ways of thinking. The three principles of DNR offer a “perspective that provides a language and tools to formulate and address critical curricular and instructional concerns” (Harel, in press, p.17). Furthermore, Harel’s DNR-based instruction provides a framework that elucidates how the research on students’ ways of understanding and thinking, along with the knowledge about student learning from psychology and cognitive science, can be unified and translated into effective teaching products and instructional practices.

The Application of Harel’s DNR to Biology

According to the Benchmarks for Scientific Literacy, students should be developing “habits of mind that enable citizens to ... make sense of how the natural and designed worlds work, to think critically and independently, to recognize and weigh alternative explanations of events and design trade-offs, and to deal sensibly with problems that involve evidence, numbers, patterns, logical arguments, and uncertainties” (AAAS, 1993, p. XI). The “habits of mind” described by the Benchmarks encompass the “ways of thinking” in DNR-based instruction—conceptual tools that govern students’ understanding of subject matter. Therefore, the intended goal of DNR-based instruction —“developing mental acts whose products and characters are desirable and eventually mathematically acceptable” (or in this case
scientifically acceptable)—is a goal that biology educators should consider adopting. Focusing only on subject matter in terms of ways of understanding limits students’ opportunities to become independent thinkers and creators of science. Forming cognitive objectives for instruction in terms of ways of thinking can help students develop scientific beliefs, problem solving approaches, and justification schemes reflective of the larger biological community. Furthermore, the Necessity and Repeated-reasoning principles provide a direction for applying what we know about students’ learning to the teaching of biology.

Therefore, in this study, I sought to determine how the principles of the DNR perspective on teaching and learning in mathematics could be applied to the teaching and learning of biology. Could the principles of DNR be used in biology education to help students develop the ways of thinking and the ways of understanding of biologists? I selected the field of ecology as the context for this study because ecology integrates many sub-domains of biology. (I discuss this point in the subsequent section).

In the present study, I set out to answer the following research questions:

1. To what extent can the Duality Principle be applied to ecology education?
   • What are some of the ecological ways of thinking?
   • What are some of the ways of understanding that might help students develop these ecological ways of thinking?

2. What constitutes intellectual necessity for ecology learning?
   • What does intellectual necessity within an ecological context look like?
   • What does learning look like in an ecology context when instruction is based on creating intellectual need in the student?
The purpose of this research is to contribute to the development of theory for reconceptualizing biology instruction. My findings, presented in the following chapters, broaden the existing knowledge about students’ learning and thinking in biology.

**Ecology as the Context for the Application of DNR to Biology**

The science of ecology is the study of organisms (or groups of organisms) and their interactions and relation to their environment. Ecology is one of the cornerstone sciences underlying the broader field of environmental studies, which integrate all the social and scientific disciplines that pertain to the environment (ESA, 2004; Hale, 1991; Krebs, 2001). The science of ecology over the past 100 years has provided a large body of knowledge about complex interrelationships between producers, consumers, and decomposers and their surroundings, including physiological responses of individuals, structure and dynamics of populations, interactions among species, organization of biological communities, and processing of energy and matter within ecosystems. Many studies in ecology involve making sense of observations and patterns in nature and building intellectual models that attempt to represent the realities of nature. To accomplish this, ecologists integrate concepts and findings from other areas of biology such as systematics, physiology, genetics, behavior, evolution, and paleontology. In addition, ecology incorporates concepts from the physical sciences such as chemistry, meteorology, physics, and earth science.

The field of ecology consists of a set of scientific disciplines that can be studied from several different perspectives—individual organisms, populations,
communities, ecosystems, or the entire biosphere. Each smaller ecological system exists as a subset of a larger system. Studies of organisms, populations, and communities tend to focus on biotic factors and their interactions. Ecosystem studies focus on the assemblage of organisms together with their physical and chemical environments. In an ecosystem approach, organisms and their activities are described in terms of the amounts of energy needed and the various chemical elements essential to life, such as oxygen, carbon, nitrogen, phosphorus, and sulfur. Biogeography and macroecology focus on the distribution of species on the planet and the processes underlying these patterns.

Ecology, then, is a highly integrated science that focuses on examining the relationships between living organisms and their environment. Ecologists aim to understand these interrelationships and the dynamic functioning of natural systems. They account for ecological phenomena, such as loss of biological diversity or the homogenization of species, by identifying causal relations and developing or applying predictive and explanatory models. Thus, the context of ecological systems affords an opportunity to develop cognitive goals for instruction that include reasoning schemes from multiple domains of biology.

The Ecosystem as a Context for Problem Tasks. Since interdependent relationships among the biotic and abiotic factors in the system enable an ecological system to function, understanding ecosystems requires coordination of a number of interdependent processes. All the elements of an organic system are part of an integral network in which each element interacts directly or indirectly with all others and
affects the function of the whole (Bergandi and Blandin, 1998; Eberhardt and Thomas, 1991; Mayr, 1982; Spector, 2001). The two major forces linking the biotic and abiotic elements are the flow of energy through an ecosystem and the cycling of nutrients within the ecosystem. Energy flow refers to the capture of light energy by green plant or algal photosynthesis and its dispersal as chemical energy throughout the food web to plant- or algal-feeding animals, predators, and eventually decomposers. Nutrients are chemical elements and compounds necessary to living organisms. Unlike energy, which is continuously lost from the ecosystem, nutrients are cycled through the ecosystem in biogeochemical cycles. Decomposers play a key role in many of these cycles, returning nutrients to the soil, water, or air where the biotic constituents of the ecosystem can use them again. Thus, explaining ecological phenomena requires an ability to think about biologically mediated processes (such as energy and material flows) that contribute to the functioning of these systems.

Revisiting the Goals of the Study. As stated previously, educational studies report that students of all ages have not yet developed an understanding of many biological processes, or their interrelationships, from typical classroom experiences. For instance, Lin and Hu (2003) investigated 106 seventh graders’ understanding of energy flow and matter cycling in ecological systems and found that none of the students demonstrated an understanding of the complex interrelationships and interdependencies of the living world; rather, they created linear mappings of the interrelationships in a community. My pilot data demonstrates that many college
students with prior biology learning experiences also rely on direct simple linear connections when looking for relationships in a community structure.

Helping students develop ways of thinking about non-linear causal relations in ecological systems is an important cognitive goal for biology instruction. Identifying other ways of thinking and ways of understanding common within the ecology community is necessary to establish other appropriate cognitive objectives for biology instruction. For example, what problem solving approaches are institutionalized in the biology community? What is the nature of biologists’ reasoning schemes? Finding answers to these questions is the first research goal for this study.

A second goal for the present study is to identify how to implement intellectual necessity in an ecology learning environment. What types of situations will constitute an intellectual need for a particular population of students relative to the concept to be learned? If students are not intellectually stimulated to find a solution to a problem, they are not developing ways of understanding the target concepts that could later lead to desirable ways of thinking in biology. Identifying the types of problems that provide students with an intellectual need for what we intend to teach them may be the most challenging aspect of applying Harel’s DNR to biology instruction because biology is not often taught as a problem solving science.

To develop appropriate problem tasks one must start from an understanding of students’ mental models. This knowledge can emerge from teaching experiments designed to develop models of student thinking and identify obstacles to learning; that is, what students pay attention to when considering different problems, how students
interpret the problems, what relationships the students draw on to answer the problems, and what categories of problems cause the most difficulty for students.

From this knowledge, theories can be generated to describe the different relationships that students take into account when considering different contexts within biology. This information can then lead to the refinement of problem tasks. Acquiring this knowledge, however, is a very gradual and slow process; this research study is the first step in contributing to this task.

**Overview of the Dissertation**

The design of this research study was guided by the principles of DNR-based instruction. I used the DNR instructional framework to rethink and restructure instruction in ecology to determine if a DNR-based approach to instruction will help students begin to develop specific ecological ways of thinking and understanding. In chapter 2, I discuss several elements of the DNR theoretical perspective that informed the design and implementation of problem tasks used in the teaching experiments. I also include a discussion of both a constructivist perspective on learning and a sociocultural perspective because I believe these two perspectives provide the theoretical foundation upon which DNR is based.

In chapter 3, I present an overview of the relevant research in science education. I include an analysis of the research that deals with ways of thinking that are desirable in ecology and those ways of thinking that have been identified as problematic for developing ecological understandings. I also summarize the studies that examine students’ ways of understanding particular concepts in ecology and the
literature on problem solving in biology. In chapter 4, I describe the methodology used to conduct this research.

Chapters 5 through 7 report the results of the study. Chapter 5 provides a detailed description of the evolution of my understanding of a way of thinking that characterizes ecologists’ acts of accounting for phenomena. I present transcript evidence from both students and professionals to support the claims made regarding ecologists’ ways of thinking and my model of students’ ways of understanding. The chapter closes with a discussion explicating how I designed instruction based on the Necessity Principle. In chapter 6, I present analyses from a teaching experiment in which three students responded to a series of problems intended to help them develop (a) a way of understanding biologically mediated processes such as energy and material flows, respiration, photosynthesis, decomposition, and (b) a way of understanding the interrelationships among these processes. From the students’ ways of understanding revealed during the experiment, I infer their ways of thinking, and discuss the changes or lack of changes in these ways of thinking. Chapter 7 addresses the types of situations that created an intellectual need in students to develop the desired ways of understanding and outlines the characteristics of effective problem situations.

The final chapter begins by summarizing the results of the study and discusses the application of DNR-based instruction to biology education. I include a discussion of what my results tell us about biology instruction, and what it is about the current
situation that makes the implementation of Harel’s DNR difficult. The dissertation closes with a discussion of directions for future research.
Footnotes:

1. The term “concepts” will be used in this paper to refer to those ideas that a community of biologists has identified as important for developing an understanding of the field. In the domain of ecology, these ideas are still in contention. For example, Cherrett (1988) surveyed the members of the British Ecological Society to try to identify the nature of modern ecology. Using a questionnaire, he asked ecologists to rank what they thought were the ten most important ecological concepts from a list of 50 provided and their own additions if desired (see below). According to Cherrett, there was little agreement among the respondents suggesting that the science of ecology does not yet appear to have a strong philosophical or theoretical base (Cherrett, 1988; Hale, 1991).

Cherrett’s (1989) List of the 20 Most Important Ecological Concepts in Order of Their Rank in a Survey of the Membership of the British Ecological Society:

| 1. Ecosystem                  | 11. Food webs          |
| 2. Succession                 | 12. Ecological adaptation |
| 5. Competition                | 15. Density-dependent regulation |
| 6. Niche                      | 16. Limiting factors   |
| 7. Materials cycling          | 17. Carrying capacity  |
| 8. Community                  | 18. Maximum Sustainable Yield |
| 10. Ecosystem fragility       | 20. Predator-prey interactions |
CHAPTER 2: THE DNR INSTRUCTIONAL PRINCIPLES AND BIOLOGY

Current biology instruction takes a prescriptive approach to the field: formal and theoretical ideas are presented first, often followed by prescribed laboratory activities. Textbooks are commonly used to organize and structure the sequence of lessons and, therefore, instructional objectives are based on students acquiring biology concepts. This approach results in teachers and professors defining what students should know in terms of chunks of subject matter, and characterizing what a student knows in terms of the content mastered. Such a pedagogical approach has had limited success in helping students develop a biological understanding of target concepts, and, furthermore, has unintentionally led to the development of undesirable overarching views about the field of biology that influences the learners’ understanding of new concepts. For these reasons, there exists a need for an alternative approach to biology instruction where a primary cognitive objective is to help students develop the conceptual tools that govern biological thinking. Instructional approaches that promote the development of this biological thinking should be grounded in evidence-based knowledge of how students learn from the fields of psychology and cognitive science.

DNR-based instruction in mathematics (Harel, 1998; 2001, in press) is an instructional principle that considers both the subject matter content and the broader overarching conceptions students should develop. The DNR instructional system can be interpreted as being grounded in and unifying two theories of learning—the cognitive and social learning theories. This theoretically grounded instructional system has the potential to be both practical and applicable for the transformation of biology
instruction. Therefore, I begin this chapter by describing several elements of the DNR-based instructional system for mathematics. This is followed by a description of the two theoretical perspectives on learning that, I believe, serve as the basis of Harel’s DNR. I conclude my discussion of DNR instruction principles by considering the application of DNR to biology instruction.

**DNR-based Instruction in Mathematics**

Harel (1998; 2001; in press) developed DNR-Based Instruction in Mathematics, an instructional treatment guided by a system of learning-teaching principles that represents a unified theoretical perspective about the learning and teaching of mathematics. As stated in chapter 1, DNR is an acronym for the three foundational principles of the system: Duality, Necessity, and Repeated-reasoning. Harel describes DNR as a “partial action theory” limited to the learning and teaching of mathematics, “with a particular focus on students’ intellectual need and the integrity of the mathematics taught” (2006, p.7). Harel’s DNR “stipulates conditions for achieving critical goals such as provoking students’ intellectual need to learn mathematics, helping them acquire mathematical ideas and practices, and assuring that they internalize, organize, and retain the mathematics they learn” (Harel, in press, p.4). In this section, I elaborate on the brief descriptions of the foundational principles of the DNR system from chapter 1, and define them in more detail.

**The Duality Principle**

Harel’s (1998) early interest in defining mathematical thinking resulted in the identification of two types or categories of knowledge affecting mathematical
reasoning: “ways of thinking” and “ways of understanding.” He defines “ways of understanding” as the particular meaning a student gives to a term, the solution he provides to a problem, or the evidence offered to justify an assertion. Ways of understanding include definitions, theorems, proofs, solutions to a problem, and interpretations one gives to a term or symbol. “Ways of thinking” are the general theories underlying the student’s actions. Ways of thinking govern one’s ways of understanding, “and thus expresses reasoning that is not specific to one particular situation (as in way of understanding) but to a multitude of situations” (Harel and Sowder, 2005, p.6). A student’s ways of thinking may be inferred from a multitude of ways of understanding.

Harel (2006) describes three interrelated classes of knowledge involved in a person’s ways of thinking: (1) beliefs about mathematics, (2) problem-solving approaches, such as heuristics, and (3) proof schemes, what constitutes truth for an individual. Beliefs would include, for example, an opinion that “it is advantageous to possess multiple interpretations of a concept [in mathematics]” (p.7). Examples of problem solving approaches include “drawing a diagram” or “guess and check.” Finally, the deductive proof scheme is an example of a desirable proof scheme.

As students engage in various problem situations, they develop ways of understanding specific content. How students come to understand that content influences their ways of thinking, and, conversely, students’ ways of thinking affect their ways of understanding. Harel (2001) labels this idea the Duality Principle. For instance, if the objective in mathematical instruction is for students to reason
proportionally, then the only way to achieve this way of thinking is through specific content and problems. Reasoning proportionally cannot be directly taught, but rather is developed as one repeatedly reasons about the relationship between co-varying quantities in specific problem situations.

Harel describes the distinction between ways of thinking and ways of understanding as arising from the discrepancy between many teachers’ learning objectives and the overarching conceptions about the subject matter that govern students’ understanding. Teachers’ objectives tend to be focused on helping students develop concept understanding: particular definitions, algorithms, techniques, theorems, or proofs. These objectives, however, ignore the “intellectual tools that learners should acquire when learning particular topics, tools that define the nature of mathematical practice,” such as problem-solving approaches and proof schemes (2006, p. 14). Thus, Harel argues that the concepts of ways of understanding and ways of thinking offer compelling reasons for the importance of objectives set in terms of subject matter.

**A Triad of Determinants.** Ways of understanding and ways of thinking are necessarily linked to the mental acts involved in the construction of knowledge. According to Harel (2006), “a mental act is a term observers (i.e. researchers) use to describe, analyze, and communicate about certain aspects of humans’ activities, specifically those that are carried out mentally” (p.14). DNR based instruction focuses on the product and character of students’ mental acts:

A person’s statements and actions are products of her or his mental acts; they represent the person’s ways of understanding associated with those
mental acts. Repeated observations of one’s ways of understanding associated with a given mental act may reveal certain characteristics—persistent features—of the act. These characteristics are referred to as ways of thinking associated with that act (Harel, in press, p.5)

Thus _product_ is a particular outcome of a mental act carried out by an individual, whereas _character_ is a particular feature of that mental act. Respectively, they are referred to as a way of understanding and a way of thinking associated with the mental act.

An example of the character and product of a mental act further illuminates these concepts:

Two first graders, Aaron and Betty, solve the problem “3 + 4 = ?”. From conversations with the two, we may observe that Aaron interprets the “=” sign merely as a command—add 3 and 4 and write the result in the place of the question mark—whereas Betty interprets the sign as equality between two quantities—the quantity that results from combining the two quantities 3 and 4 and an unknown quantity to be found. These different interpretations are products of Aaron’s and Betty’s interpreting act—they are their ways of understanding the “=” sign in the sentence “3 + 4 = ?”. We may infer on the basis of multitude of observations the characters of, or the ways of thinking associated with, Aaron and Betty’s interpreting acts. We may find, for example, that while Aaron’s interpreting act is characteristically devoid of quantitative considerations, Betty’s is quantitatively based (Harel, 2006, p.16).

Mathematical ways of thinking include characters of problem-solving acts, proving acts or beliefs. Some problem-solving mental acts include interpreting, generalizing, inferring, structuring, symbolizing. The students’ meanings, solutions, or justifications are the _products_ associated with these acts, while problem solving approaches are examples of the _character_ of the mental acts, or the associated ways of thinking.
Similarly, proof schemes are ways of thinking associated with the act of proving, while the actual proof one constructs is, by definition, one’s way of understanding.

Beliefs, on the other hand, are associated with the mental act of interpreting and are “restricted to the character of one’s interpretation of (a) what mathematics is, (b) how it is created, and (c) its intellectual or practical benefits” (Harel, 2006, p.19). Harel defines beliefs as instances of didactical contracts (as defined by Brousseau, 1997), which are analogous to Cobb and Yackel’s (1996) construct of sociomathematical norms. These beliefs result from the student-teacher interpretations of the nature of mathematics.

**Developing Instructional Objectives.** Mental acts, ways of thinking, and ways of understanding comprise a triad of determinants useful for guiding instructional objectives in mathematics. Rather than focusing on helping students perform the right procedure in order to obtain the right answer—as most current mathematics instruction does—DNR-based instruction posits instead that instruction should help students construct desirable ways of thinking in mathematics. “The ultimate goal…is for students to develop ways of understanding and ways of thinking compatible with those that have been institutionalized in the mathematics discipline, those that the mathematics community at large accepts as correct and useful in solving mathematical and scientific problems” (Harel, 2006, p. 23).

For example, in current mathematics instruction, much focus is placed on engaging students in recognizing number patterns. As a result, students and teachers pay attention to patterns in numbers rather than underlying mathematical relationships.
This way of thinking—when one generalizes from regularity in the results, rather than from regularity in the process—is referred to as Result Pattern Generalization (RPG). RPG influences how one ascertains the truth of a conjecture and persuades others of this truth. “Students’ certainty in an assertion seems unshakable if it is based on an observed pattern of a finite number of results” (Harel, 2006, p. 27). When a learner becomes convinced of his solution through RPG, he has no doubt and therefore no need to justify his assertion. Alternatively, a Process Pattern Generalization way of thinking would lead one to determine the “reason underlying certain mathematical patterns and, in turn, develop it into a mathematical proof” (p. 27). This more desirable way of thinking is an example of a more appropriate cognitive goal for instruction.

**The Necessity Principle**

The Necessity Principle states that “for students to learn what we intend to teach them, they must have a need for it, where ‘need’ refers to intellectual need, not social or economic” (Harel, in press, p.18). This principle is grounded in the Piagetian theory of equilibration.

Student learning is a continuum of disequilibrium-equilibrium phases together with (a) the ways of understanding and ways of thinking that are utilized or newly constructed during the various phases and (b) the cognitive, social, and affective stimuli that result from or instigate these phases. (Harel, 2006, p.11)

According to Harel (1998; 2001), an intellectual need arises when we encounter a situation that is incompatible with, or presents a problem that is unsolvable by, our existing knowledge. Students’ existing knowledge influences how they interpret
situations. The existing knowledge provides a contrast to the new knowledge and thus facilitates the acquisition of the new knowledge. Therefore, teaching situations must provide opportunities for students to confront their existing knowledge and perturb that knowledge. If no conflict occurs, then the student cannot appreciate the new knowledge and no learning occurs. From this point forward, I will refer to situations that create conflict for students as “problem situations”.

Problem situations in mathematics are used to try to create intellectual necessity. According to Harel, students construct desirable ways of understanding and ways of thinking only by solving problems that are intrinsic to the student. Intrinsic problems are problems the learner understands and appreciates. In DNR-based instruction, concepts and ideas are always born out of a need to solve problems. Determining the intellectual stimuli that might create this need requires a great deal of research on students’ existing ways of thinking and ways of understanding.

There is an important distinction between the necessity principle and other cognitively based instructional approaches: the necessity principle posits that learning results from a need to resolve a conflict, not that students must discover scientific ideas. Once a problem situation creates in a student cognitive disequilibrium, the knowledge or information that re-establishes equilibrium does not have to be discovered, but can be read, told, or experienced through hands-on activity, depending on what is most appropriate for the knowledge in question. This does not negate the fact that students must make sense of the new information to re-establish equilibrium, but rather, implies that students can construct meaning in a variety of different
circumstances, including, in some cases, lectures. This clarification is especially liberating for biology instructors. The *discovery learning* instructional approach popular among science educators presents an obstacle for teaching many of the concepts and processes of biology. Students cannot easily *discover* concepts such as cellular energetics or the steps in photosynthesis. Such knowledge often needs to be explained or described. The distinction here is that rather than presenting students with information, definitions, and context specific examples followed by a project task or a laboratory experiment intended to demonstrate the scientific ideas, students engaged in a DNR-based curriculum are presented with a situation that creates a need for a specific way of understanding. Once this need is established, new information that facilitates the reorganization of their conceptual schemes is purposeful and meaningful to the student. In short, problem situations should provide opportunities for students to be intellectually puzzled, followed by opportunities to reason through and make sense of biology concepts that emerge through the solution process.

**Repeated Reasoning**

The Repeated Reasoning principle states that students must practice reasoning in order to internalize and interiorize specific ways of thinking and ways of understanding (Harel, 1998; 2001; Harel and Sowder, 2005). To internalize refers to an ability to re-present an idea or concept within a particular context. Interiorization refers to the further abstraction of that concept; when a learner has interiorized a concept, he can reason and apply that concept in a novel situation.
Reasoning, in this case, is in contrast with the drill of answering routine problems. Harel and Sowder (2005) suggest that, rather than presenting students with routine problems and procedures for solving them, an alternative approach would be to provide students with problems so that the mathematical (or scientific) concepts emerge through the solution process. The Repeated Reasoning principle suggests that only after the students have had several opportunities to reason and construct solutions should the teacher provide the concept definition. As students’ solutions move from novel to schematic the students begin to abstract and generalize the procedures they generate to solve the problems helping them develop a way of mathematical thinking—mathematical efficiency.

Most instructional approaches in mathematics and science limit students’ opportunities to develop efficient ways of thinking because they preclude the reasoning process by directly teaching the solution procedure. Algorithms do not represent efficiency in mathematics when taught explicitly before students have been given the opportunity to reason and practice on their own. According to Harel, instruction that deprives students of reasoning should not be used in mathematics curricula because it is through reasoning in situations that we develop ways of thinking.

**Summary of the Principles of DNR-based Instruction**

The Duality Principle combined with the Necessity Principle and Repeated-Reasoning comprise the system of learning-teaching principles Harel proposes for
advancing mathematical learning (1998; 2001). Harel posits that, together, these three learning-teaching principles can lead to advanced mathematical-thinking.

The DNR framework contributes to the field of mathematics education not only because it presents a unified theoretical perspective on learning, but also because it empowers an instructor to modify the curriculum based on the students’ knowledge. The teacher’s role is to identify ways of understanding and ways of thinking that she wants to help students develop, along with identifying students’ current ways of thinking and understanding. From this, teachers can construct situations or problems that may create in students the intellectual need to learn what the teacher desires for them to learn. This suggests that teachers must possess a deep and broad knowledge of their subject so they can recognize changes in students’ ideas and develop scenarios that will create an intellectually perturbing environment.

**The Relationship of Harel’s DNR to Theories on Learning**

As stated in the introduction, instructional approaches that promote the development of biological thinking should be grounded in evidence-based knowledge of how students learn from the fields of psychology and cognitive science. I submit that Harel’s DNR (1998; 2001; in press) integrates both the cognitive and social theories of learning. Below, I briefly summarize the aspects of these two theories as they are incorporated into the learning and teaching principles of DNR-based instruction in mathematics.
Cognitive Theoretical Perspective on Learning

Constructivism is a term that has been widely used in educational research over the past 30 years and presents a variety of different meanings. Therefore, it is necessary to begin by defining my interpretation and use of the term constructivism. Constructivism is a theory about how students learn that focuses on the productive role of learners’ existing ideas and their interpretation of the reality they experience (Cobb, 1990; Smith, diSessa, and Rochelle, 1993; Steffe, 1991; Steffe and Thompson, 2000; von Glasersfeld, 1995). Originating from Piagetian roots, learning from this perspective is the reorganization of cognitive structures or accommodation: when a new conceptual structure is formed or an existing structure is reorganized or modified to account for an experience that does not conform to previously constructed structures (Steffe, 1991; Steffe and Thompson, 2000; von Glasersfeld, 1995).

From this perspective, cognition is viewed as “an instrument of adaptation, the purpose of which is the construction of viable conceptual structures” (von Glasersfeld, 1995, p. 59). When confronted with a new situation, a learner will either assimilate or accommodate the new information to maintain cognitive equilibrium. If the experience can be explained or understood within the learner’s existing cognitive structure, then the learner maintains her cognitive structure: assimilation. If, however, the experience contradicts the learner’s cognitive structure, this results in disequilibrium (perturbation). The desire to maintain cognitive equilibrium drives the learner to reorganize her existing cognitive structure or generate a new one: accommodation.
Since learning from this perspective derives from a need to maintain cognitive equilibrium, many researchers suggest that instruction should provide an experiential basis for cognitive conflict such that the complex and gradual process of cognitive change can take place (Chinn and Brewer, 1993; Hammer, 1994; Minstrell, 2001; Posner, Strike, Hewson, and Gertzog, 1982; Smith, diSessa, and Roschelle, 1993). This assumption posits that if a learner’s cognitive structure cannot account for an experience (for anomalous information) then the learner will likely modify his or her cognitive structure. To effect this cognitive change, however, the learner must view the information as contrasting with existing knowledge.

The constructivist theoretical assumptions about learning and cognition include viewing learners as active builders of knowledge, and learning as fundamentally interpretive in nature. DNR-based instruction in mathematics corresponds with this view of learners and learning. In Harel’s DNR, the teacher’s role is to try to create a model of students’ initial ideas such that instruction can lead to cognitive disequilibrium and provide an opportunity for the student to develop a cognitive structure that more closely aligns with the scientifically accepted understanding.

**Social Theoretical Perspective on Learning**

Educational researchers from a social perspective believe that learning and understanding are inherently social and cultural activities (Brown, Collins and Duguid, 1989; Cobb and Yackel, 1996; Gilbert and Yerrick, 2001; John-Steiner and Mahn, 1996). Cognition and learning can be examined as situated in a broad social institution, a cultural setting, or through interpersonal interactions. In each of these
settings, there are various ways to theorize about the relationship between the social context and the individual’s knowledge construction. In this section, I briefly address the differences between three of these social learning perspectives: the sociocultural perspective, the emergent perspective, and social constructivism.

**Vygotsky’s Sociocultural Perspective.** From the sociocultural perspective, education and learning are viewed as situated in a larger social and cultural structure. Vygotsky believed that each human mind was unique and affected by “social, historical, cultural, and material processes” (John-Steiner and Mahn, 1996, p.196). From this perspective, the link between the community and individual processes is a direct one. Ideas, thoughts, and knowledge occur first on a social plane and are then internalized into the psychological plane (Cobb and Yackel, 1996; John-Steiner and Mahn, 1996). “Any higher mental function,” Vygotsky (1978) argued, “was external and social before it was internal” (p. 197). Vygotsky used dialectics to make sense of the contradiction between individual and social processes: the individual constructs the social and, at the same time, is constructed by the social (Confrey, 1994; John-Steiner and Mahn, 1996). Sociocultural research focuses on how this “co-construction of knowledge” (social meanings and individual meanings) is internalized.

For sociocultural theorists, collaboration is an essential component for facilitating internalization because thought and speech are intertwined (Confrey, 1994; John-Steiner and Mahn, 1996; Lemke, 2001). Language and thought are internal processes in a constant state of change depending on the social context. The people present, the situation, and the previous words that have been said influence one’s
decision to speak and the words one uses (Sfard and Kieran, 2001). All these factors affect what thoughts the individual generates.

**Emergent Perspective.** According to Cobb and Yackel (1996), students construct their knowledge in the context of participating in a classroom community. From this perspective, there exists a reflexive relationship between mathematical practices (from the sociocultural perspective) and individual conceptions (from the psychological perspective). Here, the link between the community and individual processes is indirect. To coordinate the interactionist perspective on communal classroom practices with the psychological constructivist perspective on individual activity, Cobb and Yackel (1996) developed a framework that analyzes social norms, sociomathematical norms, and mathematical practice within a classroom environment. Sociomathematical norms are norms specific to mathematical activity and include those actions and ideas that develop as one constructs a conceptual understanding of mathematics. For example, “what counts as different mathematical solutions, a sophisticated mathematical solution, an efficient mathematical solution, and an acceptable mathematical explanation” are all socio-mathematical norms (Cobb and Yackel, 1996, p. 178).

Applying this construct to science education, one socioscientific norm that might develop is the ability to analyze data in such a way that explanations are based on what is observed, and conclusions are based on evidence and logical argument. The development of this socioscientific norm would require that, when possible, the
teacher allow the observational evidence to be seen as the validator of ideas rather than the teacher.

**Social Constructivism.** From the perspective of social constructivism, the situation or context is seen to afford or constrain the mental models the learner constructs. The learner is studied as an individual within a particular setting, and the mental processes of the individual are connected to the social setting. From a social constructivist perspective, “interpersonal interaction patterns and classroom routines and norms are carefully examined” (Confrey, 1993, p. 41). Brousseau (1997) describes the study of teaching situations to identify phenomena that result from the communication of knowledge as didactical research. From such studies, Brousseau (1997) developed the theory of didactical situations to describe the complex dynamics that arise within the mathematics classroom due to the transposition of knowledge. This theory is based on the perspective that learning is both an individual and social activity and the development of a microscientific community in the classroom is necessary for the communication of knowledge in didactical situations. Although Brousseau acknowledges that students construct their knowledge, he also believes that teaching should guarantee the socialization of students’ conceptions.

Brousseau (1997) explains that during this socialization process, a system of reciprocal obligation forms in which the teacher and the student determine who will have the “responsibility for managing and, in some way or other, be responsible to the other person for” (p. 31). As the teacher and students interact together in the
classroom, negotiation of expectations occurs. This negotiation results in a relationship that forms between the teacher and the students—a “didactical contract.”

**Sociocultural Perspectives and Harel’s DNR.** Common to each of the three social perspectives on learning described above is the premise that “learners and social organizations exist in recursive relation to one another” (Beach, 1999, p.104). Learners do not begin by developing a representation of a concept and then consider the contextual influences. Instead, the environment influences how the learner cognitively represents concepts and solves problems. In Harel’s DNR (1998; 2001), the problem situation, along with the expectations of the teacher and students, influence the learning. In this way, the classroom community constrains the scientific activity. Consequently, one must consider the social norms established in the teaching environment when designing problem situations with the potential to create intellectual need.

**Summary of the Relationship of Harel’s DNR to Theories on Learning**

From both the cognitive perspective and the social perspective, the image of the learner is one of an active constructor of meaning. However, a detailed image of the instructional practices that would be associated with student outcome goals for each of these perspectives is not as clear. Within the research, there exists a predominant belief that teachers must design an instructional practice that parallels the constructivist epistemology of student learning (Posner, Strike, Hewson, and Gertzog, 1982; Strike and Posner, 1985). Yet the theories regarding the social aspects of learning must also be considered because they help to account for differences in
student learning as a result of context and interpersonal interactions. Harel’s DNR-based instruction in mathematics (1998, 2001) meets the need for an instructional framework that supports students’ construction of knowledge from both of these perspectives. Viewing learning as a process of both individual and social construction provides a conceptual framework for understanding the learning of students. This coordination of the cognitive and social perspectives is best captured by the term “social constructivism” (Simon, 1995).

Conclusion: The Application of DNR-based Instruction in Biology

The concepts of ways of thinking and ways of understanding offer a meaningful way to consider the appropriate cognitive objectives for biology learning. For example, recall the interview results from my pilot data. All of the students focused primarily on direct relationships between various organisms and their environment. When asked about possible effects of an introduced organism, an abiotic change, or possible causes for changes in the community structure, the students’ responses reflected simple linear causal reasoning. This way of thinking about ecological relationships affects students’ ways of understanding ecological phenomena such as food web relationships and ecosystem functioning. Therefore, one cognitive objective for ecology instruction should be to help students develop non-linear causal reasoning. Developing ways of understanding the biological processes underlying ecological systems—such as matter cycling and energy flow—could lead to developing ways of thinking about the complex causal relationships that maintain the structure of ecological systems. Conversely, focusing the cognitive objective for
instruction on helping students construct non-linear causal reasoning schemes could help students modify and refine their ways of understanding material and energy flows in ecosystems.

Furthermore, we know that students’ beliefs about the nature of biology influence their approach to understanding biological phenomena. Ecology—and biology in general—is not a compilation of precise facts, but, rather, a search for systematic relations, explanations of patterns in the living world, and unifying concepts. My interviews with college biology majors revealed that the students did not see the relationship between matter cycling, the biological processes in ecosystems, and the resulting composition of the ecosystem. Up to this point in their education, they did not have an intellectual need to make connections between these different categories of biological knowledge; quite possibly, because they did not possess a way of thinking about the integrated nature of biology. Thus, their way of thinking about the nature of biology influenced their way of understanding biological concepts. These developmental interdependencies reflect Harel’s Duality Principle (1998; 2001).

The biology education research literature does not provide any instructional approaches that effectively and efficiently address or express the interdependent relationship between one’s ways of thinking about biology and their ways of understanding. As such, the application of Harel’s (1998; 2001) DNR principles to biology learning can be used to elucidate the differences between the ecologists’ knowledge, which influences how they account for biological phenomena, and the students’ knowledge. This result can be used to determine cognitive objectives for
instruction. The Necessity and Repeated-reasoning Principles, then, provide an instructional approach for helping students develop the knowledge shared among the community of biologists.
CHAPTER 3: REVIEW OF EXISTING RESEARCH

As previously stated, this study aims to determine how the DNR perspective on teaching and learning in mathematics (Harel, 1998; 2001) can be applied to the teaching and learning of biology. The first step in achieving this goal entails determining cognitive objectives for instruction in the form of ways of thinking and the interdependent ways of understanding. Once these objectives are explicated, the existing research in education and psychology can provide insight into students’ existing ways of thinking and understanding that might hinder or facilitate students’ development. Chapter 3 surveys this relevant literature. In the first section, I review research that addresses ways of thinking that are desirable in ecology and those ways of thinking that have been identified as problematic for developing ecological understandings. In the following section, I summarize the studies that examine students’ ways of understanding particular concepts in ecology. In the final section, I review the literature on problem solving in science.

The Research on Ways of Thinking in Biology

Harel’s (1998; 2001) DNR-based instruction identifies three categories of ways of thinking in mathematics: beliefs, problem solving approaches, and proof schemes. Similarly, within biology, I have identified ways of thinking associated with beliefs, problem solving approaches, and justification schemes. Beliefs are associated with the mental act of interpreting. Desirable beliefs include the belief that biology is a problem solving science, is subjective, and is based on observation and inference. Another desirable belief contends that biological knowledge is tentative and changes...
as a result of technological advancement or the revision of assumptions (Del Solar and Moron, 2001). Undesirable beliefs include the belief that biology is a compilation of facts or that biological knowledge is certain. Problem solving approaches are associated with a multitude of mental acts, including, but not limited to, explaining, identifying causes and effects, inferring, synthesizing information, and modeling. Identifying desirable reasoning schemes associated with the mental act of explaining, became a focus of this study. Chapter 5 includes an elaboration of this mental act in an ecology context. Finally, justification schemes are associated with the act of justifying one’s claims. I use the phrase “justification schemes” in place of “proof schemes” because of connotations associated with the words “proof” or “proving” in science. Nevertheless, the acts of ascertaining and persuading, identified by Harel as comprising the act of proving in mathematics, are compatible with scientists’ activity as they try to justify a claim. Explication of the ways of thinking associated with justifying is beyond the scope of this present study.

The existing studies in science education and psychology have identified particular ways of thinking and reasoning associated with both beliefs and problem solving approaches. In this section, I summarize these studies and, when appropriate, demonstrate how DNR principles can provide a useful framework with which to consider the instructional implications of these findings.

**Beliefs Influencing Students’ Interpretations**

According to Harel (1998; 2001), one’s beliefs are a way of thinking that also influences one’s ways of understanding: a learner’s beliefs influence her
interpretation of a situation and thus her learning. Beliefs, then, are existing cognitive structures or schemes influencing a student’s actions. Although I am not aware of any specific studies in the biology education literature explicitly addressing this relationship, there are studies in other domains of science education that attend to the influence of one’s beliefs on developing understanding. For example, Hammer (1994) describes how two students’ beliefs about the structure and content of physics influenced their solution processes for a problem involving two blocks connected by a cord. Both students applied $F=ma$ to find acceleration, which led to two different accelerations for the blocks, and thus, an unexpected result. By analyzing the students’ thinking through interviews and observation, Hammer was able to identify how the students’ epistemological beliefs influenced their learning. He found that one student’s beliefs led him to examine his solution conceptually and resolve the conflict. Alternatively, the other student showed only minor concern that his common sense should apply to the problem solution, and thus did not consider modifying his solution.

Hammer (1994) discusses similar findings as students solved a pendulum problem. In those situations, the students interpreted their solutions through their existing belief structures:

In each of these cases, the subject explicitly recognized a conceptual difficulty with a result, showing, I argue, enough content-level knowledge at least to question the validity of the solution. Each chose to reject the common-sense notion, without trying to account for why it might not apply (p. 175).
Hammer was able to demonstrate that the students’ epistemological beliefs about the structure and content of physics affected how the students used and developed their conceptual knowledge. Hammer suggested that some students might retain their existing conceptions, because, “in part, they do not think that conceptual knowledge is essential or that they should try to modify their own understanding” (p.179). Thus, their existing beliefs influenced their interpretation of the learning situation.

Students’ views of the nature of science (NOS) are another aspect of one’s beliefs that are accounted for within the DNR framework. In science education, the nature of science is defined as the values and assumptions inherent to science, scientific knowledge, and/or the development of scientific knowledge (Lederman, Abd-El-Khalick, Bell, and Schwartz, 2002). Although decades of research literature exists regarding students’ beliefs about the nature of science, Lederman and his research team have established themselves as leaders in this domain over the past decade. His group has identified seven aspects of the NOS that he suggests are target ideas that students should develop and adults should understand (see Figure 2). To help students develop these institutionalized views of the nature of science, some researchers suggest an explicit approach to instruction (Abd-El-Khalick and Lederman, 2000; Moje, Collazo, Carillo, and Marx, 2001; Sandoval and Morrison, 2003; Schwartz, Lederman, Khishfe, Lederman, Matthews, and Liu, 2002). Other researchers however, find that students are not changing their ideas about the nature of science from such explicit instructional objectives (Feldman, 2003). The DNR instructional principles can account such findings. One tenet of the duality principle
contends that ways of thinking cannot be taught directly. Instead, ways of thinking develop from ways of understanding. As students have multiple opportunities to reason through problem situations, they can abstract from these experiences ways of thinking. Consequently, from this perspective, desirable beliefs about the nature of science would develop from multiple opportunities to reason about science while solving scientific problems.

The Science Education View of the Nature of Science

Science is...
1. subjective
2. socially and culturally embedded
3. is based on both observations and inferences

Scientific knowledge ...
4. is tentative
5. is based on and/or derived from observations of the natural world
6. is created from human imaginations and logical reasoning.
7. Theories and laws are different kinds of scientific knowledge

Figure 2: The science education view of the Nature of Science

Problem Solving Approaches

The mental acts in which one engages when problem solving in biology include explaining, making connections, identifying causes and effects, inferring, modeling, and synthesizing information. The research in biology education should provide information about how to help students develop these mental acts. Yet, because biology is not usually taught as a problem solving science, there is limited research on students’ problem solving approaches in biology. The majority of
literature focuses on students’ concept knowledge. Nevertheless, certain noteworthy
studies address this area.

**Causal Relating**

According to Mayr (1982), all sciences are devoted to explaining, generalizing,
and determining the causation of things, events, and processes. Since the beginning of
science, a central goal has been to attempt to “subsume the vast diversity of the
phenomena and nature under a much smaller number of explanatory principles”
(Mayr, 1982, p.23). For example, the Greek philosophers initiated the approach of
trying to understand the causation of natural phenomena. Aristotle, for example,
searched for causes asking both “how” questions and “why” questions. In this way, the
foundation of all science is a search for an explanatory framework for observed
phenomena. Although scientists from various domains aim to identify causal
relationships, the nature of their reasoning may be quite different from that of
biologists’ reasoning. Therefore, it is important to identify the character of biologists’
causal reasoning rather than generalizing from the research on the causal reasoning of
physical scientists.

**Causal Reasoning in Biology.** Ecological systems are an archetype of
complexity, and, therefore, present appropriate contexts for examining the nature of
biologists’ causal reasoning. In ecological systems, the net effects of all biotic and
abiotic relationships interact simultaneously, and ecologists must consider a variety of
combinations of components to explain ecological interactions. As White (2000)
argues, identifying causal relations in ecology “involves not just identifying the cause
of some effect, but also integrating collections of individual events into an organized representation of chains and networks of causal relations” (p.606). Thus, explaining ecological phenomena requires one to consider the interrelationships and interconnections of the functioning whole, as well as the stochastic nature of the causal interactions.

Mayr (1982) provides an excellent example of the difficulties in thinking simplistically about causal relations in ecological systems:

Let us say a species consists of one million uniquely different individuals. Each individual has a chance to be killed by an enemy, to succumb to a pathogen, or encounter a weather catastrophe, to suffer from malnutrition, to fail to find a mate, or to lose its offspring before they can reproduce. These are some of the numerous factors determining reproductive success. Which of these factors will become active depends on highly variable environmental constellations, which are unique and unpredictable. We have, therefore, two highly variable systems (unique individuals and unique environmental constellations) interacting with each other. Chance determines to a large extent how they mesh together. (p.58)

The order inherent in the functioning of natural systems cannot be explained by simple cause-effect relationships. One must think differently about the types of causal relationships interacting in these complex systems. Understanding in ecology requires a way of thinking about causal relations that allows one to recognize multi-causal relationships, cyclic and other non-linear relationships, and consider the effects of causal relations over varied temporal and spatial scales. Furthermore, ecological systems—in fact, most biological systems—are often unpredictable because their great complexity results in causal inferences that are often stochastic in nature.
The Research on Students’ Causal Reasoning. Several researchers have studied students’ causal reasoning as they try to account for phenomena in biology. This research suggests that how students reason about causality influences how they analyze specific instances of causation in science class and beyond (Driver, Squires, Rushworth, and Wood-Robinson, 1994; Keselman, 2003; Grotzer and Perkins, 2000; Grotzer and Basca, 2003; White, 2000). These studies report that students’ causal models are in some sense less than adequate for learning complex science concepts. Grotzer and Perkins (2000) and White (2000) show that students hold assumptions about the nature of causality that lead to alternative conceptions. They claim that complex forms of causality play a role in the difficulty students have when learning many science concepts.

Grotzer and Basca (2003) examined students’ causal reasoning in an ecological context and found that students have a simplistic understanding of the nature of causality. Students’ responses to questions about cause-effect relationships in a forest environment revealed an inability to reason about causality in a systemic sense, as well as an inability to deal with the specific types of causal patterns embedded in ecosystems. Without a way of thinking about cyclic and multivariate causality, the students imposed a simple linear pattern to organize new information that they were learning about ecosystems. The findings of Grotzer and Basca exemplify the duality principle—that one’s ways of thinking affect their ways of understanding. Similarly, Leach, Driver, Scott, and Wood-Robinson (1996b) found that when analyzing food webs, students used simple linear causal reasoning. The linear cause-effect sequences
focused on direct relationships between entities rather than changes throughout the food web. The authors suggest that “this may explain the fact that pupils are more likely to infer changes to food webs up through trophic levels rather than down: lack of food causing starvation is a stronger cause-effect link than an absence of predators causing increased chances of survival” (p.140).

White (2000) studied undergraduate students’ causal reasoning and judgments about food web dynamics and found that students have a simple physical model of food web dynamics. He cited several studies to support his claim that “ecology research supports the contention that, beyond a minimal level of system complexity, people engage in unidirectional causal reasoning about food” (White, 2000, p.621). When assessing the effects of perturbations, students traced the route out from the site of the perturbation until they reached a terminus to the food web, and then stopped. Students did not consider complex interactions or simple feedback. In other words, students’ ways of thinking about the effects of a perturbation were governed by local considerations only. Furthermore, students believed that population levels underwent lasting changes following a perturbation: the greatest change would be observed in species closest to the perturbation, the least in species furthest away. White refers to this belief as the dissipation effect. Such a belief is problematic because dissipation is not a usual feature of effects of perturbations on food webs. If people believe that dissipation is characteristic of the effects of perturbations, then they believe that species remote from perturbations in terms of the structure of the food web are less affected by them. “Consequently,” explains White, “people may act on the basis of
inappropriate beliefs about the likely consequences of their interventions, and may be slow to realize the scale of the effects that run counter to common tendencies in their reasoning” (p. 648).

White’s (2000) studies of students’ models of food webs lead him to claim that “people have a naïve conception of system properties within a general framework of unidirectional causal reasoning” (p. 622). In other words, rather than understanding that complex interactive processes maintain equilibrium by negative feedback, students believe that a balance between influences and resistances maintains the natural equilibrium of the system. This way of thinking influences how students interpret relationships within food webs:

Under this model people make causal judgments by applying naïve conceptions of influence and resistance in a process of unidirectional causal reasoning. A perturbation is conceived as a change that acts to influence properties of the system, in this case population levels. The structure of the food web is essentially a map of channels for the transmission of influence through the system. Locations in the system possess resistance to change. The central proposition in the model is that the judged change to the population of a given species following a perturbation is a function of the amount of influence reaching that location in the system and the amount of resistance possessed by that location. More influence implies greater judged change. More resistance implies less judged change (p. 641).

White recognizes that the influence and resistance model can be described as a kind of two-way causal thinking. He argues, however, that this thinking is simpler and different in character from the kind of two-way causal thinking that characterizes expert reasoning about food webs: “In expert reasoning each species is affected by interactions involving the whole of the rest of the food web in processes of negative feedback” (p. 642). White associates his findings with diSessa’s (1987) notion of p-
prims, more specifically, with Ohm’s p-prim, which comprises this idea of resistance. He argues that, “It is possible that notions of force and resistance play a very general and fundamental role in our understanding of the world, in modeling physical systems, in organizing meaning in language, and in causal cognition in general” (p.644).

In summary, the research reveals that when students reason about causal relations in complex systems, they generally look only for sequential chains of causes and effects when other causal patterns are in play (Driver, Squires, Rushworth, and Wood-Robinson, 1994; Grotzer and Perkins, 2000; Grotzer and Basca, 2003; White, 2000). Students often think in terms of a simple linear model. A scientific explanation, in contrast, often involves analyzing cause as embedded in an interaction or a relationship. Akin to the results obtained from my pilot data, Grotzer and Perkins (2000) found that most students, when accounting for phenomena, were unable to offer more than very basic explanations that involve one entity and one outcome in a linear form. Although correct, the students’ explanations were often shallow: “The type of causality underlying students’ models tend to be simple in form and to lead to simplified interpretations of the information in the more complex models” (p.3). Both White (2000) and Grotzer and Perkins (2000) found that students have trouble focusing at the level of the system and try to analyze effects locally. Furthermore, students have difficulty recognizing effects when they are removed in time and space from causes (Grotzer and Perkins, 2000). Finally, White (2000) concludes that students have a naïve version of a feedback model in which equilibrium is maintained by the balance between influences and resistances. Thus, the character of students’
causal reasoning influences their interpretations of situations involving causal relations.

A “Complex Systems” Way of Thinking

Wilensky and his colleagues at Northwestern’s Center for Connected Learning and Computer-Based Modeling (CCL) argue that instruction at the precollege and undergraduate level should be modified to help students develop a “complex systems perspective” (Jacobson and Wilensky, in press; Wilensky and Resnick, 1999).

According to these researchers, the study of complexity offers a new way of thinking about science, “a fundamental shift from the paradigms that have dominated scientific thinking for the past 300 years” (Wilensky and Resnick, 1999, p.5). They argue that nearly all biology—for example, the brain, the immune system, or the behavior of organisms such as ants and bees—can be considered from a complex systems perspective.

In short, complex phenomena can arise from simple components and simple interactions. In complex and dynamical systems, a small action may have interactions in the system that contributes to a significant and large-scale influence. This is opposed to a linear relationship between the size of an action and its corresponding effect. Furthermore, from a complex systems perspective, system control emerges as part of de-centralized interactions of elements. Novices, on the other hand, tend to favor explanations that assume central control and deterministic causality when they identify patterns in the world, an approach the researchers refer to as a “deterministic/centralized mindset” (Resnick and Wilensky, 1993; Wilensky and
Resnick, 1999; Wilensky and Reisman, in press). These studies report that people have difficulty making sense of emergent phenomena (global phenomena that arise from distributed interactions) that are central to the study of complex systems.

A “complex systems perspective” and a “deterministic/centralized mindset” can be interpreted through Harel’s DNR as different ways of thinking associated with the act of identifying a causal mechanism to account for phenomena. As students and professionals identify patterns and try to create explanations, the character of the mental act of identifying causal relations differs, as described above. In one study, Wilensky and Resnick (1999) proposed that helping students develop an understanding of the concept of “emergent levels” (that is, levels that arise from interactions of objects at lower levels) will help people transform their view of systems. They expected that this transformation would enable people to develop better causal accounts of the interactions and relationships among elements of the systems they encounter: “It is only through fluidly shifting between levels that learners can develop an understanding of the mechanisms underlying the patterns they see in the world” (p.17). Through the discussion of three cases in which students interacted with the StarLogo (Wilensky, 1997) modeling program, the researchers illustrated students’ difficulties with the concept of levels, and how they began to develop an understanding of levels. From a DNR perspective, these researchers sought to help students develop ways of understanding the different “levels” that characterize a system with a number of interacting parts, and with the intent that this understanding would lead to a complex systems way of thinking.
Wilensky and Reisman (in press) also focused on helping students develop a complex systems view, and presented two extended examples from a biology context in which students use agent-based embodied modeling tools to model the micro-rules underlying a biological phenomena. The goal was to demonstrate how students could use individual-based computer modeling tools to model and explore biological phenomena and through this process begin to develop a “complex systems perspective.” They suggest that this “model-oriented approach” to learning biology shifts the focus of students from learning answers to assessing theories for themselves. The researchers add that “while content knowledge, or many of the “answers” in today’s textbooks are already out of date, the skill of assessing the validity and plausibility of answers is not so easily made obsolete” (p.28).

In one of the extended examples presented (Wilensky and Reisman, in press), an undergraduate student, Paul, who had previously worked with the modeling program, sought out a “distributed mechanism” to explain and design his model of firefly synchronization. The researchers claim that his previous experience in their project allowed Paul to overcome the deterministic/centralized mindset and consider leaderless non-deterministic mechanisms to develop his model. “In a wide variety of domains, ranging from the movements of particles in a gas, to the schooling of fish and the growth of plant roots, Paul had seen how stable organization could emerge from non-deterministic underlying rules” (p.30). From a DNR perspective, Paul had engaged in multiple opportunities to reason about group organization arising without a
“leader” and, as a result, developed a new way of thinking about mechanisms of coordination underlying biological phenomena.

**Comparing students’ reasoning as they develop models of complex systems**

Hogan and Thomas (2001), as part of a study examining students modeling in an ecology context, aimed to help students develop a systems view of biotic/abiotic interactions, including those between humans and the environment. The researchers sought to understand students’ reasoning processes as they engaged in modeling ecological systems. Tracking students’ reasoning as they built quantitative ecological models using a software program, these researchers found that students had very different approaches to the model tasks as a result of their view of whether systems were “dynamic” or “static.” The authors suggested that students’ broader epistemological beliefs played a significant role in students’ reasoning—whether they saw knowledge as coherent or fragmented, certain or tentative—as well as their beliefs about the nature of science and their perspectives on learning science. Hogan and Thomas offer a framework for making sense of the interactive facets of cognition (object-level, metalevel, and affective) that affected students’ modeling expertise.

In their study of the differences in students’ reasoning, Hogan and Thomas (2001) found that one pair of students, Jason and Rob, tended to focus on the whole picture of model behavior, while other groups tended to zoom in on representing individual relationships without being guided by a notion of how the model would function. In short, Jason and Rob focused on net interactions rather than individual relationships. Further, Jason and Rob probed why their model produced the given
output and referred back to their model structure and quantities after obtaining output. In contrast, other students exhibited a greater tendency to reason about their model output in terms of how the real world would have behaved. Finally, with respect to model revision, Jason and Rob added new elements to their models, made new interconnections among the model parts, and changed their model values and equations. The other students did not engage in significant model revision because these students did not use output to guide adjustments to their models. Instead, they waited until the end of their modeling session to run output, using it as a summative evaluation of the accuracy of the model. Consequently, they did not give themselves an opportunity to explore relationships between system structure and system function.

From this study, Hogan and Thomas suggest that students’ beliefs and modeling strategies affected their activity and learning. Jason and Rob regarded their models as representing whole, dynamic systems. They considered each variable within the larger context of other interacting variables. In doing so, they brought to the tasks a “dynamic systems view.” While other students included various factors for the purpose of describing a system, Rob and Jason were more concerned about how factors might interact to affect a certain system variable. The authors describe this difference as a top-down modeling approach, where one thinks in terms of how adding or modifying model parts affects system behavior. Such an approach is contrasted with a bottom-up modeling approach, where one thinks primarily about individual system components and relationships without any consideration about how the components
would affect the system output. Together, these represent two distinct ways of approaching modeling.

The findings of Hogan and Thomas (2001) suggest that the students’ modeling approaches affected their learning and actions during the modeling activities. From a DNR perspective, these modeling approaches can be considered the students’ ways of thinking. Hogan and Thomas recognize the reflexive nature of how a student’s views can influence his activity, and how his activity could influence his views: “Although having a systems view can support productive approaches to modeling, modeling in turn should develop students’ system views” (p. 343). This relationship can be more clearly articulated by considering these ideas through Harel’s Duality Principle (1998; 2001): the students’ approaches to modeling influenced their way of understanding network interactions.

Although Hogan and Thomas’ stated goal was for students to develop an understanding that complex systems have general characteristics, the researchers were in fact working with the intention that students’ knowledge would affect their approaches to future modeling: “students’ systems concepts should in turn serve as tools for representing and exploring specific systems” (p. 343). Thus, Hogan and Thomas implied that students’ ways of thinking about complex systems would affect their approach to modeling complex systems, which is precisely what they discovered. Rob and Jason had ways of thinking about modeling complex systems very different from their fellow classmates, and, as they engaged in the modeling activities, approached the activity differently, thus developing different ways of understanding
complex systems. Hogan and Thomas’ study exemplifies the importance of considering students’ existing ways of thinking because these ways of thinking influence their way of understanding. The duality principle provides an efficient and practical way to discuss the students’ different types of knowledge.

Hogan and Thomas’ (2001) research and the research of the Northwestern’s Center for Connected Learning and Computer-Based Modeling are unique within biology education because they transcend the notion of teaching students various biological concepts and theories, and emphasize the notion of helping students develop a “systems view” of natural phenomena. In Hogan and Thomas’ (2001) words, “one goal of education then, should be to foster systems thinkers—people who habitually analyze phenomena and problems as situated in larger contexts, consider multiple cause and effect relationships, anticipate the long-term consequences and possible side effects of present actions, and understand the nature of change over time” (p.319). To articulate the reasoning strategies of the students that were beneficial in helping them develop a systems view of ecological interactions, Hogan and Thomas (2001) focused on students’ beliefs and problem solving strategies rather than on their concept knowledge. Similarly, Wilensky’s studies at Northwestern aimed to help students develop beliefs about the nature of science and to learn science by engaging in activities in which they “reason about scientific order.” For Wilensky and Reisman (in press), “particular facts and theories need a context of processes and beliefs in order to be integrated with existing knowledge and retained” (p.44). Thus,
these research projects consider the larger implications of students “ways of thinking”
with respect to problem solving.

**Anthropomorphic and Teleological Reasoning**

Research on developing explanations also shows that, in the biological sciences, providing an explanation does not only imply cause-effect relationships (showing how a particular event leads to or brings about a particular outcome) but also evokes another kind of explanation known as teleological reasoning. Where causal relations deal with cause-effect, teleological relationships deal with means-end. Research studies confirm that many students use teleological reasoning to explain phenomena in nature (Hellden, 2000; Leach, Driver, Scott, and Wood-Robinson, 1996a; Tamir, 1985; Tamir and Zohar, 1991). The results from my pilot study are consistent with this finding.

As mentioned in chapter 1, anthropomorphism refers to the attribution of human reasoning to nonhuman beings, and teleological reasoning is the attribution of conscious purpose to something within a simple physical or natural phenomenon. Teleological explanations are not causal explanations. Teleology refers to cases in which ends are used as explanations for the way certain structures are built, or for the manner in which certain functions are performed. As Tamir and Zohar (1991) explain, “this kind of explanation seems to imply that the benefit derived from a particular structure or process is a sufficient explanation, and hence there is no need to look further for a mechanism which accounts for it. Also, acceptance of teleological
explanation implies the attribution of consciousness to nonhuman beings, or to
different organs, and hence is misleading” (p.57).

Tamir and Zohar’s (1991) study of high school students’ reasoning found that
a large percentage of students provided anthropomorphic explanations: 30% of high
school students believed plants wish, try, or strive, and 62% believed that animals
wish, try, or strive. These researchers categorized 29% of students as teleological
reasoners because they consistently relied on teleological explanations. Fifty-seven
percent were categorized as partially teleological because they revealed teleological
explanations some but not all of the time. Teleological reasoning in relation to
evolution was found to be held by 71% and 56% of the students in grade 10 and 12,
respectively.

Similarly, Preece and Janvier (1992) found that several 14- and 15-year olds
gave anthropomorphic interpretations of graphs based on ecological contexts. For
example, when students were asked to interpret a graph showing the effect of changes
in oxygen on organisms living in a stream, the students described how the shrimps
moved away from the sewage because sewage was “nasty,” and moving away is an
appropriate response to something nasty.

Teleology plays a role in students’ understanding of food chains as well.
According to Reiner and Eilam (2001), students believed a “food chain is a series of
organisms, which support each other’s need for food” (p. 564). The authors call this
explanation of why an element is part of a food chain a mental causal model. Leach,
Driver, Scott, and Wood-Robinson, (1996b) also found that some students used
teleological reasoning in stating that organisms are plentiful to fill a demand for food in another population. Twenty-two percent of 16-year olds, when asked to explain why an insect population was so large, stated that, because birds eat insects—and there are “lots of birds”—then there needed to be “lots of insects” to support the bird survival. In other words, populations of organisms at lower trophic levels were large in order to satisfy organisms at higher trophic levels.

Thinking teleologically about the nature of biological processes can hinder students’ development of the scientific way of understanding. Explaining biological phenomena in terms of purpose and intention does not account for the causes by which these processes are brought about. Therefore, teleological explanations are one type of “causal scheme” to anticipate when asking students to generate explanations to account for biological phenomena.

**Summary of the Research on Ways of Thinking in Biology**

The existing research studies on students’ beliefs and problem solving approaches confirm that students’ ways of thinking govern their science activities. Hammer (1994) demonstrated that students’ epistemological beliefs about the structure and content of physics affected how the students used and developed their conceptual knowledge. Hogan and Thomas (2001) found that students’ beliefs and modeling strategies affected their approach to modeling complex systems. Grotzer and Perkins (2000) and White (2000) show that students hold assumptions about the nature of causality that can lead to alternative conceptions. These studies, however, focus primarily on students’ existing ways of thinking and offer only superficial solutions
for modifying instruction to help develop more desirable ways of thinking. In other words, these studies lack a coherent framework for guiding the development of scientific thought. As I have tried to show throughout this section, the principles of Harel’s (1998; 2001) DNR-based instruction provides a way to consider both the subject matter content and the broader overarching conceptions (or ways of understanding and thinking) that we want students to develop.

**A Review of the Literature on Students’ Current Ways of Understanding Ecological Concepts and Processes**

Harel’s (1998, 2001) DNR-based instruction focuses on helping students develop mathematical ways of thinking and ways of understanding by provoking students’ intellectual need to learn. This entails identifying those situations that create cognitive disequilibrium for a particular population of students relative to the concept to be learned. The task is challenging yet essential. If students do not have a need to find a solution to a problem, they are not developing ways of understanding the target concepts that could later lead to the desired ways of thinking. Identifying those problem situations requires knowledge about students’ existing ways of thinking and ways of understanding. Towards this end, I include a comprehensive review of the literature on students’ concept knowledge from ecology education.

The ecology education community has identified several biological concepts as fundamental for developing an understanding of ecological interactions: the cycling of matter, the flow of energy, and the related conversion processes of respiration, photosynthesis, and decay (Anderson, Sheldon and Dubay, 1986; Anderson, Sheldon, and Dubay, 1990; Carlsson, 2002a, 2002b; Leach, Driver, Scott, and Wood-Robinson,,
1995, 1996a,b; Roth and Anderson, 1987). The literature reveals that students have qualitatively different ways of understanding these biological processes and concepts from the biological community. This section of the dissertation provides a summary of the literature on secondary and college students’ ways of understanding these ecological concepts. Although none of the researchers specifically address ecological “ways of thinking,” they recognize the above biological concepts and processes as the key to tying the living and the non-living elements of an ecosystem into a functional whole.

**The Role of Photosynthesis and Respiration in Ecosystems**

Photosynthesizing plants are the primary energy source of life for most organisms on earth. Thus, understanding the process and products of photosynthesis is essential for developing an understanding of the role of plants in an ecosystem. A biological understanding of photosynthesis and respiration therefore, acts as a bridge between the living world and the non-living world in terms of energy flow and matter cycling.

Anderson, Sheldon, and Dubay (1986) surveyed undergraduate students’ conceptions of photosynthesis, respiration, and food, and found that very few students had ways of understanding compatible with those of biologists. Students tended to use the terms “respiration” and “food” in ways that conformed with standard English language usage, but not with accepted biological usage. Furthermore, students seemed to have basic misconceptions about how plants and animals use matter and energy. In
fact, Leach, Driver, Scott, and Wood-Robinson (1995) found that 16-year old students
did not differentiate matter from energy and food in the context of ecosystems.

Sources of matter and energy for plant growth. Several studies worldwide
document students’ ideas about the sources of matter for plant growth. Primarily,
students of all ages believe that plants receive their food from the soil (Bell, 1985;
Hellden, 2000; Roth and Anderson, 1987; Stavy, Eisen, and Yaakobi, 1987; Waheed
and Lucas, 1992; Wandersee, 1983) or that plants make direct use of solar energy to
meet their energy needs (Barker and Carr, 1989a,b). Several authors found that
students recognize water as essential for plants, but not directly related to plant
nutrition (Barker and Carr, 1989a,b; Roth and Anderson, 1987).

In a study investigating students’ ideas about selected ecological concepts,
Leach, et al. (1996a) documented through interviews and written comments that
students of all ages spontaneously suggested that plants need some source of food:
“Food is seen as something which organisms take in from their environment and not
as being synthesized within the plant” (p. 22). Almost 50% of students ages 14 to 16
stated that plants need soil as a source of food; whereas, only 10% of the 16-year olds
suggested that plants make their own food. The researchers also found that only one
third of 16-year old students stated that plants need carbon dioxide to stay alive and
healthy.

Even at the college level, students tend to define food as substances that plants,
like animals, take in from their environment. Anderson, Sheldon, and Dubay (1986)
found that only two percent of the undergraduate students surveyed said that plants do
not absorb food through their roots. These researchers also surveyed students’ ideas about sources of energy for plants and animals and found that although 90% of the students indicated that plants obtain energy from the sun, only 10% circled only sun. The others indicated that plants additionally obtain energy from other sources, such as water, soil, and fertilizer. With animals, students thought that along with meat and potatoes, air, water, sunlight, and exercise provided energy. In general, students believed that both plants and animals obtain energy from a wide variety of sources in their environment.

Conceptions of Photosynthesis. Photosynthesis is the production of energy rich organic materials (carbohydrates) through the conversion of solar energy. The research examining students’ ways of understanding photosynthesis reveals that few students demonstrate this biological understanding (Anderson, Sheldon and Dubay, 1986; Barker and Carr, 1989a,b; Carlsson, 2002a; Roth and Anderson, 1987; Waheed and Lucas, 1992; Wandersee, 1983). Anderson, Sheldon, and Dubay (1986), for instance, found that only 28% of the undergraduate college students studied mentioned the conversion of sunlight to food energy or some equivalent form of energy when asked about photosynthesis. Instead, photosynthesis was viewed as the plant’s form of respiration in which carbon dioxide is taken in and oxygen passed out (Barker and Carr, 1989; Carlsson, 2002). My pilot studies are consistent with this finding. Even after instruction in which students participated in experiments testing starch in leaves, Barker and Carr (1989) found that only 42% of students stated that photosynthesis was a food making process.
Carlsson (2002a) examined preservice teachers’ understanding of photosynthesis through interviews based on two different ecosystem contexts. She found that ideas of consumption and production rather than transformation were common among college level students. Most students believed that “plants take in and use some components, while others are produced, independent of the intake” (p. 694).

Roth and Anderson (1987) claim that middle school students believe that photosynthesis is not important to plants, but rather is something that plants do for the benefit of people or animals: “Plants are important because they make oxygen for people and animals to breathe. Plants are also an important source of food for animals, but they are not the only source” (p. I-6). This view represents a teleological way of thinking.

Conceptions of Respiration. The process of respiration in plants is unknown to a majority of students at all levels (Barker and Carr, 1989; Hellden, 2000; Leach, Driver, Scott, and Wood-Robinson, 1996a; Lin and Hu, 2003). In fact, Leach, et al. (1996a) conducted interviews based on a variety of ecological contexts and claimed that none of the interviewees mentioned the process of respiration at any stage during the interviews. This suggests that students do not see the role of oxygen in the respiration of food as relevant to the context of the cycling of matter and the flow of energy in ecosystems. In addition, Anderson, Sheldon and Dubay (1986) studied college non-biology majors’ conceptions of how plants and animals acquire and use matter and energy, including the roles of respiration and photosynthesis, and found
that students refer to respiration as “breathing,” rather than the biological definition of cellular respiration.

**Matter and Energy in Ecological Systems**

Matter is cycled and recycled through the biotic and abiotic components of an ecosystem. As matter flows through living systems, and between living systems and the physical environment, chemical elements are recombined in different ways, but matter is always conserved. Energy, although still conserved, is transformed and passed through the chain of consumers and decomposers, but is gradually dissipated to the environment as heat.

The processes of feeding, decay, and production are all matter and energy conversion processes; however, the issue of transformation of matter and energy are not commonly understood by students (Carlsson, 2002; Haidar, 1997; Hellden, 1995; Kesidou and Duit, 1993; Leach, Driver, Scott, and Wood-Robinson, 1995a, 1996a,b; Renstrom and Anderson, 1990; Watson and Dillon, 1996). Rather, ideas of consumption are most common among students (Carlsson, 2002; Goldring and Osborne, 1994; Kesidou and Duit, 1993; Reiner and Eilam, 2001; Solomon, 1982; Taber 1989).

**Conceptions about matter.** Renstrom and Anderson (1990) conducted a phenomenographic study of 13- to 16-year old students’ conceptions of matter after one to three years of instruction in chemistry and found that only one out of twenty students had developed a scientific understanding of matter. Six distinctly different conceptions of matter were identified, some of which can be found in the history of
science. Their finding that the nonconservation of matter was of no concern for some students is particularly relevant for this study. Students believed “substances can come into existence from nothing and they can also completely disappear, especially when they are divided into increasingly smaller pieces” (p.560).

Conservation of matter is an important concept in ecology for a variety of reasons, including the increasing use of natural resources by humans and the large quantities of disposed waste humans are accumulating. Current studies reveal that concepts related to the conservation of matter are not well understood among high school or college level students (Anderson, Sheldon and Dubay, 1986; Haidar, 1997; Leach, Driver, Scott and Wood-Robinson, 1995, 1996a; Renstrom and Anderson, 1990). In fact, Haidar (1997) examined 173 prospective chemistry teachers’ microscopic and macroscopic understandings of conservation of matter and found that they did not have an appreciation for the small size of atoms, failed to make predictions based on the conservation of atoms, and had no understanding of the conservation of mass.

Leach, Driver, Scott, and Wood-Robinson’s (1995) study explored the understanding of conservation of matter for students aged five to 16 and found that most did not apply the concept of conservation of matter in the context of ecosystems. “The idea that all matter is conserved, in spite of the apparent reduction in size [of an apple] during decay, was not noted in the explanations of the majority of 16-year-olds” (p. 31). Anderson, Sheldon and Dubay (1986) also found that most
undergraduates fail to conserve matter in their reasoning about chemical transformations, particularly those involving invisible gases as reactants or products.

Hellden (1995) examined students’ understanding of the transformation of matter through clinical interviews and found that students did not consider air as substantive. He conjectured that because students did not recognize gas as a material, the students reasoned that matter was renewed, modified, transmuted or disappeared. Issues related to understanding the nature of a gas may present ontological challenges for students. Many students believe that if they cannot observe something, it does not exist (Driver, Squires, Rushworth, and Wood-Robinson, 1994; Leach, Driver, Scott, and Wood-Robinson, 1996a). To use an example cited by Leach, et al. (1995a), “In the case of photosynthesis, pupils found it difficult to conceptualize plant body mass as coming from an invisible atmospheric gas and water, rather than a more ‘solid’ substance such as soil” (p. 31).

Understanding the role of gases in the cycling of matter signifies a shift in the concept “air” between ontological categories—one must change one’s conception of air from nonsubstantive to substantive. Without this change, one will have difficulty understanding that a plant assimilates a gas as a raw material in building up the plant, or to understand that water and carbon dioxide are the major end results of the decomposition of plants (Leach, Driver, Scott, and Wood-Robinson, 1996a; Wood-Robinson, 1991).

Conceptions about Decomposition. Decomposition is a key process in the cycling of matter in ecosystems; however, decomposition is not seen as a stage in the
cycling of matter for many students (Hellden, 1995; Leach, Driver, Scott, and Wood-Robinson, 1996a). Hellden (1995) found soil to be the endpoint concerning decomposition in nature. Leach, et al. (1995a) found that none of the students in their sample showed evidence of relating decay to a comprehensive model of the cycling of matter in ecosystems. “Indeed, the most common reason for decay suggested by pupils referred to decay as a natural fate of organisms, with no evidence of viewing decay as a chemical process” (Leach, Driver, Scott, and Wood-Robinson, 1996b, p.141). Eyster and Tashiro (1997) claim that “students easily forget that photosynthetic organisms use up much oxygen at night and that microbial decomposition of dead organisms continues to use up oxygen” (p.363).

**Conceptions of energy.** Aspects of the ideas of energy transformation, energy conservation, and energy degradation are at the very center of the biologist’s energy concepts, yet are conceptually difficult for students (Kesidou and Duit, 1993; Solomon, 1982; Taber, 1989). From a biologist’s perspective, energy is transformed, is passed on from one organism to another, and the biological value of the energy is lost to respiration each time it is transferred. During these changes, the total amount of energy does not change; it becomes less usable.

The research shows that students’ understanding of the nature of energy is not as sophisticated. Anderson, Sheldon, and Dubay (1986) found that students tend to be too inclusive in their definitions of energy. Anderson et al. felt that this broad and vague understanding of energy limited students’ ability to see how energy is transformed and conserved during biological processes or to appreciate the uniqueness
and importance of energy conversion processes such as respiration and photosynthesis. Solomon (1982) found that energy is thought to be a quality rather then a quantity. She argued that if students are not thinking about energy quantitatively, then they will have difficulty understanding photosynthesis and the storage of energy in foods.

Kesidou and Duit (1992) completed a comprehensive study of students’ conceptions of the second law of thermodynamics and found that the idea that energy is used up in processes is common. Students, however, had no concept of energy degradation. From the students’ perspective, energy was usually seen as something that brings actions and effects. Actions and effects are hampered by resistances. Ideas of energy transport, transformation, conservation, and degradation are generally missing in this framework. Only two students out of 34 reflected that one form of energy might be transformed into a different form. The physicist’s view of energy conservation was also used very rarely.

Andersson (1999) studied Swedish ninth graders’ conceptions of energy flow by asking students to follow energy from the sun to motoring or domestic lighting. The authors found that students usually described the events and objects but not the flow of energy, despite being urged to follow the energy. “The individual student does not generally possess a thorough and detailed knowledge of how the energy flow from the sun passes on through natural and technical systems” (p.61). In ecological systems, the flow of energy is represented in the context of food webs.

Conceptions of food chains and webs. Instructors often view food webs as a simple concept for students to understand and thus spend little time helping students
develop a biological understanding of food webs. Food webs, however, represent very complex energy transfer relationships in a community. One can memorize what a food web is, but to understand the complexity and connectedness of food webs, one must develop an understanding of various other biological relationships: the functional roles of producers and consumers in a system; the concept of matter cycling in relation to the length of food chains; and an understanding of energy from a biological perspective to appreciate the inefficiency of energy transfer along the food chain (Pimm, Lawton, and Cohen, 1991).

The research reveals that many students do not understand the dynamic relationships in food webs or the complexity of interactions that occur within a food web (Barman, Griffiths, and Okebukola, 1995; Eilam, 2002; Gallegos, Jerezano, and Flores, 1994; Griffiths and Grant, 1985; Munson, 1994). As Munson (1994) explains, “Students appear to see the species at the “top” of a food chain as having advantages such as gaining the most energy, being able to feed on all species lower on the food chain, or being a part of a population that will increase in numbers” (p. 32). When considering food webs, matter is perceived only as food, and energy is seldom mentioned or considered (Eilam, 2002). Grotzer and Basca (2003) found that elementary teachers confuse energy transfer as cyclic; they think energy is recycled in the food web.

Reiner and Eilam (2001) examined 14- and 15-year old students’ concepts of ecosystem and habitat through the construct of food chains. Through pre- and post-tests, the authors found that the major factors considered by students in identifying a
food chain are eating events (involves eating), size hierarchy (orgs get larger in size as
you go up the chain), and total elimination (for an element to be part of a food chain it
must be totally eliminated after consumption). As they describe it, “Students tend to
view food chain as an eating order rather than a conversion process of matter or
energy; decay and production are not necessarily part of a food chain. Matter
conversion is not related to the processes of a food chain” (p. 565). Further, students
did not often include the idea that a producer is the first link in a food chain. Reiner
and Eilam consider this view of a hierarchy of support for survival a “mechanistic
view.” This mechanistic schema excludes the roles of the producer, energy
 conversions, and decomposition in a food chain. Adeniyi (1985) reported similar
findings with Nigerian students.

Leach, Driver, Scott, and Wood-Robinson (1996b) also examined students’
conceptions of food webs and found that a number of pupils at all ages misinterpreted
the direction of predator-prey relationships. Many students talked about organisms in
the singular. In general, pupils made the least links between the removal of a top
predator and the rest of the food web, and most links between the removal of
producers and the rest of the food web.

Webb and Boltt (1990) studied 15- to 17-year olds’ ideas about trophic
relationships and found that only two percent of the students considered effects being
transmitted along more than one route. When asked to consider other routes, however,
72% could identify them. The authors claim that "students cannot successfully
integrate their ideas to produce a holistic concept of food web” (p.190). Barman and
Mayer (1994) found that “students tend to provide a basic and unsophisticated description of the concepts of food chains and food webs, and that some students revealed one or more misconceptions about these topics” (p.160). All of the students failed to describe the feeding relationships as a means of energy transfer among organisms. Some students viewed a food web as several single food chains rather than an interconnected unit.

**Students’ Conceptions of Food.** The notion that food is organic matter that provides matter and energy—rather than something “taken-in” by plants or animals—presents an obstacle for students (Roth and Anderson, 1987). Furthermore, students do not view eating as matter and energy consumption, but rather, as the elimination of the element eaten (Reiner and Eilam, 2001).

At a young age, students appreciate that food is an essential requirement for the growth of living things. Leach, et al. (1995a) found, however, that the scientific explanation that the body matter of all organisms is “chemically transformed food” “posed huge problems to learners, as evidenced by the absence of this view in the explanations of 16-year olds, even after relevant teaching” (p. 31). Students do not seem to be able to consider food at both a macroscopic and microscopic level. Rather, they think of food as being consumed, providing energy, and being excreted. They do not consider the chemical components of food to be similar for all species in a system.

**Summary of the Research on Students’ Ways of Understanding**

The biological processes of photosynthesis, respiration, decomposition, cycling of matter, and transformation of energy are the essential processes underlying an
integrated ecological system characterized by mutual dependencies. This summary of
the ecology conceptions research reveals that secondary level and college students
have not yet developed a biological understanding of these processes. In fact, Leach,
Driver, Scott, and Wood-Robinson (1996a) examined students’ understanding of the
relationship between these different processes in ecology and found that none of the
students showed evidence of relating photosynthesis, respiration, and decay into a
view of the cycling of matter in ecosystems. Furthermore, students seem to have very
limited understanding of the transformation of matter and energy (Carlsson, 2002b)
and the use of food webs to represent this relationship. With a limited understanding
of food webs and the associated interrelationships, students may have a difficult time
understanding phenomenological effects such as how overgrazing could have a
devastating effect on an ecosystem. Unfortunately, many university instructors believe
that students come to the undergraduate classroom with far more biological
understanding than the research reveals.

My observations of students in ecology classrooms concur with the research
findings. For example, a university student enrolled in my biodiversity review section
e-mailed me the following question:

Professor X was talking about the late Silurian-early Devonian
angiosperm explosion being like the Cambrian explosion in that there
were major environmental changes like decreased CO2 levels and
increased O2 levels. Why would this type of environment be a place for
PHOTOSYNTHESIZING organisms to flourish? It seems like it would
have to be the other way around. (sic)

I conjecture that this student did not understand that just as animals respire to
breakdown consumed materials into energy and matter, plants must also respire to
breakdown the glucose they make during photosynthesis. The idea that only animals respire is a common naïve conception among students of all ages (Barker and Carr, 1989; Hellden, 1999; Leach, Driver, Scott, and Wood-Robinson, 1996a). Thus, attention must be paid to students’ understanding of the biologically mediated processes that contribute to the functioning of ecological systems if we expect students to develop a biological understanding of these systems.

The research literature informs us of those concepts and processes in ecology that are particularly difficult for students to learn. Students’ difficulties reveal obstacles from which to develop problem situations that promote intellectual necessity. Providing students with a situation in which they are invested in resolving the conflict it presents can facilitate students’ accommodation of new knowledge. As students develop biological ways of understanding matter cycling, energy flow, respiration, photosynthesis, decomposition, and the relationship between these processes, they may begin to develop more desirable ways of thinking about the interrelatedness of ecological systems.

The Research on Problem Solving in Science Education

Problem solving in science classrooms usually involves textbook problems in which the solutions are found by applying formulas or definitions found in the preceding chapter. There is, however, some literature in science education on alternative approaches to textbook-oriented problem solving. One area of research distinguishes between well-structured problems and ill-structured problems and examines the cognitive and affective predictors of performance on each type of
problem. A related field of study generating much interest at the university level is an instructional strategy called problem based learning (PBL) which utilizes ill-structured problems. These approaches provide insight into the development of problem tasks for biology; however, each falls short of providing a theoretical basis for designing, developing, and implementing curricula targeted at helping students develop their knowledge. Throughout this review of the existing research into problem solving, I show how the DNR-based instructional principles can provide such an organizing framework.

**Well-structured versus Ill-structured Problems**

Typically, science teachers assign well-structured application problems at the end of a conceptual unit. Well-structured problems

- present all elements of the problem
- are well defined problems with a known solution
- engage the application of a limited number of rules and principles that are organized in a predictive and prescriptive arrangement with well-defined, constrained parameters
- involve concepts and rules that appear regular and well-structured in a domain of knowledge that also appears well-structured and predictable
- possess correct, convergent answers
- possess knowable, comprehensible solution methods in which the relations between decision choices and all problem states is known or probabilistic,
- have a preferred, prescribed solution process (Jonassen, 1997).

In classrooms organized around well-structured problems, the procedures and concepts required to solve the problem are often the focus of instruction.

Many of the problem solving studies in physics over the past two decades examine the differences in problem solving strategies between experts and novices as they solve well-structured problems (Chi, Feltovich, and Glaser, 1981; Larkin,
McDermott, Simon, and Simon, 1980; NRC, 1999). These researchers have suggested that experts have more interrelated and connected mental structures, as demonstrated by their ability to recognize features and patterns in problem situations that are not noticed by novices.

Ill-structured problems have been contrasted with well-structured problems in the research literature. Ill-structured problems

- fail to present one or more of the problem elements
- have vaguely defined or unclear goals and unstated constraints (Voss, 1988)
- possess multiple solutions, solution paths, or sometimes no solutions at all
- possess multiple criteria for evaluating solutions
- represent uncertainty about which concepts, rules, and principles are necessary for the solution or how they are organized
- offer no general rules or principles for describing or predicting most of the cases
- have no explicit means for determining appropriate actions, and
- require learners to make judgments about the problem and defend them often by expressing personal opinions or beliefs about the problem interpretation (Shin, Jonassen and McGee, 2003).

Researchers have claimed that the skills used to solve well-structured problems may not be sufficient for solving ill-structured problems (Sinnott, 1989; Voss and Post, 1988). For instance, the process required for solving ill-structured problems involves constructing multiple problem representations, instead of a single one, for providing evidence for the development of an argument (Jonassen, 1997). Thus, an obvious advantage of ill-structured problems is that they have divergent solutions, providing an opportunity for problem solvers to develop and justify their position.

Several studies examining the cognitive components of solving both well-structured and ill-structured problems found that well-developed domain knowledge is
a primary requisite in successfully solving either type of problem (Chi, Glaser, and Rees, 1982; Jonassen, 1997; Roberts, 1991; Shin, Jonassen, and McGee, 2003). These studies, though, do not address how the learner is supposed to develop this domain knowledge. DNR-based instruction (Harel, 1998, 2001) offers a method for developing this “domain knowledge”—the Necessity and Repeated-reasoning Principles. Inherent in Harel’s DNR is the notion that problem situations can be used to create opportunities for disequilibrium-equilibrium phases that can lead to the construction of desired knowledge. These problems often include several characteristics of ill-structured problems; however the intent of the problem is for students to develop “domain knowledge.” Students do not acquire the domain knowledge first and then apply it to well-structured or ill-structured problems, but rather, problems are designed to help students develop specific ways of understandings.

Problem-based Learning

Problem-based learning is an instructional approach that began in the early 1950s in medical schools. More recently, problem-based learning has expanded from the medical profession to a variety of other professional programs as well as diverse content domains such as science and social science classes at both the undergraduate and secondary levels. Problem-based learning (PBL) is used to refer to “many contextualized approaches to instruction that anchor much of learning and teaching in concrete problems” (Gijbels, Dochy, Van den Bossche, and Segers, 2005, p.29). This instructional strategy proposes that students work in small groups to develop solutions
to contextualized, ill-structured problems. From this perspective, the problems should be unorganized, unsynthesized, and open-ended because this allows for student processing (Albanese and Mitchell, 1993). Below is a sample problem designed by Barbara Duch for a biology course at the University of Delaware:

John H. Martin, the director of the Moss Landing Marine Laboratories, thinks the potential problem of global warming could be addressed by dumping iron into the ocean waters off Antarctica. He and his coworkers have demonstrated that the amount of chlorophyll found in ocean water samples collected (in 30 L bottles) from the Gulf of Alaska can be increased up to nine-fold by the addition of iron.

When they repeated this fertilization experiment with samples collected from a few hundred miles off the Antarctic coast, he and his colleagues found that for every unit of iron added to Antarctic sea water, the organic carbon content increased by a factor of 10,000.

a. What is the basis of Martin’s premise that seeding the ocean with iron would help combat potential greenhouse warming?

b. What organisms found in sea water account for the increase in chlorophyll content and increase in biological productivity Martin and his research group observed? (http://www.udel.edu/pbl/cte/spr96-phys.html)

In the second part of this problem, the students are provided with a graph of the composition of 7,000-foot deep Antarctic ice cores and asked if they agree with Martin that the information provided by ice core analysis supports his hypothesis, and why or why not. Finally, in the last part of the question, a research proposal by a member of Martin’s team is briefly outlined and the student is told that the applicant has not adequately addressed the possible ecological impact of such a large-scale endeavor. The student is then asked if they would recommend funding the project, and why or why not. (See http://www.udel.edu/pbl/cte/spr96-phys.html for the full problem.)
There exists a multitude of studies examining the implementation of PBL at the college level. One review by Albanese and Mitchell (1993) reported that although students found PBL to be more nurturing and enjoyable, and the students performed as well on clinical examination as those receiving conventional instruction, PBL students scored lower on basic science examinations. Similarly, Gijbels, Dochy, Bossche, and Segers (2005) conducted a statistical meta-analysis of 40 empirical studies of PBL, classifying the method of analysis within these studies into three categories: understanding of concepts, understanding of principles that link concepts, and linking of concepts and principles to conditions and procedures for application. These researchers report that students in PBL performed better on assessments measuring the second and third category; however, the effect of PBL on the knowledge base of students tended to be negative.

Although the general goal of PBL is to develop successful problem solving in two dimensions—the acquisition of knowledge and the application of knowledge (Gijbels, Dochy, Bossche, and Segers, 2005)—the research reports that students are not acquiring the domain knowledge intended. This may be because PBL did not emerge from any particular theoretical perspective. Noticeably absent from any of the literature on PBL is a theoretical basis for designing problem tasks. Although proponents of PBL feel “intuitively” that PBL offers an approach that “reflects the way the mind actually works” (Rhem, 1998), there are no theoretical principles guiding problem design. The general guidelines are to develop problems that are open-
ended and present real-world situations. Without a theoretical basis guiding the purpose and design of problem tasks, student learning is unpredictable at best.

In contrast, problem situations are used in DNR-based instruction (Harel, 1998, 2001) because “learning grows only out of problems intrinsic to the students, those which pose an intellectual need for them” (in press, p.21). Therefore, the problems used in DNR-based instruction are designed specifically to create cognitive puzzlement for students—to create an intellectual need for a specific way of understanding. Accordingly, the instructor seeks out those ideas and concepts that are particularly difficult for students to develop. Only those problems that present students with a situation in which they are invested in resolving the conflict it generates will have the potential to create intellectual need and promote learning. Thus, in DNR-based instruction, problem design is focused and grounded in the premise that intellectual stimuli are needed for disequilibrium-equilibrium phases, and that creating these phases has the potential to lead to the desired understanding.

**Conclusion**

In this chapter I have summarized the existing research literature in biology education from a new perspective—Harel’s DNR (1998; 2001). I reinterpreted the research on students’ problem solving approaches and beliefs about science as students’ ways of thinking. Likewise, I reconceptualized the literature on students’ and professionals’ concept knowledge in biology as students’ ways of understanding. Helping students develop expertise was reinterpreted as helping students develop ways of understanding and thinking compatible with those that have been institutionalized
in the biology community. Finally, the claim that “science is both a product and a process” can be rephrased from a DNR perspective as, “science is both a way of understanding and a way of thinking”. Instructional practices in biology must consider the dependent relationship between these two categories of knowledge if we are to help our students develop the cognitive tools that define biological knowledge.

I have found that although a number of research studies offer instructional implications for their findings, they lack a framework that would inform how the research knowledge on students’ ways of understanding and thinking in biology, along with the knowledge about student learning, can be unified and translated into effective teaching products and instructional practices. In other words, how can biology educators coordinate the social constructivist perspective on learning with the goal of helping students develop the conceptual tools that the biology community at large accepts as correct and useful in solving scientific problems? I submit that Harel’s (1998; 2001) DNR principles provide a useful framework for considering the instructional implications of this existing research.

Harel’s DNR posits that there exists an interdependent relationship between what students produce and the character of their mental acts—between their ways of thinking and their ways of understanding. Identifying the ways of thinking and ways of understanding that have been institutionalized in the biology community, then, is essential for establishing specific cognitive goals for instruction. One goal of this dissertation is to begin to explicate these ways of thinking.
Furthermore, Harel’s (1998; 2001) DNR instructional framework posits that desirable ways of thinking can develop through repeated opportunities to reason through situations. For example, as students develop ways of understanding nonlinear causal relationships in particular ecological situations, they can begin to develop a desired way of thinking (nonlinear causal reasoning). Therefore, ecological ways of thinking can develop from opportunities to reason about the complex and non-linear mechanisms and processes (such as the cycling of nutrients between organic and inorganic forms) that contribute to the functioning of ecological systems (populations, communities, and ecosystems).

In order to provoke in the students an intellectual need to develop the desired ways of understanding, one must build from students’ existing ways of understanding. We know from the literature that students have not developed biological understandings of many of the concepts and processes that contribute to ecologists’ ability to analyze a natural system or entity (for example, an organism, population, or ecosystem) and make connections between interacting components (whether biotic or abiotic). Therefore, research to improve students’ learning in biology must begin by identifying those problem situations that create the cognitive disequilibrium necessary for the intended learning to occur. This is the second of my two goals for this study.
CHAPTER 4: METHODOLOGY

As previously stated, the purpose of this study is to contribute to the development of theory for reconceptualizing biology instruction. Within this chapter, I describe the methods used to identify certain ways of thinking and understanding in the biology community as well as to determine what constitutes intellectual necessity for ecology learners. This chapter discusses (a) the methodological implications of the theoretical framework; (b) the interview and teaching experiment methodology; and (c) my experimental design.

Methodological Implications of the DNR Framework

Implications of the Duality Principle. An essential element of Harel’s (1998; 2001) DNR perspective is that mathematics curricula should not compromise the mathematical integrity of its contents. According to Harel (2006), “The mathematical integrity of a curricular content is determined by the ways of understanding and ways of thinking which have evolved in many centuries of mathematical practice and continue to be the ground for scientific advances” (p.3). To design and implement biology curricula that aim to help students develop and construct the ways of understanding and thinking compatible with those that have been institutionalized in the biology discipline, one must take into consideration the epistemology of biology. For this reason, I examined several philosophy of biology and history of biology texts (see Appendix 2) over a period of 18 months that aided the effective identification of ways of thinking and understanding that I encountered during my participation within the community of biologists and my interaction with biology students. My intent was
not to investigate the origin or genesis of these ways of thinking in biology, but rather, to develop a deeper understanding of the evolution of biological thought over time with an eye to expanding and refining my understanding of the current ways of thinking of biologists, and for the purpose of developing appropriate cognitive goals for instruction. (A discussion of the evolution of my understanding of the ways of thinking associated with the mental act of accounting for phenomena is presented in chapter 5.)

Implications of the Necessity Principle. According to the theoretical perspective on learning in which DNR is based, intellectual stimuli are needed to create in learners cognitive disequilibrium-equilibrium phases. Harel (1998) argues that this intellectual stimulus arises when “we encounter a situation that is incompatible with, or presents a problem that is unsolvable by our existing knowledge” (p. 501). Therefore, research focused on helping students develop desirable ways of understanding and thinking necessitates that one identifies factors that might contribute to creating problematic situations for students. For instance, what are students’ existing ways of understanding and thinking, and how does this knowledge affect how they interpret a problem situation? What are the influencing social forces and classroom norms that cause a student to initially engage in a problem and to pursue its solution? These questions necessarily imply that a researcher have access to those environments in which students encounter potentially problematic situations.
Consequently, my study was conducted in two phases. In the first phase, I conducted semi-structured clinical interviews with undergraduate university students to create models of “students’ biology” (Steffe, 1991) and to begin to identify those specific situations that may cause puzzlement for the students. From these findings, I developed several problem situations that I predicted would create an intellectual need to learn specific ways of understanding in ecology. In the second phase of my study, I developed a hypothetical learning trajectory (Bowers, Cobb, and McClain, 1999; Simon, 1995) and conducted a teaching experiment with a small group of students in which I refined the goals and lessons of the experiment each day in reaction to the students’ development.

**Interview and Teaching Experiment Methodology**

**Interviews.** Semi-structured clinical interviews allow the researcher to collect and analyze data on mental processes “at the level of a subject’s authentic ideas and meanings and to expose hidden structures and processes in the participant’s thinking that could not be detected by less open-ended techniques” (Clement, 2000, p.547). According to Schoenfeld (1985) “out loud” protocols are particularly useful if the experimenter wants to conduct an exploratory study as a preliminary step in generating a framework. The participant’s conscious thinking can help a researcher formulate a hypothesis and provide an initial path for the researcher to explore. Furthermore, conducting semi-structured clinical interviews enabled me to probe the students’ and ecologists’ specific thoughts without interference restrictions (Ginsburg, 1997). My ultimate purpose was actually to interfere by causing the participant to
think about something they might not have consciously thought about and shared, thus leading to a better understanding of the participant’s thinking. Through the semi-structured clinical interviews, I uncovered the ways of understanding and inferred ways of thinking underlying the students’ and ecologists’ verbalizations. I used my model of students’ current understandings to identify problem situations that had the potential to create cognitive disequilibrium.

**Teaching Experiment.** Identifying problematic situations for students is not sufficient to help students develop the intended ways of understanding. One must also identify the contributing factors that lead to a desirable product. Thus, a teaching experiment was conducted in which I, as the researcher, acted as both a teacher and an observer in an instructional situation. The goal of the teaching experiment was, to use Steffe and Thompson’s (2000) phrase, to “bring forth the schemes that students have constructed through spontaneous development” and use them in the formulation of a model of students’ learning (p.290). Steffe and Thompson (2000) describe the use of teaching experiments to uncover the mathematical constructive processes of students; that is, *how* students make meaning of math and the meanings they make. The teaching experiment allows the researcher to experience first hand students’ mathematical (or in this case biological) learning and reasoning. In teaching experiments, the researcher or teacher assumes that learners construct their understanding based on what they already know, but might not be aware that they know it or that their knowledge is applicable in this instance.
The teaching experiment methodology is both similar to and different from the methods of the clinical interview. The clinical interview endeavors to understand students’ current knowledge; the teaching experiment begins with understanding students’ current knowledge and then tries to use the students’ knowledge scheme to help them learn by challenging this knowledge scheme. Thus, the teaching experiment is directed toward understanding the progress students make over extended periods. The similarities of the two methods lie in the exploration of students’ ideas by developing hypotheses about what students understand and testing those hypotheses. During both a clinical interview and a teaching experiment, the researcher must think on their feet and probe students’ thoughts about concepts and ideas.

In the present study, the teaching experiment allowed the evolution of the students’ biology understanding to be observed and analyzed. As researcher and teacher, I investigated the development of, and changes in, students’ understandings as a result of various influencing factors. As theories emerged from the analysis of video of students’ problem solving, I was able test my hypotheses in the subsequent sessions.

Setting

A public university located in a large southwestern city provided the site for this study. This university attracts a wide range of students in terms of age, gender, and ethnicity; the average GPA and SAT scores for entering freshman are considered well above average (the average high school GPA of enrolled freshmen for fall 2005 was 3.93, and the average SAT score was 1251). Both phases of the study took place
at this university and drew from different groups of students. In the sections that follow, I describe the participants, methods of data collection, and data analysis for each phase of the study separately.

**Phase 1: Observations and Interviews**

The first phase of the research took place over two consecutive quarters, fall 2004 and winter 2005. This portion of the study made primary use of observations of practicing ecologists, semi-structured clinical interviews, and teaching interviews. The interviews were carried out in various conference rooms of an administration building on campus. Participation and observation in ecology laboratory meetings and ecology instruction occurred in those respective laboratories and classrooms.

**Observations**

Interactions with both biology students and practicing biologists played an important role in expanding and refining my knowledge of the ways of thinking and understanding of biologists. In all three quarters of 2004 and the winter quarter of 2005, I participated in an ecology professor’s weekly laboratory meetings as his ecology research group discussed both their current research projects and various published ecology research studies. The discussions were audio recorded, and I reviewed the recordings a minimum of one time. Participation in these meetings helped provide support and confirming evidence for the identification of ways of understanding and thinking of ecologists.

Furthermore, in both the fall and spring quarters of 2004 and 2005, respectively, I served as a teaching assistant for introductory ecology courses. The fall
2004 course was an upper division introductory ecology course; the spring 2005 course was a lower division evolution, behavior and ecology course. Through this experience, I had the opportunity to gain knowledge of students’ understandings and difficulties in ecology.

**Semi-structured Clinical Interviews**

During fall 2004 and winter 2005, I conducted semi-structured clinical interviews (Clement, 2000; Ginsburg, 1997; Schoenfeld, 1985) with three practicing ecologists and six undergraduate students. My goal in these interviews was to assess the participant’s ways of understanding and ways of thinking as they engaged in trying to account for ecological phenomena in an ecology context. The interview protocol followed a particular pattern. The initial task and presentation of the task was given to all participants in the same way (see Appendix 3). As the interviewer, I interpreted the participant’s response on the spot, developed a hypothesis as to why the participant might think that way, and from that, generated unique questions to test that hypothesis. In other words, I was responsive to the data as they were collected by generating new questions that clarified and extended the investigation (Clement, 2000). In these interviews, I was specifically interested in uncovering the participant’s existing ways of understanding about the functioning of an ecosystem. Why does he or she think that? What knowledge does he or she have that causes him or her to think that way? The interviews were conducted one-on-one and lasted approximately one hour. Each interview was video recorded and transcribed.
Clinical Interview Participants. I recruited the three professional ecologists—two male and one female—by personally asking them to participate in my study. These participants had varying degrees of experience and backgrounds in ecology. The student participants for the interviews were recruited from a lower division evolution, behavior, and ecology course during the fall quarter 2004. This particular course is one of three lower division biology courses required for general biology majors; however, several non-biology majors also enrolled in this course (from disciplines such as anthropology, engineering, chemistry, physics). Approximately 350 students were enrolled in fall 2004. On the first day of class, the professor permitted me to explain my research interests to the students and solicit volunteers to participate in the interviews. Fifty-one students completed the volunteer sheet (see Appendix 4), however only 31 responded to a follow up email. From this group of 31, I interviewed six students—three males and three females—that represented a cross section of majors and varying experience with college level biology courses. I also selected six additional students from the remaining 25—three males and three females—to participate in two group teaching interviews for the winter quarter. These six were selected because they agreed to participate in multiple interviews during the winter quarter.

Interview Data Analysis. Since my study dealt with behaviors in which little theory exists, it was generative in nature (Clement, 2000). For this reason, I interpreted large sections of transcript, and formulated observation categories that described the mental structures or processes grounded in the data. My goal for the interview portion
of this study was to create models of the students’ and ecologists’ ways of thinking and understanding. These types of analyses entail high levels of inference on the part of the researcher concerning the thought processes of the participants. Therefore, I began by examining the transcript of participants’ explanations in which they accounted for the functioning of a simple dynamic biological system (a self contained miniature ecosystem) and identified their ways of understanding specific concepts in ecology (for example, photosynthesis, feeding relationships, composition of plants and animals, etc). Identifying their ways of thinking, however, was more complex; one can only identify ways of thinking of individuals by inferring them from ways of understanding. According to Harel’s DNR perspective, to infer a way of thinking from a way of understanding one must: “(a) identify the mental act whose character is being used by the person being observed; (b) identify the person’s ways of understanding that are associated with that mental act; and (c) identify a common property among these ways of understanding” (Harel, 2006, p.22). This common property is a way of thinking associated with the identified mental act. Explicating the distinction between the learners’ and the professionals’ ways of thinking took several months and this distinction is described in detail in chapter 5.

**Teaching Interviews**

After creating models of students’ ways of understanding, I began to develop problem situations that had the potential to create cognitive conflict for students. To explore the effectiveness of these problem situations, I conducted one long term teaching interview with a group of three students. This teaching interview differed
from the clinical interviews because I presented the problem situations and then provided opportunities for students to develop the intended understanding. The teaching interview was similar to a teaching experiment in that I was interested in observing the development or refinement of the students’ understanding. However, I did not have an observer that collaborated with me and analyzed the lesson after each teaching session. The intent of this experiment was solely to refine the problem situations by observing students’ behavior as they assimilated and solved the problem situations. From this point forward, I will refer to this long term teaching interview as the Pilot Teaching Experiment.

Participants. As stated above, I recruited six students—three males and three females—from the original group of 31 volunteers to participate in two group teaching interviews for the winter quarter. Based on their availability, I selected two males and one female for the first pilot teaching experiment. These three students participated in six one-hour long teaching sessions. I chose groups of three students for two reasons. First, the benefit of using multiple participants for observation during the experiment provided an opportunity to focus on the behavior of one student explaining their thinking to another student while solving the problem together. This strategy better illuminated the participants’ reasoning. Second, the problem situations were intended to be difficult for the students. Working collaboratively improved the students’ chances of challenging each other’s thinking and developing a solution. Each session was video recorded and transcribed.
I did not conduct a second pilot teaching experiment, but rather, conducted one additional group interview at the end of the winter quarter with the final three initial recruits. The purpose of this latter interview was to test out one new problem situation.

Teaching Interview Data Analysis. Each teaching session was transcribed and reviewed prior to the following meeting. As with the interviews, I segmented the protocol and made observations from each segment. This interpretive approach is consistent with Schoenfeld’s (1985) problem-solving protocol framework. In Schoenfeld’s framework, the data is parsed into major episodes to capture much of the “essence” of a problem-solving session without getting lost in the details. An episode represents a body of consistent behavior on the part of the problem solver(s). As Schoenfeld (1985) explains, “The macroscopic approach allows one to get a sense of the apparent causes of success or failure in a problem solution” (p.185).

I used students’ statements and solution paths to make revisions on the next lesson’s problems and to modify the previous problems for future use. The knowledge from the teaching interviews and the pilot teaching experiment informed the development of a hypothetical learning trajectory for the primary teaching experiment (see Phase 2 below).

Phase 2: Primary Teaching Experiment

The primary teaching experiment was conducted during spring quarter 2005. As stated previously, the purpose of the teaching experiment was to construct models of students’ ecology learning as they engaged in DNR-based instruction. This included determining students’ ways of understanding and thinking, and observing how that
knowledge changed as a result of solving ecology-based problem situations in a small group context.

**Participants**

The student participants for the final teaching experiment were recruited via an email message sent to all biology majors and minors at the university (see Appendix 5). Sixteen students enrolled in the one unit lower division biology workshop course. During the first class session, the students were seated randomly in small groups and were video recorded as they solved a non-ecology based identification problem (see Appendix 6). I recorded each group for approximately ten minutes with the purpose of selecting three students to become the “video group” for the subsequent nine sessions. Each student also completed an information sheet describing their experiences in previous biology courses. Three students were chosen based on (a) their willingness to communicate with their group members while being recorded; and (b) their varied backgrounds in biology.

**Class Format**

The teaching experiment class met for 80 minutes, once each week for ten consecutive weeks. The classroom utilized large tables rather than desks and was arranged so that students worked in small groups of three or four. During class sessions, the students worked on tasks both individually and collaboratively, and participated in whole-group discussions. Formal lectures were not delivered; rather, the students worked on solving problem tasks together and prepared a group solution to present to the class. In the class discussions following the presentation of solutions,
I introduced terminology, asked for evidence or justifications for claims, summarized students’ work, and elicited connections between prior knowledge, the current activity, and previous lessons.

**Data Collection**

All class sessions of the teaching experiment were video recorded and transcribed. A single camera, run by an assistant, was placed in the back corner of the room near the video group’s table. While students worked in small groups the camera recorded the activity of the video group. During whole class discussions and presentations, the camera was focused on the presenters in the front of the room. Following each lesson, I observed and transcribed the video.

During these lessons, the students worked on a problem statement page or blank sheets of paper that I provided. The students’ individual papers were collected at the end of each lesson. Each group’s diagrams were recorded on individual white boards that were erased at the end of each session; however, they were captured on video when presented to the class. The students’ papers, the recorded diagrams, and the transcripts constitute the data set obtained from the teaching experiment.

**Data Analysis**

*Simultaneous*. The teaching experiment was conducted with both an instructor (author) and an observer. The observer was familiar with the goals of this project, the field of ecology, and the DNR perspective. Following each lesson, I transcribed the contents of the video recording and forwarded a copy of the transcript to the observer. Prior to the next lesson, we read the transcript, and then met to discuss ideas about
students’ learning, replaying appropriate segments of the video as needed. This retrospective analysis helped to bring past interpretations of students’ activity during the teaching session to the surface (Steffe and Thompson, 2000). Regularities and differences were identified in the students’ actions and language as they solved problem situations while interacting with the teacher, the other students, the problem, and related materials. From discussions about the teaching session and the students’ actions, the observer and I developed hypotheses about the students’ thinking, and modified the next lesson to test these hypotheses.

Subsequent. After data collection ended, I conducted a fine-grained analysis of the teaching sessions to begin to explicate the different schemes that emerged from engaging in the problem solving tasks. From careful analysis of the recorded teaching sessions, I was able to better understand student progress and document students’ ecological reasoning, learning, and development over time (Steffe and Thompson, 2000). I achieved this by means of the cyclical, interpretive analysis cycle described by Clement (2000) and adapted from Glaser and Strauss’ (1967) constant comparison method. I began by focusing on only one student at a time. I segmented the protocol and made comments about that student’s ways of understanding. I then inferred their ways of thinking by searching for regularities and patterns in their ways of understanding. I developed a description of the participant’s knowledge, and then returned to the transcript to compare that description with his or her actions and statements. I continued to analyze the video and modify my account until I formed a description that fit the data and presented a reasonable, coherent perspective of the
student’s ways of understanding and thinking. I then returned to the data and repeated this process for the other two students in the video group. From this intensive analysis, I constructed a viable model of the evolution of each of the three student’s ecology knowledge.

Another goal of the teaching experiment was to identify what constitutes intellectual necessity for ecology learners. For this analysis, I returned to the transcription data. This time, though, I analyzed all three students working together on the same task. I began to identify those problems that did indeed create cognitive puzzlement for the students. Towards this end, I examined each problem task segment separately. I parsed the data into major episodes (Schoenfeld, 1985) and examined the students’ interpretation of the problem and their statements while they developed a solution. I then returned to those sessions in which intellectual need was created and searched for the particular supports—such as questioning, interaction with curricular materials and artifacts, and instructional supports—that aided in creating intellectual necessity and helping students overcome difficulties. I abstracted from these findings the common factors that seemed to contribute to creating intellectual need (see chapter 7).

To clarify the distinction between the interview phase of my study and the final teaching experiment, I have used different labels for the participants. The interview participants are identified as Student One, Student Two…Student Eleven, or Ecologist One, Ecologist Two…Ecologist Four. The final teaching experiment participants from the video group are given the following pseudonyms: Franjelica, Austin, and Rachel.
Brief descriptions of the backgrounds of each student participant discussed in this study can be found in Table 1.

<table>
<thead>
<tr>
<th>Participant’s Pseudonym</th>
<th>Level of participation</th>
<th>Description of biology experience at the time of the interview</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student One</td>
<td>Interview</td>
<td>Math education major. Currently enrolled in 1BILD 3. No previous biology courses at the college level.</td>
</tr>
<tr>
<td>Student Two</td>
<td>Interview</td>
<td>Chemistry major. Completed BILD 1 and 2. Currently enrolled in BILD 3.</td>
</tr>
<tr>
<td>Student Three</td>
<td>Interview</td>
<td>Biology major. Completed BILD 1 and 2. Currently enrolled in BILD 3 and biometry.</td>
</tr>
<tr>
<td>Student Four</td>
<td>Interview</td>
<td>Aerospace Engineering major. Currently enrolled in BILD 3. No previous biology courses at college level.</td>
</tr>
<tr>
<td>Student Five</td>
<td>Interview</td>
<td>Biology Major. Completed BILD 1, 2 and currently enrolled in BILD 3 and genetics.</td>
</tr>
<tr>
<td>Student Six</td>
<td>Interview</td>
<td>History Major Graduate. Returning to college to complete prerequisites for veterinarian school.</td>
</tr>
<tr>
<td>Student Seven</td>
<td>Interview (pilot study)</td>
<td>Biology major. Completed BILD 3. Tested out of BILD 1 and 2 through AP exam.</td>
</tr>
<tr>
<td>Student Eight</td>
<td>Interview (pilot study)</td>
<td>Biology major. Currently enrolled in BILD 3. Took AP biology in high school.</td>
</tr>
<tr>
<td>Student Nine “Susan”</td>
<td>Interview (pilot study)</td>
<td>Linguistics major. Previously completed one lower division non-majors biology course. Two yrs HS bio.</td>
</tr>
<tr>
<td>Student Ten “Maria”</td>
<td>Interview (pilot study)</td>
<td>Human development major. Took AP biology in high school. No previous college level biology.</td>
</tr>
<tr>
<td>Student Eleven</td>
<td>Pilot teaching experiment</td>
<td>Biology major. Previously completed BILD 1, 3 and two marine biology courses at a community college.</td>
</tr>
<tr>
<td>Student Twelve</td>
<td>Pilot teaching experiment</td>
<td>Biology major. Previously completed BILD 1, 3 and two upper division biology courses.</td>
</tr>
<tr>
<td>Student Thirteen</td>
<td>Pilot teaching experiment</td>
<td>Biology major. Previously completed BILD 1, 2, 3 and upper division genetics.</td>
</tr>
<tr>
<td>Franjelica</td>
<td>Final teaching experiment</td>
<td>Psychology major. Formerly a biochem major. Previously completed BILD 1 and 3.</td>
</tr>
<tr>
<td>Austin</td>
<td>Final teaching experiment</td>
<td>Biology major. Currently enrolled in BILD 3. Tested out of BILD 1 and 2 through AP exam.</td>
</tr>
<tr>
<td>Rachel</td>
<td>Final teaching experiment</td>
<td>Biology major. Tested out of BILD 1 and 2 through AP exam.</td>
</tr>
</tbody>
</table>
Footnote:

1. BILD is an acronym for Biology: Lower Division. BILD 1, 2, and 3 are the three lower division biology courses required for general biology majors at the university.
CHAPTER 5: THE DUALITY AND NECESSITY PRINCIPLE APPLIED TO ECOLOGY EDUCATION

The triad of determinants useful for guiding instructional objectives identified in DNR-based instruction are mental acts, ways of thinking, and ways of understanding. To determine the extent to which the Duality Principle applies to ecology education, I began by identifying *accounting for phenomena* (or *explaining*) as a mental act representative of the practice of ecologists. The tasks and questions I posed to both ecologists and students during the study were designed to engage the participants in this mental act. I sought to determine if there were differences in the ways of thinking and understanding of ecologists and students, to explicate those differences, and to design problem situations to determine if building on students’ ways of understanding influenced the students’ ways of thinking.

In the sections that follow I present (a) an explication of the mental act of accounting for phenomena; (b) the evolution of my understanding of ecologists’ ways of thinking associated with this act; (c) a model of students’ existing ways of understanding ecological processes that informed the design of problem tasks used in the teaching experiment; and (d) an overview of the process of designing instruction based on intellectual necessity. Claims made about ecologists’ and students’ ways of thinking and understanding are supported with transcript evidence.

**Mental Act: Accounting for Phenomena**

One of the central roles of an ecologist is to account for observations of the living world. Ecologists seek to understand and account for phenomena, such as loss of biological diversity, the dead zone in the Gulf of Mexico, or the bleaching of corals.
As they develop explanations for their observations, their activity is governed by particular ways of thinking. Therefore, accounting for phenomena (or explaining) constitutes the mental act of focus in this investigation.

One aspect of explaining biological phenomena is to identify causal relations and develop predictive and explanatory models (Hale, 1991; Krebs, 2001; Mayr, 1982). There are, however, just as many instances when biologists use scientific models to describe, explain, and predict. Anderson (2003) labels these two different aspects of scientific practice “inquiry” and “application.” Anderson (2003) defines “inquiry” as reasoning from evidence by finding patterns in observations and constructing explanations for those patterns. “Application” is defined as reasoning from scientific models by using models and patterns to describe, explain, predict, and design (see Figure 3).

Figure 3: Scientific knowledge and practices (from Anderson, 2003)
Although both practices form an integral part of the activity of biologists, my study focuses primarily on the practices associated with developing explanations to account for observable phenomena by applying existing models (arrows going right to left in Figure 3) rather than collecting and synthesizing data to create a model. From this point forward, when I use the term accounting for phenomena (or explaining) I am referring to application as it is defined by Anderson (2003). Inquiry differs from application in that it includes development of theoretical models based on data collected. The iterative process of collecting and synthesizing data to develop a theoretical model is a mental act that warrants a study of its own. Within the scope of this dissertation, I am primarily interested in characterizing the differences in students’ and professionals’ explanations as they try to make sense of phenomena they observe by drawing on existing explanatory models. The unit of analysis in this case is the explanations or accounts provided by the participants.

The Ways of Thinking of Ecologists Associated with the Mental Act of Accounting for Phenomena

Inferring ecologists’ way of thinking associated with explaining phenomena was a complex and dynamic process. Although I recognized a qualitative difference between professionals’ and students’ accounts early on, it took more than a year of study to explicate this difference. In the section that follows, I describe the evolution, up to this point, of my understanding of the ways of thinking associated with accounting for phenomena. It was the distinctions between the accounts given by ecologists and students that illuminated the characteristics of the ecologists’ ways of thinking. I therefore present segments of transcript from interviews with ecologists
and students in the current chapter. I anticipate that my articulation of the way of thinking associated with explaining phenomena in the living world will continue to evolve as my research continues.

**Stage I: Interconnectedness**

The pilot study interviews provided the first indication that there was something qualitatively different about the ecologists’ accounts of biological phenomena and students’ accounts. The interview tasks were designed in such a way that students would consider the effects of changes on an intertidal community (for example, an invasive species or a change in the ocean temperature). One of the first characteristics I identified from interviews completed in the pilot study was that ecologists viewed the net effects of all ecological system relationships as interacting simultaneously and considered the interdependence of organisms on each other and the environment. For example, in an interview with Ecologist One, a graduate student in ecology, I found that rather than focusing solely on direct relationships (as the university freshmen had done), she considered various indirect relationships as possible causes for phenomena. Moreover, she considered *multiple* possible causes for changes in the intertidal ecosystem presented to her, as well as changes at time scales both short and long term. Her accounts differed from the accounts of undergraduate biology students at the university, who focused predominantly on direct relationships and the identification of simple linear relationships between organisms.

I labeled the ecologists’ way of thinking at that time “profound interconnectedness.” This description, however, was not sufficient to identify all of the
qualitative differences that distinguished the students’ and the ecologist’s accounts. In the pilot study, as the ecologist identified causes and effects, the character of this mental act could be described as non-linear causal reasoning. She searched for multiple indirect relationships and considered the net effects of these relationships. Yet there was also something less obvious governing the ecologist’s reasoning as she considered the interactions within the intertidal community. To cite one example, when she was asked about the relationship between the various entities within the community, she included a discussion of the function each component served within the community:

Um…these three, the seagrass, the turf and the barnacles all create a, um, habitat for other animals. So- or plants or whatever. So, in different ways these are all basically providing a three-dimensional structure, in which, um, they’re contributing to the biodiversity of other organisms that are living in the same habitat. So you can think of them as analogous to a coral reef, right? You have- or even a forest. You have some organism that is providing a three-dimensional structure that is big enough to provide shelter and food for a lot of small organisms that live among them. Um, all three of these do that.

Later, when Ecologist One discussed the possible effects of an ocean water temperature increase, she again referred to the role of the various factors in the system:

So something like the seagrass which provides a lot of three-dimensional structure, and when the tide is out provides protection against desiccation for a lot of animals underneath. Um, if it’s not able to survive there and if it’s not replaced by something that does a similar job, then none of those other animals will be able to survive either. So, um, or, anything that happens to be eating it will not be able to survive too.

In these excerpts, Ecologist One considered the functional role of the seagrass and turf algae in facilitating the survival of a variety of organisms in the ecosystem, rather than
focusing solely on the simplistic feeding relationship between mollusks and the
seagrass or turf algae. Thus, not only did she demonstrate an understanding of the
interdependence of each component within the ecosystem, but she viewed the
organisms in the community as serving a function that facilitated the survival of the
whole system. Although “profound interconnectedness” addresses the
interdependency recognized by Ecologist One, it was not specific enough to capture
all of the differences between the students’ explanations and the ecologists’. Further
tasks were needed to develop a better understanding of, and explicate the
characteristics of an ecologist’s explanation of the functioning of an ecological
system.

**Stage II: Multi-dimensional Relating**

During phase one of this study, while developing of a set of ecological
problem situations intended to create an intellectual need in students to develop
particular ways of understanding, I interviewed three ecologists and six students in
order to expand my understanding of the character of ecologists’ accounts. I began the
interviews by presenting an Ecosphere (a self contained miniature ecosystem; see the
section below entitled “Designing Instruction Based on Creating Intellectual Need” for
a full description) to the participants and asked why the sphere system was able to
function for several years. The following excerpt presents one ecologist’s response:

Ecologist Two: So generally, the only outside source of anything this
probably needs is light. So the way I would try to explain this to
my class before I even brought one out is probably that life on
earth is sort of (?) but it requires, sort of, it’s a cycle that requires
certain inputs and outputs right? So you need sunlight, or some
sort of heat, you need energy input. And that energy input is
converted by primary producers like plants which they have in here. Algae, I'm not really sure what-

Interviewer: Yeah, its algae.

Ecologist Two: So, algae that convert that energy into something that higher consumers can use. And then consumers either reproduce or die, if they reproduce, then the circle keeps going, and death is also part of the cycle because then the bacteria need to breakdown whoever died in there so they're not just floating and accumulating over the years. And um, and then the rotting animal carcasses that are produced by that are broken down by the bacteria, are also used as raw resources for plants to make, make, well, part of plant is sugar but the rest of it is nitrogen, things like that, that (?) come from the carcasses of these little guys, and they're broken down partly by the bacteria.

Ecologist Two began his account of the functioning of the sphere by considering energy as an input to the system, demonstrating his understanding of the connection between energy flow and the dependent relationships between species. He mentioned cycling in the sphere in terms of various factors—such as heat, energy, raw resources, consumers, bacteria, and reproduction—suggesting an understanding of the connection between matter cycling and energy flow and macro-level properties of the system.

Conversely, students’ accounts of the functioning of the sphere focused primarily on identifying the food sources and gas exchange relationships of the different species. The following account that explains why the sphere functions was representative of five of the six students interviewed.

Student One: Um, I think, I mean it’s self sufficient in that the algae is producing CO₂. Is that right? No, it’s producing O₂ (pause) which the little brine shrimp need. But they also need to live in the water. Then bacteria, cleaning? But what's making it dirty. Oh, the brine shrimp. Cause the brine shrimp will die, and you know, /excrete

Interviewer: /excrete waste.
Student One: and stuff. And then since there is nothing to clean it up (pause) and, maybe they eat the bacteria possibly. Because they do need to eat.
Interviewer: Okay.
Student One: Um, and then they need (pause) they need water to survive, to live in, and they need oxygen to live, and they need something to eat. So (pause) we have the bacteria, and we have the water, and there has to some level of oxygen in here, in order for, I mean, to like filter through the water, and then algae is necessary to keep the oxygen supply.

This student’s approach in accounting for the functioning of the sphere was to consider what each species in the sphere needed to survive and, in some cases, to consider what the species produced. Five of the six students interviewed began by focusing on the need for oxygen in the sphere, and then referred to the oxygen-carbon dioxide gas exchange between plants and animals. In fact, two of the students’ diagrams representing the functioning of the sphere only included the gas exchange relationship (see Figure 4 – Student Two’s diagram). Although all six students drew cycles to represent the functioning of the sphere, five of the six students’ explanations focused primarily on discussing the relationships between species in the sphere in terms of what they take in and excrete. In contrast, the ecologists’ diagrams were more complex and included multiple connections representing the cycling of matter and the flow of energy among organisms.
One student’s account of the functioning of the sphere stood out as different from the others. This student’s account had characteristics that were more closely related to the accounts of the ecologists. The recognition of the qualitative differences between this student’s account and the five other students’ accounts helped clarify differences in the ways of thinking associated with explaining phenomena. I present below part of his response explaining why the sphere system is able to function.

Student Three: The Lion King comes to mind; the circle of life.
Interviewer: Okay, so what do you mean by that?
Student Three: Like these guys are alive or whatever, and they create waste that decomposes the bacteria brings it, takes in the waste and turns it into something useable for the other living organisms in there. And so it can keep going. But I don't know why the (pause) yeah it just, the cycles it will keep going for that long until, you know, physics takes over and it really can't recycle things for so long without the thing completely degrading. So, I figure, the shrimp eat the algae, excrete all over the place. The bacteria eats it, ah, which gives something for the algae to eat, and the algae keeps growing.
Student Three continued by describing the relationships between organisms in the sphere as circular because each species provided requirements for other species. According to this student, “one’s waste is another’s dinner. That’s why it cycles.” Throughout Student Three’s account of the sphere, he referred to the recycling of materials in the sphere. Although he discussed the food sources of each species, he focused on how the relationships between species supported the cycling of elements through the sphere.

**Revisiting Ecologists’ Accounts.** Analysis of Student Three’s account helped to elucidate the multiple levels—molecular, cellular, organismal and ecological—on which the ecologists explained biological phenomena. More than the levels themselves, it was the connections established between these levels that best characterized the ecologists’ accounts. For example, in Ecologist Two’s interview, he was asked why the sphere is self sufficient.

Ecologist Two: Well, if, this sort of goes back to the equilibrium thing. If it is at equilibrium, ideally the, my definition of equilibrium is that you don't need to open it. So there is plenty of sunlight for the algae to produce sugar to photosynthesize. And there, so there is also an issue of carbon dioxide and oxygen which, and there is a little bit of an air pocket there so there is a lot of (?). We are assuming that the algae can survive, make the sugar, make the oxygen, and the consumers can consume enough algae to stop them from overgrowing, and bacteria can breakdown the consumer for algae to persist. And then, you don't need to open it because there is plenty of production of all things necessary for it to survive with all those three things. And just enough that they survive and not so that, not one of them, so one of them won’t get out of control essentially. Increase in numbers exponentially in a way that will prevent the other ones from spreading.
Here Ecologist Two described the relationship between the sunlight, the process of photosynthesis, and the algae, connecting the organismal level with the cellular level. In the earlier segment (see the passage excerpted from Ecologist Two’s interview at the beginning of this section), his references to heat, energy, raw resources, consumers, bacteria, and cycling all suggest that he connected his ways of understanding molecular, cellular, organismic, and ecological processes to explain why the sphere functioned.

Throughout the interview, as Ecologist Two discussed various aspects of the functioning of the sphere, his statements included references to various elements such as carbon, oxygen, nitrogen and phosphorus. While discussing the loss of bacteria, for example, Ecologist Two concluded: “Well the algae would probably run out of nitrogen. And it would become really nitrogen or phosphorus limited.” He added that without nitrogen the algae would not photosynthesize, and as a result, the other organisms in the sphere would die. Later, while discussing photosynthesis, he began describing the algae as “a major source of fixing carb—carbon fixation.” As he continued, he made connections between carbon, the process of photosynthesis, and the survival of the organisms in the sphere:

Ecologist Two: … so as algae starts photosynthesizing they're making some sort of carbon—so I'll just say $C_{X}H_{X}$. Ah, some, they are fixing carbon by making some sugar, plus ah, they are making ah, um, $O_{2}$, and eventually the consumers could survive…

…

Ecologist Two: So they would, the consumers, they would consume oxygen and sugar and break it down into hydrocarbons.
His responses reflect an understanding of the relationship between processes and elements: he discussed photosynthesis as a process resulting in the formation of a carbon hydrogen compound, a sugar. Furthermore, he associated consumption of this sugar by consumers and the use of oxygen to break it down. Although above he stated that consumers breakdown sugars into hydrocarbons, he later described in more detail that a six carbon sugar would be broken down by a consumer into six carbon dioxide molecules.

Statements involving elements and biological processes in the same sentences occurred throughout the interviews of all three ecologists. These statements provide evidence that they were making connections between organismic level processes (such as feeding relationships among species), cellular level processes (photosynthesis and respiration), and molecular level processes (flow of energy and cycling of matter). I labeled this way of thinking “multi-dimensional relating”—making connections between macro-level properties and micro-level interactions (see Figure 5). This was the second stage in my understanding of the way of thinking associated with accounting for phenomena.
Figure 5: Evolution of my understanding of ecologists’ ways of thinking

Wilensky and Resnick (1999) discuss the concept of “levels” in developing a complex systems view. By levels, they do not mean a hierarchy or chain of command, but rather, they are referring to levels of description that can be used to characterize a system with a number of interacting parts. They focus on levels that arise from interactions of objects at lower levels: “There is something almost magical in the way behaviors at one level arise out of very different behaviors at another level” (p.6).

Wilensky and Resnick’s description of levels is compatible with my description of the multiple dimensions considered by ecologists when explaining ecosystem phenomena—an understanding that complex phenomena can arise from simple components and simple interactions.

**Stage III: Expanding Multi-dimensional Relating**

**Student Example 1.** After an initial analysis of the students’ ways of understanding and thinking from the 10-week teaching experiment, it became apparent that multi-dimensional relating was not sufficient to capture all the aspects of the ecologists’ accounts. As anticipated, the students’ accounts focused predominantly on
the level of the organism with little, if any, mention of the underlying micro-level interactions. I also recognized, however, that students’ accounts appeared to be descriptive stories about objects they were observing within a particular setting (for example, what a species in the community needed to survive). I returned to the interviews to explore this idea.

In the following segment, Student One was drawing her diagram to represent why the Ecosphere was able to function for a long period of time.

Student One: Okay, I'm trying to think. Rocks are surface area. Okay so then the waste, the bacteria, there is some other thing (she moves her hand in a circular shape on the paper.) There needs to be circle going on.
Interviewer: Why do you think there needs to be a circle going on?
Student One: Because if the bacterias keep reproducing, (long pause) what do the shrimp eat? (pause) Oh, that's what it was, the shrimp also eat the bacteria. (long pause) Oh, there we go, there we go. There we go. (Draws an arrow from bacteria to shrimp.) Eat the shrimp, produce more waste (with her hands she is moving between bacteria and shrimp in a circular fashion.) Okay, so, and yeah, so, okay. And they continue- they produce waste this way. (Draws an arrow from shrimp up toward the top shrimp) (pause) solid, there we go. And then they produce waste this way (draws an arrow connecting the bottom shrimp to the plants via CO₂). There we go, I have a circle. Why do I need circle? I need a circle because if there was no circle and I just ended up with bacteria, then these wouldn't be self sufficient and I'd end up with a whole lot of bacteria which would be really boring to watch.

Student One’s explanation and diagram of the Ecosphere comprise a narrative account of who eats whom in the community. Although she was confident that there needed to be a cycle, her justification for the cycle focused only on the organisms themselves, describing the inputs and products of the different species. The conclusions Student One, and many of the other students, made about the relationships between species in
the sphere were ad hoc (explanations reflecting improvised or impromptu statements).

As long as the relationships she created resulted in a circle, she was content with her diagram. Later, when asked questions that probed deeper into the relationships between species, Student One changed her diagram to accommodate her new ideas.

During the interview, Student One concluded that the shrimp and algae would survive if the bacteria were removed from the sphere.

Interviewer: And of course, that begs the question, what if we took out the bacteria, and left the algae and the shrimp?

Student One: It would be really dirty, I think. Well, not dirty, but it would be, no, would it? I'm just think- when we had fish we had those little snails that sucked up all the algae. So, I mean, it would get, if we consider them the cleaners, (quietly) then it would get dirty, nothing would be eating the, um, solid waste, if, if the shrimp died or whatever. Nothing would be-

Interviewer: so it would accumulate waste and dead organisms?

Student One: Yes. But that, the shrimp would survive until, it got really, really gross. ...

Student One: Yeah, cause the shrimp would survive and so would the algae, without bacteria, I think.

Student One based her conclusions on what made sense to her at that moment. She used her prior understanding of snails as cleaners in fish tanks to conclude that the bacteria exist in the Ecosphere to keep it clean. Thus, her accounts focused primarily on the level of the organism. Her explanations did not include any consideration of the need for elements to cycle or energy to flow in the Ecosphere.

**Student Example 2.** Another student, Student Two, also developed explanations based on information that made sense in the moment. In the following segment, Student Two was discussing what might happen in an Ecosphere with no bacteria.
Interviewer: So you’re thinking that the bacteria control the shrimp population. How might it do that?
Student Two: It’s like, um, it’s like we getting diseases and stuff. And like probably the bacteria’s cause the shrimps to die earlier. Or on a certain range of age or like time, and then -
Interviewer: Limit their life time?
Student Two: Yeah, yeah. And then if they are gone, that means they [shrimp] can live longer.

Student Two concluded that, with no bacteria, there would be an overgrowth of shrimp, resulting in a decrease in oxygen. According to Student Two, the algae would not be able to replenish the oxygen fast enough, and the shrimp would eventually die. Interestingly, in responding to the next question, the same student concluded that, in a community without shrimp, the bacteria would over multiply and use up all the oxygen, and the algae and bacteria would die without shrimp replenishing the carbon dioxide. Thus, over the span of a few moments, the student concluded that the bacteria consume the shrimp and, conversely, that the shrimp consume the bacteria. Many of Student Two’s explanations seemed to be constructed ad hoc, she frequently changed her ideas, and her conclusions were often inconsistent with previous conclusions.

**Student Example 3.** During the teaching experiment, a group of three students created an explanation to account for the functioning of the sphere. Similar to the interviews conducted with students, this group focused primarily on the inputs and products of each species.

Franjelica: Okay, so we've got..we've got the waste for the shrimp- its probably eaten by the algae or bacteria, neutralized somehow.
Austin: Mmhmm.
Franjelica: Waste of the algae would be oxygen and, what is algae waste?
Austin: Oxygen.
Franjelica: Oxygen?
Austin: Yeah. I think that's it.
Franjelica: Okay. And /bacteria
Rachel: When it dies.
Austin: That's what I'm thinking. How does the algae keep on living?
Rachel: When the bacteria decomposes.
Austin: Ooohhh.

A few moments later, Austin summarized for the instructor the group’s explanation for
the functioning of the sphere:

Austin: Okay. That algae provides oxygen for the place. Like for the
water. And then they also might provide food for the bacteria.
And then the bacteria is food for the brine shrimp. Cause we see
them all over. They are not even caring about the algae.
Instructor: Okay.
Austin: And then the brine shrimp provides food for the bacteria through
excrement, fertilizer and stuff. And then seawater just a place
where pH.

The explanation these students created for the functioning of the sphere focused
primarily on the interactions of the objects they could “see” in the sphere. Although
they mentioned oxygen and carbon dioxide, these invisible objects were introduced as
inputs or products of visible objects. Austin’s explanation was presented in terms of a
descriptive story about the feeding relationships and gas needs of each species in the
sphere.

Consistent with the accounts from the student interviews, this group’s
conclusions were also guided solely by what made sense to them at that moment. For
example, the group concluded that bacteria were food for the brine shrimp because
“we see them all over. They are not even caring about the algae.” The discussions that
led to these conclusions also reflected ad hoc explanations. For example, in the
segment above, Rachel suggested that the algae survive because the bacteria decompose. The group accepted this idea without any further discussion.

These three student examples provide evidence to support the claim that when explaining ecological phenomena, the students’ accounts were characterized by (a) a focus on the objects they could see, (b) descriptive stories about the objects they could see, (c) ad hoc explanations, and (d) inconsistent conclusions (see Figure 6).

<table>
<thead>
<tr>
<th>Characteristics of Students’ Accounts</th>
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<tr>
<td>*Focus on organismal level primarily</td>
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<tr>
<td>*Narratives about objects in view</td>
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<tr>
<td>*Ad hoc explanations</td>
</tr>
<tr>
<td>*Inconsistent conclusions</td>
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Figure 6: Characteristics of students’ accounts of phenomena

**Revisiting Ecologists’ Accounts.** After determining that the students’ accounts not only focused on one dimension, but also reflected narratives focusing on what they could “see” in the sphere, I returned to the ecologists’ interviews to reanalyze their accounts. I found that the ecologists’ accounts focused on processes within a system rather than objects in their view. In Ecologist Two’s account above (see Stage II: Multi-Dimensional Relating), the ecologist began his explanation by stating that life is a cycle that has inputs and outputs. He did not focus on one species’ inputs and outputs, but rather, viewed the community as a system. Energy was viewed as a necessary input to this system, and the ecologist discussed the role of producers in converting this energy. He continued by discussing that a functioning system needs to be in equilibrium. His statements reveal that his focus was on processes that occur within a system to keep the system functioning.
Evidence from Ecologist Three. All three ecologists’ accounts of the functioning of the sphere reflected a focus on processes within a system rather than objects within a setting. Below is a segment of Ecologist three’s account:

Interviewer: Can you provide an explanation for why this Ecosphere is able to sustain itself for a long period of time?
Ecologist Three: So I guess when you have live things you have to think about what each of them needs and uses up and what each of them produces that could possibly be bad. So if you had like a, any one of these things by itself, the algae, or the brine shrimp, or the, the microorganisms or whatever they are, then they would use up whatever it is that they use and they would produce so much of whatever it is that they excrete, that they would eventually kill themselves off. So you have to think about how, how all these things, sort of the relative levels of how they contribute to what the other ones use. So I guess the idea that makes it work is that what is waste for one species is input for another species.

Note in the first sentence, her use of the word “bad.” Her statement about considering the needs of each species is embedded in the central idea that these species interact within a system. Her reference to “bad” refers to the idea that the accumulation of something in a system would be “bad” for the system, an assertion to which she returns to later in the segment and throughout her interview.

Ecologist Three: So what makes it work then is that it is a good balance between the different components. So they, its not just that you have- so you can think of it as like you draw out cycles of what uses what and what spits out what. And it’s not just that you have complete cycles of everything, so that you don’t have accumulation of something that is bad, but the rates in the cycles are well matched so that nothing really gets ahead of the other things. So ah, so yeah, it works for so long because someone either thought about it or experimented carefully to make sure that the uses of these different things were balanced out.
Ecologist Three’s account includes references to the “relative levels” of things, a “balance between the different components,” and having well matched “rates” in the cycles. These comments suggest that her focus was on processes occurring within the system.

Later, Ecologist Three discussed the role of each species in converting matter into a form that was usable by another species.

Ecologist Three: So that looks like it could be a closed system in itself. So ah, it’s not just carbon and oxygen and carbohydrate and stuff that matters here. There is also other things. So brine shrimp, besides excreting carbon dioxide they excrete various waste products (draws arrow on her diagram) (pause) which I guess build up on the rocks on the bottom. So you have bacteria there and they take these waste products and make them into, ah, useful chemicals. By useful chemicals, of course this is biased, useful to the algae and useful to the brine shrimp. The waste (pointing to shrimp) was useful to the bacteria.

Interviewer: Okay.

Ecologist Three: So these useful chemicals, which I don't know what they are, ah, undoubtedly help the algae in some way because you need other things to photosynthesize. (?) And then ah, these contain things like nitrogen and phosphorus which I know (?). And then these useful chemicals also are going to the brine shrimp.

Here, Ecologist Three described the relationships between organisms in terms of conversion of resources. Although she discussed the inputs and products of each species, she based her explanation on the process of matter transformations in the system, rather than describing the needs of each species. Note also the connections she made between macro-level properties and micro-level interactions. She discussed elements in terms of being incorporated into organisms’ structures, then converted through some process (such as photosynthesis) into another form. These statements
provide evidence that she understood the relationship between molecular level processes, cellular level processes, and organismal processes. These findings are representative of all three ecologists’ accounts of the Ecosphere.

**Model-based Reasoning.** The qualitative differences can, in part, be accounted for by Anderson, Mohan and Sharma’s (2005) description of model-based reasoning. These authors’ model-based reasoning offers a way of thinking compatible with Harel’s (2001) description of ways of thinking; however, I modified Anderson et al.’s model to reflect those aspects that best represent my findings about the character of ecologists’ act of explaining (see Table 2). Model-based reasoners’ accounts reflect a connection between observations and processes. In the sections that follow, I describe the features of model-based reasoning that characterize the mental acts of ecologists as they created explanations to account for phenomena during the interviews.
Table 2: Modified explication of Model-based Reasoning

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<th>Nature of the account:</th>
<th>Perception-based Reasoning</th>
<th>Model-based Reasoning</th>
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<td>Object Oriented: accounts are focused on objects or events in settings.</td>
<td>System Oriented: accounts are focused on processes within systems.</td>
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<th>Constraints on Accounts:</th>
<th>Perception-based Reasoning</th>
<th>Model-based Reasoning</th>
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</thead>
<tbody>
<tr>
<td>Common sense constraints: student decides if the “story” or explanation makes sense. Ad hoc explanations.</td>
<td>Explicit theoretical constraints: Principles and laws provide tools that limit the nature of permissible accounts.</td>
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<tr>
<th>Connections between processes:</th>
<th>Perception-based Reasoning</th>
<th>Model-based Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>One dimensional: processes are described at either the observable scale (growth, death, consumption), the cellular scale (photosynthesis or respiration), or molecular scale (matter cycling and energy flow in ecosystems)</td>
<td>Multi-dimensional: connections are made fluidly among processes at the observable scale, the cellular scale, and the molecular scale.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Causal relating</th>
<th>Perception-based Reasoning</th>
<th>Model-based Reasoning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Linear: Events are one-time happenings that have specific direct causes</td>
<td>Non-linear (cyclical or multidirectional causal relating): Processes repeat or continue as a result of multiple dynamic and complex interrelationships.</td>
<td></td>
</tr>
</tbody>
</table>

Nature of Accounts. The transcript evidence given above demonstrates the distinction between the nature of the students’ and the ecologists’ explanations.

Students’ accounts tended to focus on accounting for each individual object they could “see.” In the case of the Ecosphere, the students focused primarily on identifying the inputs and products of each species. I labeled this characteristic of the students’ accounts “Object Oriented” because the students appeared to be focusing on accounting for the objects in a setting to explain the phenomena.
Ecologists’ explanations for the functioning of the sphere focused on processes within systems. For example, Ecologist Three explained that what made the sphere work “is that it is a good balance between the different components,” and she added that there cannot be accumulation of something that is bad for the system. The ecologists described relationships between species in the sphere in terms of their roles in cycling resources for the system. I labeled this characteristic of the ecologists’ accounts “System Oriented”.

Connections between Processes. The relationships between organisms can often be explained in terms of cellular and/or molecular level interactions. For example, organisms and their organs can be viewed as the complex outcomes from cellular and genetic level interactions, which in turn, can be viewed as complex outcomes from molecular interactions (Wilensky and Reisman, in press). The cycles that the ecologists’ drew and discussed to explain the functioning of the sphere represented the interrelationship between the species in the sphere and their roles in matter conversion and energy flow. The ecologists drew on their understanding of biologically mediated processes such as energy and material flows, respiration, photosynthesis, decomposition, and interrelationships among these processes to explain the functioning of the sphere. The connections they made reflected multidimensionality—connecting macroscopic properties with the underlying microscopic interactions.

One-dimensional relating, on the other hand, represents a focus on only one scale or level at a time, usually the organismal level. Although the students also drew
cycles to represent relationships, their cycles were representations of feeding relationships and/or gas exchange relationships. The students’ descriptions and explanations did not reveal connections between the survival of the organisms and the cycling of matter or the flow of energy through the system. Furthermore, the students’ explanations of cellular level processes such as the role of photosynthesis and respiration in the functioning of the sphere were limited at best. (Students’ ways of understanding these processes are discussed below in “Students Ways of Understanding.”)

**Constraints on Accounts.** The ecologists’ accounts were constrained by scientific theoretical models. I use the term “model” as Cartier, Rudolph and Stewart (2001) define the term: “a scientific model is a set of ideas that describes a natural process” (p. 2) (italics from original). Models, from this perspective, are theoretical entities—ideas about the underlying mechanism for phenomena. They are constituted by empirical or theoretical objects and the processes in which they participate, and can be used to explain and predict natural phenomena (Cartier, Rudolph, and Stewart, 2001). Thus, processes within systems are, in fact, theoretical models in science intended to explain an interaction. Accounts that focus on processes within systems are, in effect, accounts in which the person makes connections between features of a scientific model and observable phenomena. The ecologists’ accounts of the functioning of the sphere reflect coordinated reasoning about observations and scientific models and these theoretical models constrained the explanations and conclusions that biologists made.
Anderson, Mohan, and Sharma (2005) summarize the contrast between the constraints influencing the explanations of professionals and students in the context of carbon cycling:

Model-based reasoners understand that all processes associated with the carbon cycle are subject to constraints imposed by fundamental laws of nature, such as conservation of mass and energy and the fact that physical and chemical changes do not create or destroy atoms…Thus model-based reasoners can check their accounts against constraints in ways that are unavailable to narrative reasoners: “Have I accounted for all of the mass in the system? Have I accounted for all of the energy? Do any substances seem to appear or disappear in unexplained ways in my account?” (p.19)

When the ecologists discussed the functioning of the sphere they discussed the conversion of one form of matter into another form as essential in order for the system to continue to function. If one of the byproducts accumulated in the sphere, the sphere would cease to function. Furthermore, three ecologists referred to elements as potential limiting factors in the sphere. Therefore, their accounts were constrained by scientific theoretical models.

The students’ explanations, in contrast, deviate from this characteristic of model-based reasoning. Students’ accounts were constrained only by what made sense to them in the moment. For instance, on day three of the final teaching experiment, there was one point at which the students were trying to account for the source of carbon dioxide in a sphere with no brine shrimp. On an information sheet they read that there was carbon dioxide in the seawater.

Franjelica: Okay, we thought that the shrimp gave up carbon dioxide, now we know that there is carbon dioxide in sea water.
Austin: Yeah. It’s in the sea water.
At this point, the students stopped searching for the source of carbon dioxide because they were satisfied that the sea water was the source. The students did not consider the fact that the carbon dioxide in the sea water would be “used up” until the instructor questioned them about it. It was only at that point that the group decided that the carbon dioxide needed to be replenished by an organism if the sphere was to survive for a long period of time. As mentioned earlier, the students’ explanations were constrained only by what sounded plausible to them; their accounts were not constructed or constrained around underlying principles.

**Non-Linear Causal Relations.** The ecologists recognized that a change can have multiple and varied effects throughout a system. For instance, the ecologists recognized that removal of a species would not only result in the loss of food for another species, but could also have repercussions throughout the entire ecosystem. Processes repeat or continue (such as the cycling of elements) as a result of multiple dynamic and complex interrelationships. Considering cycling of elements reflects cyclical reasoning. The ecologists’ statements and diagrams suggest both cyclical and multi-directional causal relating while the students’ statements reflected simple linear relations between objects.

**Additional Example of Model-based Reasoning.** As one reasons based on institutionalized scientific models, he or she draws specific connections between data and a variety of different models (for example, matter cycling and energy flow, or evolution by natural selection). Anderson, Mohan, and Sharma (2005) provide a
descriptive example of an account characteristic of model-based reasoning within an ecology context:

[In a simple food chain] grass grows in the sunlight, a rabbit eats the grass, a wolf eats the rabbit. … In the narrative account, the food chain is like a little drama with several scenes. The wolf is a protagonist … enabling its survival for another day by finding and eating food. … The non-living environment of the ecosystem is the setting in which this drama plays out. High school students know that the wolf has organs that are made of cells, but that information is part of another story, not directly connected with this one.

In the model-based account, the wolf is one system in a complex hierarchy of systems and subsystems. Model-based accounts don’t really have “protagonists,” but conserved “entities” such as matter, energy, and information play critical roles. The wolf is not so much a protagonist, but a way-station for the matter, energy, and genomic information that flow through it. The account of the wolf is very much interconnected with accounts of its subsystems—cells and organs—and of the larger ecosystem within which it lives. Thus to “understand” the wolf we have to think about its role in a complex set of interconnected systems and processes. (p.34)

In my study, the “narrative account” is reinterpreted as a “perception-based account” because the explanation is focused on describing connections between objects perceived by the student. Rather than focusing on processes within a system, the student focuses on events caused by actors within a setting. In the model-based account, the person interprets the wolf eating the rabbit as a process. This interpretation can then be seen as a data point that can be used to calculate the wolf’s rate of food consumption, as a step in the flow and transformation of matter and energy through a food web, or as a step in the flow and transformation of genetic information through generations of wolves (Anderson, Mohan and Sharma, 2005). In either case, the person reasons about the phenomenon from the perspective of a scientific model that constrains their interpretation. In each of these interpretations, the
model-based reasoner is making connections between the organismal level (the food chain) and the underlying cellular or molecular level processes reflecting multi-dimensional relating.

Summary of the Ways of Thinking of Ecologists associated with the Mental Act of Accounting for Phenomena

The process of identifying the way of thinking associated with explaining phenomena was complex and gradual. My understanding of the ecologist’s way of thinking evolved through three stages: Profound Interconnectedness, Multi-dimensional Relating, and finally, Model-based Reasoning (see Figure 7). Each stage incorporated the characteristics of the previous stage. The differences between the professionals’ explanations and the students’ led me to characterize their ways of thinking as model-based reasoning and perception-based reasoning, respectively.

Figure 7: Evolution of my understanding of ecologists’ ways of thinking - 2
Model-based reasoning governed the explanations ecologists gave for the functioning of the Ecosphere. My data reveal that the ecologists made connections between different factors and processes within the living system, and then synthesized the information to construct an explanation. They drew on their understanding of biologically mediated processes—such as energy and material flows, respiration, photosynthesis, decomposition, and interrelationships among these processes—to develop explanations for the functioning of a system. I also found that the ecologists’ explanations of phenomena were not ad hoc, but rather, were constrained by theoretical models institutionalized in the scientific community, such as conservation of mass and energy.

Students’ explanations for the functioning of the Ecosphere, although not homogenous, were distinctly different from biologists. The students’ explanations centered on the objects and actors in the community they observed, and appeared to be constrained only by what made sense to them at the time. Students focused primarily on accounting for the inputs and products of each species within the sphere at the organismal level (for example, who eats whom), considering macro-level properties with little if any mention of the underlying micro-level interactions. The differences in the ways of thinking of the ecologists and the students are likely the result of differences in their ways of understanding molecular and cellular level processes. (I discuss this final point in more detail later in this chapter.)
Identifying ways of thinking of ecologists was one of the research questions guiding this study. A brief description and explanation of model-based reasoning, the way of thinking associated with explaining biological phenomena, would have addressed this question. Why, then, include a long description of the evolution of my understanding of the ecologists’ way of thinking associated with explaining phenomena if this was not specifically a component of the research question? From a pedagogical perspective, the sharing of this process is important. In DNR-based instruction, cognitive objectives for instruction are formed in terms of ways of thinking. Therefore, identifying the ways of thinking of ecologists is a necessary first step. Although certain ways of thinking are easily identified, for example, non-linear causal relating, other characteristics of mental acts are not as transparent. This is because ways of thinking are inferences characterizing patterns in a person’s ways of understanding. Many times multiple mental acts are occurring simultaneously as one solves biological problems. As a result, it can be quite difficult to identify those characteristics associated with a specific mental act, such as explaining. The detailed description of the evolution of my understanding of the character of ecologists’ act of explaining provides an image of the challenges inherent in this process. If Harel’s DNR is to be implemented in biology, a comprehensive list of the ways of thinking that should guide cognitive objectives for instruction needs to be identified. This identification process can be complex, and involves not only analyses of ecologists’
problem solving acts, but also an understanding of the epistemology of biology, and thus may take years of study.

Models of Students’ Ways of Understanding

As chapter 3 reports, the research in biology education reveals that many students are not currently recognizing complex relationships in ecological systems (Carlsson, 2002a; Leach, Driver, Scott and Wood-Robinson, 1996a; Lin and Hu, 2003). Although a student can memorize and reiterate definitions of ecological phenomena such as eutrophication or bioaccumulation, this does not necessarily correspond to an ecological understanding of these processes. An ecological understanding of bioaccumulation, for instance, incorporates an understanding of the dynamics of food web relationships, the transformation of matter, and the necessary role of respiration. If students have a naïve understanding of food web relationships, or matter transformation and respiration, or more importantly, if they have not considered the relationship between matter, physical structure, and feeding relations, then they will likely develop a naïve understanding of bioaccumulation. (As previously stated, the term naïve is used to refer to an unscientific understanding or an understanding associated with a memorized definition.)

The data from my pilot study and interviews from phase one of my research confirm this claim. I interviewed a total of ten students prior to the teaching experiment phase of this study: four first and second year university students in my pilot study and six university students from various undergraduate levels during the first phase of my research. Although the students’ ways of understanding biological
processes were varied, nine of the ten students did not demonstrate a biological understanding of the transformation of matter, the flow of energy, respiration, photosynthesis, decomposition, or the relationship between these concepts and a community of organisms. The purpose of the interviews was not to document students’ existing ideas, but rather, to gain insight into their ways of understanding so that problem situations could be designed to help students build on these ways of understanding. In this section, I share an overview of the students’ ways of understanding from interview data collected from nine of the ten students. The remaining student demonstrated ways of understanding compatible with the community of biologists. For this reason, I do not include his results in my model of students’ understanding.

**Transformation of Matter and Energy**

In the interviews, students revealed fragmented and unscientific understandings about matter and energy. Student Four, for example, was unsure whether plants received their energy and nutrients from sunlight: “I don't know if nutrients to a plant is in fact sunlight, or, you know, factors of sunlight”. He added, “Well the algae convert their energy intake into, you know, branches and stems and whatever kind of shape it takes.” Several students incorrectly concluded that energy was converted into matter, just as Student Four did. This is a common conception among students of all ages (Anderson, Mohan and Sharma, 2005).

Confounding matter and energy was prevalent among the students. For instance, Student One stated that, along with food, oxygen provided energy for the
brine shrimp. She added that light was energy for the plants but she was not sure if carbon dioxide was also energy for the plant. Another student, Student Two, believed bacteria could survive just by taking in oxygen—the oxygen provided the energy and whatever else was needed for the bacteria. “Cause like they, um, (pause) cause bacterias are asexual, so they can multiply. So they use oxygen to (pause) use oxygen so then they'll have a more, somehow they kind of transform into their own nutrient, and then they can use asexual to have more bacteria.”

The students often understood matter as objects. For example, Student Seven understood matter as inanimate objects such as sand and rocks. As she discussed decaying organisms, I asked her why she thought a decaying organism was matter, but a living organism was not matter:

Student Seven: Yeah um, what is it? Yeah, it’s defining, that’s kind of interesting (says under her breath). I guess a living organism is made up of matter. Not even that so much, I feel funny saying that. Um, matter you think more in terms of something that would be used by an organism, maybe…So like matter would be a rock, where an organism would live, or the food that it eats, maybe, or no not even that (mumbles) (?)plant again. Um, or just like the atoms and molecules that make up the structure.

Student Seven struggled to explain her understanding of the relationship between matter and the abiotic and biotic environment.

Similarly, many students’ understanding of matter was limited. Student Eight, a freshman biology major, stated that algae “feeds off of the energy from the sun,” and then other organisms “get the nutrients from the algae” and convert these nutrients into their own energy. When asked whether matter moved between organisms—in the
manner in which she had posited that energy moved between organisms—her response represented confusion about the relationship between matter and energy:

Student Eight: Well I know matter- cause the liquid ocean it evaporates and then goes into the gas form. I don’t know if it counts if something eats something else, I don’t know if that’s the transfer of matter. In some form of energy I guess. And, when things decompose, I guess it’d be broken down from solid to, maybe it’s a different form of solid, or it’s a gas; converted into gas. That’s all I have.

Student Eight’s response suggests that she understood matter in the physical science sense of the term, where matter comes in various forms: solid, liquid, and gas. However, she did not reveal an understanding that all things were composed of matter.

Most of the students were unsure about the composition of living organisms. Student One stated that she knew that “Branches stuff [plant material] can't come from nothing” but added that she did not know the composition of the plants: “I don't know, (pause) I know it grows because it’s being fed light energy but what's making the stuff (pause) I don't know.” Yet, in a different context, Student One mentioned carbon as a component of everything.

Interviewer: We have O₂ and CO₂, what does the plant do with the C?  
Student One: Carbon, carbon, carbon. Carbon is in everything. It’s the basis of ochem [organic chemistry], which all my roommates are taking. Um, no, but I'm sure its, I mean it’s in everything so, I'm sure it has some function.

Similarly, another student, Student Two, responded with “mitochondria” when asked what organisms were composed of. She then added “cells,” but could not provide a response when asked about the composition of cells.
Cellular Processes: Photosynthesis and Respiration

The students’ understanding of photosynthesis varied. Most understood photosynthesis as the process in which a plant uses sunlight as energy to convert carbon dioxide into oxygen, rather than a process by which carbohydrates are synthesized from carbon dioxide and water using light as an energy source. For example, Student One explained that light is a form of energy that is “transferred to the plant which uses it to create O₂ from CO₂.” In all of the students’ explanations, photosynthesis was primarily understood as serving the purpose of providing oxygen to a community; that is, they held teleological views.

When asked about the role of carbon dioxide, most of the students were unsure what a plant did with carbon dioxide, other than converting it to oxygen. Student One, for example, suggested that a plant might take in carbon dioxide solely for the purpose of producing oxygen.

Student One: Okay, the function of the plants, the algae, is to take in CO₂ and produce oxygen. But I don’t know if (pause) I mean, they take like nut- it’s like a byproduct of like (pause)
Interviewer: What’s a byproduct? I just want to know what you mean.
Student One: No that’s okay. I’m just trying to think. They, cause plants, the nutrients and stuff. Maybe it is the CO₂. I have no idea. I have no idea if their nutrients is the CO₂ or if its like, oh they can sus- you know like, they can (pause) live, survive, without the CO₂ and then they just wouldn’t be producing the oxygen.
Interviewer: Okay.
Student One: So I’m not sure if it’s essential to their, it’s essential to their function, or to their production of oxygen. CO₂ is essential to the production of oxygen but I’m not sure if it’s essential to their life.

Student One’s confusion is apparent as she tried to account for the role of carbon dioxide in the survival of algae. She was not sure if plants could survive without
carbon dioxide, and suggested that the only side effect would be cessation of oxygen production. The research shows that students of all ages have difficulty understanding that the mass that comprises plants comes primarily from gases in the atmosphere (Anderson, Mohan and Sharma, 2005; Hellden, 1995; Wood-Robinson, 1991). Recall also that Hellden (1995) reported that most students did not recognize gas as a material, and therefore, understanding that plants assimilate a gas in the air as a raw material to build up the plant would be difficult for students without a shift in the concept “air” between ontological categories. Furthermore, understanding photosynthesis only as a process to produce oxygen reflects teleological reasoning.

**Respiration.** All nine students struggled with ideas about respiration and frequently applied the vernacular use of the term—breathing or mass exchange of gases in and out. Student Seven described respiration as the opposite of photosynthesis, and then later decided that respiration was the exchange of oxygen and carbon dioxide. She added, “It doesn’t matter the direction one to the other.” She described plants and animals as having a “symbiotic relationship”:

**Student Seven:** [Plants and animals] live in this kind of symbiotic relationship, with photosynthesis and respiration, because the animals they give out the CO₂, which the plants need and the plants use that to build their structure and they give off the oxygen that the animals need.

Student Seven understood respiration as an exchange of gases rather than the biological understanding of the process—the metabolic process by which organisms obtain energy from organic materials.
Similarly, Student Eight struggled with the processes of respiration and photosynthesis:

Student Eight: The energy from the sun gets converted into photosynthesis, um, does that lead to cell respiration or is that something different (quietly to herself). I know that with photosynthesis you get, like when plants grow they do the, they go through the carbon cycle and the Krebs cycle to produce CO₂, or O₂. I’m sorry. Was it respiration, they absorb like carbon dioxide through the atmosphere, something like that.

Student Eight then explained that she was “really bad at photosynthesis” and laughed as if embarrassed. I asked her if she saw any relationship between photosynthesis, respiration, matter and energy: “Um, well a plant is a form of matter that grows off of the energy used to convert photosynthesis, which then leads to respiration.” As she made this connection, she drew her hand in a circle around the table to demonstrate a type of cyclic relationship between the concepts. The relationships she proposed, however, were not representative of a biological understanding of these concepts.

**Summary of Students’ Ways of Understanding**

Compatible with the research literature, my interview data reveal that the undergraduate university students in this present study had unscientific understandings or gaps in their understandings of some of the more fundamental concepts underlying biological systems and struggled to describe the relationships among the biological concepts presented. A model of the students’ ways of understanding the transformation of matter and energy and cellular processes is summarized in Figure 8.
Model of Students’ Initial Ways of Understanding

* Energy converts to matter
* Energy cycles in a system
* Matter and energy conflated
* Organic matter decomposes spontaneously
* Plants get energy directly from the sun
* Plant mass comes from soil and/or water
* Respiration is the exchange of oxygen and carbon dioxide

Figure 8: Model of students’ initial ways of understanding

Surprisingly two students, Students Seven and Eight, were freshman biology majors, had taken AP biology at the high school level, and felt confident in their understanding of the material. Student Seven, in fact, had tested out of the other two required lower division biology courses offered at the university level. At the time of the interviews, eight of the students had completed fifty percent or more of a lower division biology course at the university—BILD 3: Evolution, Behavior and Ecology. Furthermore, some of the students had already completed the first two introductory biology courses—BILD 1: The Cell, which covers molecular biology, or BILD 2: Multicellular Life, yet they still revealed unscientific understandings of the biological processes that underlie the functioning of a biological system. (For more information, see description of students’ biology backgrounds in Table 1, chapter 4).

As mentioned earlier, students’ ways of thinking associated with the act of explaining were distinctly different from ecologists. According to Harel’s Duality Principle (1998, 2001), one’s ways of understanding influence one’s ways of thinking because of the developmental interdependency between ways of thinking and understanding. The students’ naïve ways of understanding many biological processes
provides support for the assertion that the students’ ways of thinking were, in fact, influenced by their ways of understanding. Therefore, it follows that one way to help students begin to develop model-based reasoning, a desirable way of thinking in biology, is to help them develop biological ways of understanding some of the processes that contribute to the functioning of a biological system (See Figure 9).

**Figure 9:** Diagram of application of Duality Principle to biology instruction

One possible misinterpretation of the diagram above is that students would participate in instruction based on the Necessity Principle for a short period of time and their ways of thinking would change. In fact, ways of thinking are robust and difficult to change. Although a period of instruction may result in refinement or changes in one’s ways of understanding, ways of thinking can take months and even years of repeated opportunities to reason before more desirable ways of thinking
become robust. Therefore, short term research can only hope to find occasional indications of the development of a participant’s ways of thinking within a particular context. It would be erroneous to claim that the participant’s way of thinking had changed after short-term instruction; one can only claim that characteristics of a new way of thinking are beginning to develop.

**Designing Instruction based on the Necessity Principle**

The cognitive objective guiding the teaching experiment was to help students begin to develop model-based reasoning. I conjectured that if students developed a biological way of understanding metabolic processes in cells (photosynthesis, respiration), decomposition, and molecular level processes such as matter cycling and energy flowing, and understood the relationships among these processes, this could lead to developing characteristics of model-based reasoning when trying to account for observable phenomena in organic systems (see Figure 10).
Developing a way of understanding the interrelationships and interdependencies between biologically mediated processes and ecological phenomena is cognitively demanding. One must have an understanding of, and be able to make connections between, the macroscopic level (for example, ecosystem interactions) and the microscopic level (for example, the role of processes, elements, and energy in the system). Mayr (1982) presents a framework of knowledge in biology that captures this idea of developing connections between both macroscopic and microscopic ways of understanding. According to Mayr’s knowledge framework, there are three types of
knowledge: phenomenal knowledge (at the level of the organisms), mechanical knowledge (at the level of cells), and physical knowledge (at the molecular level). Lin and Hu (2003) apply this framework to specifically address ecological issues related to matter cycling and energy flow: phenomenal knowledge (food trophic levels, such as producers and consumers); mechanical knowledge (respiration and photosynthesis); and physical knowledge (energy and matter). These researchers agree that students need to see the interrelationship between these three dimensions of thought—micro, macro, and symbolic—in order to develop an understanding of the hierarchical and complex nature of the living world.

Considering ecological relationships from a phenomenal, a mechanical, and a physical perspective coordinated well with Wilensky and Resnick’s (1999) notion of understanding phenomena through a framework of levels. Integrating these theories helped to clarify the connection between the macroscopic and microscopic components of ecology that, I hypothesized, were necessary for understanding and explaining ecological phenomena. More specifically, I sought to help students develop an understanding that macro-level properties emerge in systems as a result of micro-level interactions. I wanted students not merely to explain macro-level properties in terms of micro-level rules, but to develop explanations that flowed back and forth between the levels. The research literature revealed that students have difficulties not only with concepts within mechanical and physical knowledge categories, but also in understanding the relationship between these categories and phenomenal knowledge.
Knowledge of these difficulties provided a basis for designing instruction in ecology guided by the principles of DNR.

**Explicating Intellectual Need in Biology**

I designed instruction based on the necessity principle to determine if building on students’ existing ways of understanding would lead to growth in their development of model-based reasoning. To create intellectual need, the learning situation must engage the student intellectually, rather than socially. Most curricular activities in biology, intentionally or unintentionally, focus on students’ social needs (the need to please an authority, the need to self advance, or the need to advance society), rather than students’ *intellectual need*. According to Harel (in press), the term *intellectual need* refers to “a behavior that manifests itself internally with learners when they encounter an intrinsic problem—a problem they understand and appreciate” (p. 2). This is opposed to a student feeling intellectually aimless, for example, when the instructor informs students what they are going to learn and then transmits this knowledge as a finished product.

An important element in creating intellectual need is tapping into learners’ internal desire to know.

For example, students might encounter a situation that is incompatible with, or presents a problem that is unsolvable by, their existing knowledge. Such an encounter is *intrinsic* to the learners, for it stimulates a desire within them to search for a resolution or a solution, whereby they might construct new knowledge. There is no guarantee that learners would construct the knowledge sought, but whatever knowledge they construct is meaningful to them since it is integrated within their existing cognitive schemes and is a product of effort that stems from and is driven by their personal intellectual need (Harel, in press, p.18).
Therefore, the necessity principle is not just about creating cognitive disequilibrium. The essence of the principle is the desire within the learner to search for a resolution or solution to regain equilibrium. Need, in this case, implies a desire for a specific way of understanding or thinking. The process of resolving the need leads to the construction of new knowledge. Thus, resolution is an essential component of intellectual necessity—it is through resolution that the students have the potential to construct new knowledge.

**Designing Instruction based on Creating Intellectual Need**

Designing instruction intended to create intellectual need means discovering the intellectual stimuli that will create disequilibrium-equilibrium phases in students. In DNR-based instruction in mathematics, problem situations are used to create in the student the need for either a way of understanding or a way of thinking. In biology, the typical instructional approach provides students with ready-made knowledge and presents opportunities for them to restate the knowledge or observe it through a laboratory activity. In such situations, most students do not see the purpose of the information they are given (Johnson and Lawson, 1998). In contrast, the necessity principle “calls for instructional attention to a priori justifications for the knowledge we intend to teach our students” (Harel, in press, p.7). In other words, learners should see the need for the concept before the concept is introduced.

Using problem situations appears to be the fundamental way to create an intellectual need in students to learn what we intend for them to learn because problems have the potential to cognitively perturb or puzzle students. However, not all
problem tasks lead to cognitive disequilibrium. Identifying some of the characteristics of problem situations that create intellectual need in biology learners was one of the goals of this project.

In the field of mathematics, there is a substantial body of literature that addresses problem tasks that create cognitive puzzlement for learners of mathematics (see Zaslavsky, in press). In the field of biology, however, a discussion of task design, analysis, and empirical testing is rare except in the case of instruction in genetics (Cavallo, 1996; Gipson and Abraham, 1985; Slack and Stewart, 1990; Smith, 1992; Soderberg, 2003). Designing intellectually-based problem situations that have the potential to create a need in the students to refine and advance their ways of understanding in an ecology learning environment means determining what might constitute intellectual need for my particular population of students.

**Designing problem situations.** As mentioned in chapter 4, I designed the problem tasks for a specific audience—first and second year university students that had not taken any upper division biology courses. Based on my population, I made the assumption that all of the students participating in the teaching experiment would have successfully completed at least one high school biology course, some may have taken one or more lower division biology courses at the university, and most would be biology majors or minors. Although my interview data suggested that the students would have naïve understandings or gaps in their understanding of many of the concepts on which I was focusing, I was confident that they would all have some level of familiarity with them.
Knowing that students’ existing ways of understanding and thinking would influence their interpretation of the problems, I began by utilizing my interview data, along with the knowledge from the research literature on conceptual difficulties students typically encounter, to develop problem situations. While developing problems, I engaged in “anticipatory thought experiments,” conjecturing about both the students’ potential learning and the means of supporting, organizing, and guiding that development (Bowers, Cobb, and McClain, 1999). I considered both the types of understanding and thinking the problem situations might provoke and the learning tools that might facilitate students’ learning.

I chose the Ecosphere as a context for the first set of problem situations because it provided opportunities for students to examine the components of a simple dynamic system. The Ecosphere is a self-contained miniature ecosystem encased in glass. Inside each Ecosphere are micro-organisms (bacteria), red brine shrimp, algae, and filtered sea water. The Ecosphere is a self-sustaining ecosystem. The small spheres can survive for more than eight years while the large spheres have been known to last for over 20 years. The set of Ecosphere problems were designed to help the students develop ways of understanding matter and energy transformations, decomposition, and the basics of respiration and photosynthesis. The subsequent problem situations were designed to help students develop an understanding of the relationship between these different biological processes; that is, to create the need to coordinate the molecular, cellular, and organismal level processes.
The problems I designed were exploratory; I did not know what types of problem situations would create an intellectual need in students to learn the biological ways of understanding that I intended for them to learn. Therefore, there were several iterations of problem design. After developing a set of problem situations, I conducted teaching interviews to try out the problems. After several iterations of problem refinement, I compiled a set of potential problems to use during the final teaching experiment. My use of the word potential here is intentional. The problems I designed provided a pool of resources from which to choose during the teaching experiment. The problems I actually implemented were chosen subsequent to my analysis of the learning after each lesson because the teaching experiment methodology required the continual refinement of the goals and lesson tasks in reaction to students’ learning. The problem situations used in the final teaching experiment are listed in Appendix 7, and the implementation of several of these problems is discussed in chapter 7.

**Hypothetical Learning Trajectory**

My consideration of the learning goal, the learning activities, and the thinking and learning in which students might engage comprised a “hypothetical learning trajectory,” or HLT (Simon, 1995). An HLT is a valuable tool in that it includes “the simultaneous consideration of mathematical [or scientific] goals, models of children’s thinking, teachers’ and researchers’ models of children’s thinking, sequences of instructional tasks, and the interaction of these at a detailed level of analyses of processes” (Clements and Sarama, 2004). Although I employ the term hypothetical learning trajectory, I recognize that development does not occur linearly, and
knowledge does not develop along a trajectory (Lesh and Yoon, 2004). Rather, I sought to identify those problem situations that reliably elicited idea development. In this way, the HLT I developed did not serve to guide students along a narrow conceptual path, but provided a tool that allowed me to envision how problem situations could be organized so as to create intellectual necessity and allow me to study students’ thinking.

Taking into consideration the anticipated ways of understanding and thinking of the university students in my study, it was evident that problem situations designed to help students develop connections must (a) address their understanding of various biological processes, and (b) foster an intellectual need to make connections between these processes. In particular, the problem situations must create questions in students about the relationship between the different ways of understanding, or “pieces” of knowledge, with which they were already familiar or had memorized in previous biology classes. Below I outline the overall structure of the learning trajectory.

Step 1: To elicit ideas and establish the didactical contract. Students’ expectations of both the teacher and themselves in the learning environment will affect the devolution of the problem. For this reason, the first problems (Questions 1a and 1b) were designed to provide an opportunity for the students to work together to bring their initial ways of understanding to the surface, to share their understanding with their group members, and to present their shared understanding with the whole class.

Step 2: To understand the cycling of nutrients in the sphere. Problems were designed to help students develop the following ways of understanding: plants and
animals function as matter-transforming systems; the transformation of matter is not limited to carbon dioxide and oxygen, many other elements are cycled in a living system; decomposition involves materials in one organism becoming part of another organism (Questions 1C and 1D).

**Step 3: To understand the need for a constant input of energy.** Problems were designed to help students develop the following ways of understanding: matter and energy are distinct in that matter cycles and energy flows through a system; the degradation of energy in a system is the reason there must be a constant input of energy, but not matter (Questions 1E and 1E Supplemental).

**Step 4: To understand photosynthesis and respiration as biological mediating processes.** Problems were designed to help students develop the following ways of understanding: plants take in carbon dioxide gases and combine them to form larger molecules; producers, consumers, and decomposers respire by breaking down these larger molecules and releasing energy and carbon dioxide (Question 1F and Exercise 1).

**Step 5: To make connections between the different processes.** Problems were designed to help students develop an understanding of the relationships between different biological processes. Producers, consumers, and decomposers contribute differently to the cycling of matter in a system. Molecular and cellular processes help to explain the functions of multicellular organisms (Question 3a and 3b).

These steps outline my hypothesis of how students might move towards my cognitive goal as a result of their engagement in the particular problem tasks. In other
words, this trajectory was my prediction as to the path by which learning might proceed during the teaching experiment. It was hypothetical because the actual learning trajectory was not knowable in advance. A detailed learning trajectory for Problem Set One is provided in Appendix 8. I discuss the outcome of the teaching experiment and the development of students’ ways of understanding in the following chapter (chapter 6). In chapter 7 I discuss the design and implementation of three specific problem situations followed by an analysis of the characteristics that likely contributed to the success of these problems in creating intellectual need and helping students refine or develop new ways of understanding.
CHAPTER 6: RESULTS ON THE EVOLUTION OF STUDENTS’ WAYS OF THINKING AND WAYS OF UNDERSTANDING

One of the goals of this research project was to determine to what extent the Duality Principle applied to biology education. Once I identified model-based reasoning as a desirable way of thinking for students to develop, it followed that I would determine whether building on students’ existing ways of understanding would lead to developing this way of thinking, as the Duality Principle asserts (see Figure 11). The teaching experiment allowed me to observe and elicit the students’ ways of understanding and infer ways of thinking, as well as build and test models of the students’ knowledge. Analyses of the students’ explanations helped to determine how their ways of thinking and understanding changed or failed to change when situations were encountered that conflicted with the students’ existing ways of thinking and understanding.

In this chapter, I present analyses from the teaching experiment of three students’ responses to a series of problem situations intended to help them develop (a) a way of understanding biologically mediated processes such as energy and material flows, respiration, photosynthesis, decomposition, and (b) a way of understanding the interrelationships among these processes. From the students’ ways of understanding revealed during the experiment, I inferred their ways of thinking and discuss the changes or lack of change in these ways of thinking. A discussion of the types of situations that created an intellectual need in students to develop the desired ways of understanding is the included in chapter 7.
In the first section of this chapter, I present a detailed analysis of the evolution of Franjelica’s ways of understanding and thinking over the course of the ten week teaching experiment. The analysis of Franjelica is descriptive and thorough to provide the reader with insight into the inferences and conclusions made. The analyses of the second and third students from the video group, Austin and Rachel, are shorter, primarily because the conclusions are similar to those for Franjelica. In this chapter, I provide evidence to support the claim that many of the students’ ways of understanding processes associated with biological systems changed throughout the
ten week teaching experiment. I also offer evidence to support the claim that all three students had begun to develop some of the characteristics of Model-based Reasoning.

**Student 1: The Evolution of Franjelica’s Ways of Understanding and Thinking**

I begin this section by presenting Franjelica’s initial ways of understanding followed by her initial ways of thinking. I follow this order because the identification of one’s ways of thinking are inferred from one’s ways of understanding. I then present Franjelica’s ways of understanding and thinking throughout instruction. Although I did not expect students’ ways of thinking to change from perception-based reasoning to model-based reasoning in the course of ten weeks, I am able to show how changes in Franjelica’s ways of understanding certain biological processes influenced her ways of thinking.

**Franjelica’s Initial Ways of Understanding**

Analysis of the initial interview and the first two class sessions reveal that Franjelica had a naïve way of understanding biological processes such as decomposition, respiration, and photosynthesis, and conflated matter with energy. Details describing Franjelica’s initial ways of understanding these processes are presented in this section.

**Initial Ways of Understanding Matter and Energy Transformation.** Franjelica’s initial ways of understanding matter and energy were difficult to uncover because she rarely referred specifically to matter or energy in her interview or during the first two lessons. When Franjelica did refer to matter, she used the term nutrients. While discussing the composition of plants and animals, Franjelica mentioned several
elements: carbon, hydrogen, oxygen, and nitrogen. She also stated that all living things are carbon based. She did not, however, connect the commonality of elements in living organisms with the cycling of elements to sustain a system.

Energy was discussed only briefly during the interview. Franjelica stated that humans ingest things for energy, but plants get their energy needs from the sun. The idea that matter cycles or that energy flows through a system was lacking from any explanation of the functioning of a biological system. Instead, Franjelica interpreted cycles in nature as who eats whom, or as the gas exchange of carbon dioxide and oxygen between plants and animals.

Initial Ways of Understanding Photosynthesis and Respiration. For Franjelica, photosynthesis was the process by which plants use the sun for energy and release oxygen. She stated several times that plants can make whatever they need to sustain themselves as long as they have water, sunlight, and minerals.

Franjelica: Plants use just light, er, photosynthesis, so they have, they are very self containing. Like you can, as long as you have minerals. Like they don't bring much into them except for minerals and water and light. So if you give them water and something, soil to grow in and then have that soil be like some way, nutrifying. You know, not just like just rock. You know? Cause um, pretty much any dirt you find will have some sort of nutrient to it. So as long as you give them like dirt and light and water, they are pretty well on their own.

Franjelica understood the mass of plants as coming from nutrients in the soil rather than carbon dioxide gas. At other times during the interview Franjelica mentioned carbon dioxide as a plant need, however, this only occurred when she was discussing gas exchange (CO₂ and O₂) between plants and animals. She did not express an
understanding of the connection between the composition of a plant and carbon dioxide.

Franjelica did not refer to the term respiration or the process during the interview or the first lesson. From various statements it seemed that, for Franjelica, respiration was the exchange of gases, carbon dioxide and oxygen, between plants and animals. She stated that whenever she thought of air she associated it with plants. Although she discussed the idea that humans “power themselves” with glucose, she did not make an explicit connection between the intake of oxygen and the breakdown of glucose.

Rachel: What else happened if the algae is removed?
Franjelica: Okay, so algae, algae provides, it turns CO₂ to O₂, so it expels oxygen, um…

For Franjelica, the exchange of CO₂ and O₂ were not associated with a process. In other words, the output of O₂ by plants was not understood as a byproduct of a metabolic process, but rather, an exchange from one form to another.

**Initial Ways of Understanding Decomposition.** During the interview, Franjelica discussed the idea that plants use waste as fertilizer; however, in lesson two, it became apparent that she did not understand that decomposers breakdown organisms or that this process is essential in the recycling of nutrients. Instead, Franjelica’s statements reflected an understanding that organisms decompose spontaneously, and then bacteria consume the decomposed parts: “So [algae] feeds the shrimp, [shrimp] decompose to feed the bacteria”. Note the phrasing—the shrimp first decompose, and then this decomposed product provides food for the bacteria.
This assertion contrasts with the biological understanding that organisms do the decomposing.

**Franjelica’s Initial Ways of Thinking**

When Franjelica explained the functioning of the sphere, she focused only on what each organism “takes in” or “releases” at a macroscopic level. For example, she stated that plants take in carbon dioxide and animals release carbon dioxide; however, she did not discuss this at the level of matter cycling. She spoke only in terms of what each organism needed at the organismal level to survive. This evidence suggests that Franjelica had not made connections between what organisms need to survive—the need for matter to cycle and energy to flow through a system—and the biological processes that mediate this flow. The following four examples provide evidence to support the inference that Franjelica’s way of thinking associated with accounting for phenomena in natural systems could be characterized as “perception-based reasoning.”

**Example 1: Focuses on objects.** When the class was first introduced to the Ecosphere, they were asked to explain why this combination of organisms allowed this sphere to survive for a long period of time (ten to twenty years in some cases). The students began by focusing on what each organism consumed and what would be excreted. After several minutes, Franjelica began documenting on paper the needs of each item in the sphere:

Franjelica: So shrimp fertilize algae, eat bacteria or whatever the grimy stuff would be. Seawater maybe neutralizes excrements, maintains pH (reading off the white board). Oxygenation, algae is oxygenation for the bacteria. Something else with the seawater. Like why would they need that much?
All three students in the video group focused primarily on the inputs and products of each organism individually, without mentioning their interrelationships or cellular or molecular level processes.

After the students developed their explanation for the functioning of the sphere, they were given an information sheet on each species in the sphere. From that point forward, Franjelica began including chemical elements in her discussion of the inputs and products of each species.

Franjelica: Okay, so, heterotrophic [bacteria] needs carbon. They get it from decaying organic, um, I can't even read my writing. That's pathetic.

…

Franjelica: Debris (quietly to self while writing). Okay, so Hydro [heterotrophic bacteria] needs carbon, they get it from decaying organic debris. And they need oxygen. Nitrifying converts ammonia to N-O and they also need carbon dioxide and oxygen. And algae just needs light, water, C-Os, nitrogen and phosphorus.

Here, Franjelica listed all the needs of both of the bacteria groups. Although Franjelica included references to elements and compounds, she continued to focus on the needs of each organism locally, rather than consider the roles of each organism in the cycling of these elements when accounting for the survival of the Ecosphere community. She realized the bacteria had nutrient needs, but did not appear to make the connection that something in the sphere must be contributing to the cycling of these nutrients.

Similarly, when asked in a subsequent session to explain how the Ecosphere community survives long after the brine shrimp are removed, Franjelica switched her focus from the inputs and products of each species, to the source of each compound on the information sheet. For instance, she tried to determine which organism produced
oxides of nitrogen, not because these elements are common among all of the organisms in different forms, but because this “object” exists in the water so it must be accounted for. Thus she focused primarily on objects, such as species or compounds, when she tried to account for the functioning of the Ecosphere community.

Example 2: One-dimensional relating. Franjelica’s statements throughout lessons two and three suggest that she was not making connections between the elements that comprise organisms and the conversion of these elements in living organisms. Although she mentioned compounds such as ammonia and carbon dioxide, she did not seem to understand these compounds as composed of individual elements that were converted through biological processes to meet each organism’s need for carbon, hydrogen, oxygen, nitrogen, and phosphorus.

For example, at one point Franjelica questioned which species needed carbon: “So algae provides oxygen, it also provides, okay, so who needed the carbon? Carbon base. Bacteria? Was it this one or this one?” Her comment suggests that she may not understand that all of the species needed a source of carbon. This conjecture is further supported by the fact that Franjelica had not considered carbon dioxide when listing the requirements for plants, as mentioned earlier (see “Ways of Understanding Photosynthesis” above).

The claim that Franjelica did not make connections between the organismal level and the cellular or molecular levels is supported by statements throughout lesson two. For instance, early in the lesson Franjelica acknowledged that shrimp consume algae, and algae are composed of carbon, hydrogen, oxygen, nitrogen, and phosphorus
(information provided on the information sheet). Later in the lesson Franjelica questioned the source from which the shrimp obtained their nutrients, specifically phosphorus and nitrogen. Although she had previously recited the composition of algae, she did not relate the consumption of algae with receiving nitrogen and phosphorus.

In the same lesson, as the group was trying to figure out which species of bacteria used which form of nitrogen, Franjelica proposed that the shrimp needed ammonia. Franjelica did not consider her previous conclusion that shrimp gained all their nutrients by consuming algae, nor that the shrimp excrete ammonia. Instead, she focused only on how to assign a compound (for example, ammonia) to a species.

These examples demonstrate that Franjelica was not relating the phenomena of consuming algae with the molecular composition of the algae. Although she could use terms such as digestion, she did not make the connection that during consumption an organism breaks down the compounds into different forms that the body can use. Instead, Franjelica reasoned only at one level at a time—usually the organismal level—without using ideas about cellular and molecular processes to explain the functions of the organisms or the system.

**Example 3: Ad hoc explanations.** As Franjelica’s explanation of the relationships between species in the sphere took shape, she attributed unique abilities to species so as to meet a particular need she discovered. For instance, in lesson two, after the class shared their accounts of why the Ecosphere was able to function, the students were told that the sphere could function for several years without the brine
shrimp. This idea contradicted the students’ conclusions that every species was essential for the sphere to function. The students were then provided with data on the composition of the water with and without brine shrimp and asked to account for why the sphere could function without the shrimp. In the following segment, Franjelica accounts for all of the needs of the bacteria and algae in a sphere without brine shrimp:

Franjelica: So [bacteria] need CO\textsubscript{2}, O\textsubscript{2}, can't they just break the C-O bond and just use that as oxygen? Or do they need them both?
Austin: Um, I think they need both of them separately.
Franjelica: Yeah, but, they convert ammonia to oxides of nitrogen.
   Okay, but this one kicks out-
Rachel: They convert ammonia to what?
Franjelica: they convert ammonia to oxides of nitrogen. So N-H-3 to N-O-X. This one kicks out N-O-X, so, think it goes backwards?
   Can it go from N-O-X to N-H-3?
Austin: You mean, can algae use N-H-3? Can they?
Franjelica: Yeah. Cause N-H-3 is inorganic and it’s a bioavailable.
Austin: Oh, so, yeah, yeah. That sounds right.

Several times throughout the first two lessons Franjelica made statements about organisms converting compounds backward and forward. Franjelica did not appear to understand that biological processes are specialized, that oxygen is used for one process and carbon dioxide for another. In a later discussion, she concluded that if the organism needed oxygen, it could simply obtain the oxygen by breaking apart carbon dioxide. Later, she asked another group, and then the instructor, if oxygen could come from the spontaneous “breakdown” of carbon dioxide in water.

Furthermore, while trying to account for the source of a compound on the data sheet, for example, carbon dioxide or NO\textsubscript{X}, Franjelica made some very simplistic assumptions about how compounds change forms. Her statements about converting compounds suggest that she used teleological reasoning—the organism releases
compounds to provide what another organism might need. This stands in contrast to an understanding that processes evolved because the trait had improved organisms’ survival and reproduction rates.

**Example 4: Simple linear relating.** Franjelica seemed to think locally about each object in the sphere, and then tied her ideas together into a type of linear relationship. This simple linear approach often resulted in simplified interpretations of the more complex interactions and relationships within the system. In the following segment, Franjelica’s simple linear argument caused her to misinterpret and make incorrect conclusions.

Rachel: Okay, what do the shrimp do?
Franjelica: The shrimp
Rachel: They excrete ammonia, which is
Austin: /for the bacteria
Franjelica: /for the bacteria.
Rachel: Which bacteria? Nitrifying?
Franjelica: Both.
Austin: They both are relying on ammonia?
Franjelica: Well, no. Nitrogen eats just ammonia. But this one can also get stuff from decaying, decomposing things.
Austin: Oh, okay. Cool.
Franjelica: And like waste decomposes so it feeds both types.
Austin: (writing)
Franjelica: Oh yeah. So shrimp is very important because if it doesn't feed the heterotrophic, then [nitrifying] can't eat the heterotrophic.

Here, Franjelica considered each species individually as providing a food source for another species. This approach led her to conclude that the shrimp provide waste for the heterotrophic bacteria, and the nitrifying bacteria consume the heterotrophic bacteria. This simple linear food chain is not representative of the relationships among these species. The data sheet provided discussed what each species consumed, and in
earlier statements Franjelica had accurately repeated the nutrient requirements of each species. Yet as she tried to account for each individual species—what they took in and what they excreted—she made linear connections between each species. This simple linear approach to explain the relationships between species led Franjelica to incorrect conclusions.

Interestingly, when the question of accounting for a sphere without shrimp was assigned, Franjelica began by trying to account for the source of each input and product, rather than considering each individual species as she had done for her previous solution. Although this reflected a change in her approach, it still indicated simple linear causal reasoning. Franjelica knew the algae needed carbon dioxide and she had concluded earlier that the carbon dioxide came from the shrimp. Without shrimp she could not account for the source. At the end of the lesson, Franjelica displayed dissatisfaction with her group’s explanation for why the sphere functioned without shrimp because she still could not account for the source of carbon dioxide for the algae.

Her struggle to account for the carbon dioxide source provides evidence that Franjelica and her group members were reasoning linearly. The relationship between the algae and the bacteria is cyclical. If the sphere community functions, and carbon dioxide is needed by the algae, then it must be coming from the only other organisms in the sphere, the bacteria. Franjelica, however, was only considering the gas exchange relationship with the brine shrimp that she had concluded earlier. Her simple linear causal reasoning seemed to impede her consideration of logical causal relationships.
Franjelica either considered each species locally, rather than considering all of the species in the system, or she focused on accounting for the source of each compound. Moreover, Franjelica’s inability to resolve the source of the carbon dioxide in the sphere without brine shrimp provides further evidence to support one-dimensional relating. Franjelica did not make connections between species’ needs and the role they play in contributing to the conversion of matter within the whole system.

**Summary of Franjelica’s Initial Way of Thinking.** Figure 12 provides a diagram summarizing Franjelica’s initial ways of thinking and understanding. Franjelica tried to account for the functioning of the sphere community by focusing on inputs and products of each species in the sphere rather than viewing the interactions among organisms as fulfilling matter and energy needs. Her statements throughout lessons two and three suggest Franjelica reasoned at only one level at a time. She did not seem to make connections between the phenomena of a functioning sphere and the processes of photosynthesis, respiration, and decomposition, nor did she refer to the cycling of matter or flow of energy. It is likely that Franjelica did not consider these interrelated processes because her way of understanding them was very limited (see the previous section entitled “Franjelica’s Initial Ways of Understanding”). The idea that matter and energy are common needs among the species in the sphere and must be met by those organisms in the sphere was not reflected in Franjelica’s solution.

When Franjelica identified causal relationships, the connections she made were simplistic and she often considered only local relationships. She did not maintain a global view of the functioning of the system, but instead, considered each individual
entity and its relation to one or two other entities. Much like Grotzer and Basca’s (2003) data revealed, Franjelica initially did not reason about causality in a systemic sense, nor did she demonstrate a way of understanding the specific types of causal patterns embedded in ecosystems. Rather, she imposed a simple linear pattern to organize information about the relationships between species in the Ecosphere.

**INITIAL WAYS OF UNDERSTANDING**

- Energy converts to matter
- Organic matter decomposes spontaneously
- Plants get energy directly from the sun
- Plants can make anything they need
- Plant composition: C,H,O,N
- Plant mass comes from soil and/or water
- Respiration is the exchange of oxygen and carbon dioxide

**WAYS OF THINKING**

- Focus on inputs and products of orgs.
- Ad hoc explanations
- One-dimensional relating
- Simple linear relating
- Teleological reasoning

Figure 12: Franjelica’s initial ways of understanding and thinking

**Changes in Franjelica’s Ways of Understanding**

Throughout the ten week teaching experiment, as Franjelica engaged in problem situations based on creating intellectual necessity, she refined and/or modified her understanding of several biological processes.

**Changes in WoU Matter and Energy Transformation.** Franjelica’s understanding of matter and energy changed as she progressed through the lessons in
the teaching experiment. By the end of lesson three she began discussing the idea that elements pass from producer to consumer and that all the species need similar elements.

Franjelica: Okay, so algae needs light, water, carbon, oxygen, nitrogen and phosphorus. And these guys both all need carbon, oxygen, phosphorus, and nitrogen. So they all need the same stuff. Except for the, yeah, they all need the same stuff.

During this lesson, Franjelica began to consider the cycling of certain elements, although the group focused mainly on nitrogen.

By lesson five, Franjelica began making explicit references to the differences between matter and energy while discussing the role light played in the functioning of the sphere. In the following segment, her group was critiquing another group’s white board diagram of the role of light.

Franjelica: I see the transfer of nutrients; I don't see the transfer of energy.
Austin: Couldn't the nutrients be the energy? ‘Cause the nutrients do contain the energy.
Franjelica: But they didn't say that.

In this and several other statements, Franjelica discussed the idea that energy and matter are not the same. This idea was revisited in the warm-up question for the sixth lesson: “Many people state that matter and energy cycle through a system. Do you agree or disagree? Why?” Franjelica shared her response with her group:

Franjelica: Like yes, they cycle, but- well energy cycles and then, no, matter cycles, and energy transfers, but it doesn't complete the cycle because you need a reliable source of energy for the algae which will be the sunlight, right?
During this lesson Franjelica introduced the idea that as energy flows through a system it is lost as heat. This understanding that energy does not cycle but flows through the system and is lost as heat reemerged multiple times over the final five lessons.

During lesson six, Franjelica demonstrated her understanding that energy does not disappear, but is converted to heat, and that heat is not a usable source of energy:

Franjelica: Not for how we were saying energy. Like not as um, like we are talking about energy as fuel for like metabolism. That is how we were talking about energy. And you can't, like a, a biological organism, lets say an animal, doesn't use heat to power it. It uses like starch and sugar. And so you can't, so once it’s no longer starch and sugar, once its heat, you’re not using it to do metabolism anymore. I think there is something to do with like homeostasis and like, and like the heat of like, having to have your body a certain temperature, otherwise things go wacky, but like, as far as metabolism goes, heat is no longer a usable energy source.

Discussions from lesson seven provide further evidence that Franjelica had developed a way of understanding energy loss and energy pyramid structures:

Franjelica: So the higher the being in the biomass pyramid (pause) like the higher up the being is in the biomass pyramid, the more energy is lost on the way to them. So the more resources they have to consume in order to survive. And so, so there- and the more resources an organism has to consume to survive, the less of that particular organism the environment can support. So, in a, in this hypothetical biomass pyramid, the top carnivores are really small because they can't support a lot of top carnivores.

Franjelica presented a biological explanation to her group members for why the biomass decreased as one progressed up the food pyramid. It is likely that Franjelica used the word “small” in the above passage to refer to the number of top carnivores, rather than their physical size, because the question included a diagram in which top carnivores were represented as a thin sliver as opposed to a long rectangle representing
the primary producers. Later, as Franjelica shared her understanding with the class, she drew a diagram using large boxes for producers and increasingly smaller boxes representing each level of consumer. She explained that the change in size of the boxes represented a loss of usable energy.

In lesson eight, Franjelica demonstrated an understanding of the differences between matter cycling and energy flow during a discussion of the role of decomposers in a system.

Franjelica: Like they [bacteria] were a very important part of the whole recycling of matter. Like not so much the cycle of energy, cause it pretty much, the energy cycle stopped pretty much when you got [to the decomposers], but for recycling matter they were very important.

While Franjelica was speaking, she kept moving her hand in a circle to represent the continuous cycling of matter.

**Changes in WoU Photosynthesis and Respiration.** Franjelica’s understanding of photosynthesis slowly evolved over the course of the ten week teaching experiment. By the sixth week, Franjelica understood that plants use the sun to make the glucose that provides an energy source for the plant.

Instructor: Okay, how does the plant get its energy?
Franjelica: Light.
Instructor: So light comes to a plant and it gets energy from it?
Franjelica: No, light comes to a plant and it goes to the chlorophyll where the glucose is made from CO₂ and water. And it produces glucose, oxygen and they make also carbon dioxide, yeah.

Although some of the details do not reflect how a biologist might describe the process, the intent of the instruction was for students to develop an understanding that plants do not get their energy directly from the sun, but use the sun as an energy source in
making glucose. Franjelica demonstrated this level of understanding several times in the last four lessons.

Franjelica’s descriptions of the distinction between the processes of respiration and photosynthesis in plants provides the most representative evidence that Franjelica changed her way of understanding photosynthesis. For instance, during lesson six, after the students created an analogy to represent the role of the producer, they were asked to explain an analogy written by a hypothetical student. The hypothetical student had suggested that two analogies are required to represent the producer: a powerhouse and a car. Franjelica’s group members struggled to understand how the car analogy corresponded to a producer, and Franjelica tried to help them see the distinction: “Yeah. But if [the hypothetical student] believed that the hydrocarbons were the powerhouse, why would he need the powerhouse?” Franjelica appeared to understand the distinction between the two processes within algae. In one case a producer generates a useful power source (the powerhouse), and in the other the producer breaks down hydrocarbons to gain usable energy (the car).

Later in the lesson, the conversation returned to the distinction between the car and powerhouse analogies:

Instructor: So tell me how it functions as a car? Explain that to me.
Rachel: The car uses the energy, um, from the, gasoline or whatever, and whatever the gasoline (?)
Franjelica: So it’s a powerhouse because it makes its own energy, but it’s a car because it uses that energy.
Instructor: So I want to know the car, what would be the analogous thing here (Instructor draws a line under gas).
Rachel: Um, the sunlight, right?
Austin: Yeah.
Rachel: Yeah, yeah, the sunlight.
Instructor: (writes sun) That's what connects to gas?
Franjelica: No, she is in the car part of it, not the powerhouse part!

During these two discussions, Franjelica displayed frustration with her group as she tried to help them understand that the car analogy represented the process of plants breaking down hydrocarbons for energy, and the powerhouse analogy represented the idea that plants produce their own energy source (glucose) through another process. For Franjelica, the gasoline in a car was not analogous with the sun, but rather, it was analogous with glucose. When she said, “No, she [the teacher] is in the car part of it, not the powerhouse part,” Franjelica was stating that the sunlight was part of the powerhouse role of plants. The instructor asked about the car analogy, and a member of Franjelica’s group mate made correlations that belong to the powerhouse analogy. Franjelica’s frustration, along with her statements, suggests that she was beginning to develop an understanding of the distinction between photosynthesis and respiration, as well as their roles within a producer.

Franjelica’s understanding of respiration was demonstrated further in subsequent lessons:

Franjelica: Respiration which is the breakdown of glucose into a, using oxygen, into CO₂ and energy.
Instructor: So what is food for a plant?
Franjelica: Glucose.

Moments later, Franjelica defined food as “available sources of energy.”

Franjelica’s final homework assignment also reflected an understanding of the distinction between photosynthesis and respiration. She wrote:

The light powers the chloroplast cells, which provide the plant it’s food by converting Carbon (C), Hydrogen (H), and Oxygen (O) into glucose,
which can then be broken down to provide E. The C, H, and O are available to the Algae by the process of Respiration (sic).

In her description of respiration, she writes, “For example, O₂ is used to breakdown Glucose and Glycogen, the ready sources of E and E storage in most organisms” (sic).

Her diagram description also asserts that “sun provides E for photosynthesis in Algae (producer)” (sic). Notice that she states that the “sun provides energy for photosynthesis,” as compared to her initial statements that the sun provides energy to the producers. This distinction is important because it reflects an understanding that plants do not get chemical energy directly from the sun, but rather, that the sun is a source of energy for the process of producing glucose.

Changes in Ways of Understanding Decomposition. Franjelica’s understanding of decomposition in a natural system appeared to develop in two steps. The first step was the understanding that organisms, specifically decomposers, do the decomposing.

Evidence that Franjelica had been understanding decomposition differently came during the fourth lesson, when Franjelica explicitly stated that she had been misinterpreting information on the bacteria fact sheet.

Franjelica: It comes from decomposing bacteria. And so what could decompose heterotrophic [bacteria]? We are assuming its, can heterotrophic decompose themself? (Begins looking at bacteria handout). “Require organic debris for growth.” (pause) Oh, I’ve been reading this wrong for three weeks. Right here, “They generally obtain nutrients from decomposing organic debris”. I was, I’ve been reading that as they get their things from things that are decomposing-

Rachel: No, they do the decomposing.

Franjelica: Yeah, now I get that.
Although earlier in the lesson Franjelica responded to a question by stating that algae would not decompose without bacteria in the sphere, she had not internalized the idea that bacteria do the decomposing until this time. From this point forward, Franjelica consistently applied the idea that organisms did the decomposing, rather than the idea that organisms decompose spontaneously and then decomposers consume the debris.

At a later point during the same lesson, Franjelica defined for Austin, who had arrived late, her understanding of decomposition. In the following segment, she was referring to a drawing on the board in which algae was lying dead in a sphere that had been sterilized (no bacteria).

Franjelica: So it hasn’t decomposed at all.
Austin: Okay, so now I look at the questions.
Franjelica: Yeah. And then, what else, we are defining decomposition as the breaking of- wait, say, cause your algae is CHONP, remember CHONP?
Austin: Mmhmm. Yeah.
Franjelica: CHONPS. We defined decomposition as breaking how its combined and all the structure as algae or whatever, or whatever and it comes out as like, CO₂, PO₄, whatever, blah, blah, blah. NH₃, all that fun chemistry stuff.
Austin: Mmhmm.

Franjelica’s reference to CHONPS refers to carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur. Both Franjelica and Austin had used this acronym in previous lessons. In this segment, Franjelica explained to Austin that decomposers change the composition of algae into various compounds. This represented a significant change in her understanding of decomposers and decomposition.

By the sixth lesson, Franjelica presented a biological understanding of the role of decomposers in a natural system:
Franjelica: So bacteria, bacteria are happy little matter converters, aren't they?

... Franjelica: Well, bacteria takes organic and makes it inorganic so algae can use it, restart the (bowl?) and recycle again.

Franjelica referred to bacteria as “matter converters” multiple times throughout the last several lessons. Although “matter converters” is not a biological term, her use represents her understanding that decomposers convert matter from one form to another, contributing to the cycling of matter in the system.

In lesson eight, Franjelica and her group were trying to recall the “players” they previously identified in their explanation of the functioning of a biological system. Franjelica responded first by stating the categories of organisms she had included in her diagram.

   Franjelica: Consumers, producers, and um, recyclers?
   Instructor: What's a recycler mean?
   Franjelica: Recycler is like, it’s kind of like, it’s a consumer and producer. It consumes from one, and it goes, it helps things to another. Like your, your bacteria are your recyclers.

Franjelica’s use of the word recycler, rather than decomposer, reflected her understanding of the role of the bacteria in sustaining the system. Thus, Franjelica developed an understanding of decomposition as the breaking down of organic material into inorganic material, and the importance of this process for the producers.

Summary of Changes in Ways of Understanding. Matter and Energy Transformation: During Franjelica’s interview and first two lessons, it appeared that Franjelica did not distinguish between matter and energy, and the only cycles she mentioned were those that represented local phenomena, such as the exchange of
carbon dioxide and oxygen between plants and animals. During the third and fourth lessons, Franjelica began referring to elements when discussing the needs and composition of plants and animals. By the fifth and sixth lessons, Franjelica was explicitly discussing the distinction between matter and energy: matter cycled through natural systems but energy was lost as heat, and therefore a constant input of energy was needed for the system to continue to function. During lessons seven through ten, she stated the importance of decomposers in the cycling of matter several times, exemplifying her understanding of the importance of the cycling of matter in the functioning of a biological system.

Photosynthesis and Respiration: Before instruction, Franjelica stated that plants could produce all of their needs if provided with sun, water, and minerals. Although she occasionally recognized the need for carbon dioxide in plants, she did not make any connections between carbon dioxide and the production of glucose during the process of photosynthesis. By the sixth lesson, Franjelica verbalized that carbon dioxide and water were the source of elements for the production of glucose. Subsequent lessons revealed that Franjelica had developed an understanding of the process of respiration and the distinction between photosynthesis and respiration. Furthermore, the transcript evidence suggests that Franjelica understood that producers must breakdown glucose just as animals do, in order to gain usable energy.

Decomposition: In lesson two, when first trying to account for the role of bacteria, Franjelica and her group struggled to discern the role of the bacteria. They proposed that the bacteria might control the shrimp population or that they might
consume the shrimp waste. They did not, however, definitively decide on the role of the bacteria in the sphere. By the eighth lesson, Franjelica had interiorized the role of bacteria such that she used a descriptive term, “recycler,” when she could not remember the technical term “decomposer.” As mentioned above, Franjelica understood the role of decomposers in the recycling of matter and the importance of these “recyclers” for the functioning of a biological system. Figure 13 provides a summary of the changes in Franjelica’s ways of understanding over the course of the ten-week teaching experiment.

Figure 13: Franjelica’s ways of understanding before and after instruction

Changes in Franjelica’s Ways of Thinking

One’s ways of thinking are often robust and can take a very long time to change. Within a ten-week teaching experiment, I did not expect students’ ways of thinking to change from perception-based reasoning to model-based reasoning, but I did intend to examine whether changes in one’s ways of understanding biological
processes would, in fact, influence students’ ways of thinking as the Duality Principle proposes.

Analyses of group conversations from lessons eight and ten, along with a homework assignment due at the start of the tenth lesson, provide the best evidence to demonstrate how Franjelica’s way of thinking associated with explaining began to reflect characteristics of model-based reasoning. In this next section I provide evidence from lesson eight, and then from lesson ten, to support this claim.

**Evidence from Lesson Eight.** In lesson eight, the students were trying to develop an explanation to account for the annual occurrence of the Dead Zone in the Gulf of Mexico. Franjelica’s group tried to make sense of the simulator data and the data from the Gulf of Mexico for more than half of the period before the instructor intervened by asking if everything that was needed for a functioning sphere is represented in the simulator. After some discussion, Franjelica stated that a biological system required producers, consumers, and decomposers to function properly and recycle matter (for transcript evidence see “Changes in Ways of Understanding Matter and Energy” and “Changes in Ways of Understanding Decomposition” above). Franjelica’s discussion of the role of bacteria, algae, and shrimp reflected an understanding that matter must cycle in a system and that different organisms play different roles in this process. Her statements indicate that she had begun to make connections between macro-level properties, such as the survival of the organisms in a system, and processes, such as matter cycling and energy flow. The producers, consumers, and decomposers she described represent the organismal scale, and the
discussion about their roles as “recyclers” of matter reveals that she was making connections between two dimensions in an attempt to account for the functioning of the system. Franjelica’s understanding of decomposers as “recyclers” of matter suggests that she was applying cyclical causal reasoning to understand the long term functioning of a biological system.

Later in the lesson, as her group struggled to explain the decrease in oxygen levels within the Dead Zone, Franjelica mentioned photosynthesis and respiration, but she could not decide how these processes helped to explain the phenomena. She eventually proposed the following theory:

Franjelica: Well, because if there's, this is like, like you'd have to produce a lot, but if the phytoplankton grows so much that the light can't filter through it, then all the other phytoplankton under it isn't getting light and therefore it's not respiring oxygen. It’s not doing photosynth- I forgot the description. One is- it’s not putting out oxygen. It’s using the oxygen, and not putting out-like plants do at night.

Although Franjelica confused the terms photosynthesis and respiration, she was able to describe their roles in the functioning of the sphere. Her explanation reveals an understanding that plants use oxygen instead of just releasing it, and, moreover, that she considered cellular level processes as she tried to make sense of the Dead Zone phenomena.

Finally, by the end of this lesson she appeared to tie together all of the separate pieces to which she had signaled earlier. Franjelica shared with the entire class her explanation for the decrease in oxygen levels in the Dead Zone:

Franjelica: The oxygen level would go down, because the more bacteria there is, the bacteria needs oxygen for respiration and bacteria
multiply like crazy, like even exponentially. So the more bacteria there is the more oxygen is being used. And so, and there is more plants, more surface area, a lot more bacteria, more oxygen is being used, and eventually the plankton, there is just not produce enough oxygen for everything there (sic).

Franjelica’s account of the Dead Zone reflects many characteristics of model-based reasoning. Although it is not evident from this excerpt, earlier in the lesson Franjelica discussed the effect of nitrogen and phosphorus on the growth of algae. Her statements reflected an understanding of the relationship between nutrients and elements—that food was composed of the elements the organisms needed for survival. Furthermore, Franjelica described “players” in a system by their role in the cycling of matter. These connections imply that she was considering cyclical relationships in a functioning system. Recall that earlier in the course Franjelica often focused only on what each organism needed or released as waste.

Evidence from Lesson Ten. Franjelica’s consideration of the interrelationships between organisms and the underlying processes within an ecosystem was also reflected in lesson ten. In this lesson, the groups began by discussing why a lake might begin to “die.” They suggested a variety of possible causes, but it was Franjelica who introduced the idea that one change could cause the entire system to fail.

Franjelica: The only thing you need is, well there is more things, but all you need is one major thing to change and mess with one organism and you screw everything up.

This statement suggests that Franjelica was beginning to apply nonlinear causal reasoning when explaining phenomena. One change does not affect only one or two
local species; a change can ripple through an entire system and produce multiple
effects.

Later in lesson ten, each group was instructed to create a presentation board
representing their homework findings. The homework assignment required the
students to provide an explanation for the functioning of a hydrothermal vent
community and to compare this unique community with a typical marine ecosystem.
Franjelica’s description of the relationships between organisms indicates that she was
making connections between the nutritional needs of organisms and the need for
matter to cycle in a community:

Franjelica: So then, it’s just like, excess from chemosynthesis feeds host,
or something like that. I don't know how to phrase that. Its just
basically cause the (pause). Okay, and then um, other marine
animals like fish and such eat those. And heterotrophic bacteria
decomposes all dead organic matter for everything and then it
goes back to the microbes.

Franjelica’s description reveals that she was making connections between the
organismic scale—organisms’ needs for nutrients—and the idea that a community of
organisms plays different roles in the cycling of those nutrients. As she described her
diagram of the relationships between species within a “typical marine ecosystem,” she
no longer drew only linear or single connections between each entity, but rather, she
drew several connections leading to each object. These connections represented
feeding relationships as well as energy moving through the system and the loss of
energy as heat. Arrows drawn on the diagram provide further support for the claim
that Franjelica was focusing on processes within the system rather than individual
entities.
Characteristics of model-based reasoning were revealed again as Franjelica shared with the whole class her group’s white board diagram of the functioning of a hydrothermal vent community. Franjelica began her explanation by making one to one correlations between items on two diagrams hanging on the front board: the hydrothermal vent diagram and a typical marine ecosystem diagram.

Franjelica: I did the vents or the chemosynthetic cycle. Okay, your vent is your sun, it’s your source of energy, your source of heat, but it’s also a source of nutrients. It’s also a source of your sulfides. Your sulfides are very necessary here because um, microbes, or your chemoautotrophic, is that the one, use it for everything. They oxidize the sulfides to feed themselves, and then your, we called them our primary consumers? Our primary consumers. But most of them, except for some crabs, don't even have a digestive system any more. They don't go through this whole step (points to fish eating smaller fish in the marine ecosystem diagram). They just host the microbes and like the plants over here (on the marine ecosystem diagram) they give off the extra oxygen for the other organisms. The microbes over here, if they are in a host organism, the excess energy, the excess nutrients that they make, they'll just give to their hosts, to keep them both alive.

In this excerpt, Franjelica pointed out the relationship between the role of the sun in providing energy for a typical marine ecosystem and the role of the vent in providing energy for the vent community. Furthermore, in her discussion, she demonstrated an understanding of the distinction between matter and energy: “…it’s your source of energy, your source of heat, but it’s also a source of nutrients.” Franjelica also pointed out the difference between the role of primary consumers in a typical ecosystem and the microbe hosts in a vent community. Her reference to the role of plants in the marine ecosystem diagram points to the fact that she was not simply thinking about
the needs of the plant, but also considering the role the plants play in the cycling of elements in the system that contributes to the functioning of the system.

Franjelica continued her explanation to the class:

Franjelica: And then your secondary consumers are the traveling fish, the octopi
Instructor: Your eels.
Franjelica: Eels. Right. They eat your primary consumers. Um, then also everything, like they also have marine snow, the marine snow is um, the bacteria forms on the sulfide sul(?) and they also form in the organisms. But it’s also given from the vents themselves. So there is never um, as long as the vent is active, there is no danger that the microbes won’t be there. Well barring some weird ecological thing.
Instructor: Right.
Rachel: Marine snow is just the dead, ah, fish and what not that (?) the floor of the ocean.
Franjelica: And then the heterotrophic bacteria does the same thing it did here (pointing to the marine ecosystem). It decomposes everything from organic dead matter back to inorganic matter that can be used for other things again. The heats, well the sun heats the atmosphere which heats the water, yada, yada. It’s very important here (pointing to the marine ecosystem diagram). But it is immediately important down here. Because this is so far down in the ocean and the water is practically freezing, (?) and um it cannot support the kind of life, or the mass of life that comes around the vent. So the heat, the vent that heats the water around it provides the environments for all this to take place.

Franjelica’s discussion of how the vent community functions reveals that she was making connections between the phenomena of organisms surviving and the need for energy to flow through a system and matter to cycle. Although she did not use the terms photosynthesis, chemosynthesis, or respiration in this particular excerpt, she described them in both the group conversations and in her written homework assignment. Twice during her explanation to the class, Franjelica referenced the importance of the sun in the marine ecosystem diagram, which suggests that she was
considering photosynthesis as a process in which the sun provided energy for the system. Franjelica also demonstrated her understanding of the role of decomposers in the cycling of matter: “[Bacteria] decomposes everything from organic dead matter back to inorganic matter that can be used for other things again.”

**Analysis of Changes in Franjelica’s Ways of Thinking.** Franjelica’s explanations of the Dead Zone in the Gulf of Mexico and the functioning of a hydrothermal vent community reveal that Franjelica was applying characteristics of model-based reasoning as she accounted for the functioning of these biological systems. Her discussion of the *whole* system, along with her diagrams representing multiple relationships between organisms indicate that Franjelica made connections between the phenomena of a functioning system, the processes within that system, and matter and energy flow (see Figure 14).

There is evidence from this analysis to support the claim that development of a biological way of understanding decomposition and the role of the decomposer contributed to Franjelica’s consideration of cyclical causal relationships. Her description of players in a system by their role in the cycling of matter reveals that she was considering both processes within the system and actors within the setting; by lesson eight she viewed consumers, producers, and decomposers as matter-processing systems. Although Franjelica’s explanation of the functioning of a hydrothermal vent community included an account of the source of inputs and products of objects, Franjelica referred to matter and energy transformations indirectly, suggesting that a theoretical model (for example, cellular and molecular processes contribute to the
functioning of organisms) may have been constraining her account. This evidence provides support for the assertion that helping students develop ways of understanding biological processes and the relationships between processes at various scales can contribute to students’ development of model-based reasoning.

Figure 14: Changes in Franjelica’s ways of understanding and thinking
Similar to Part I, I present Austin’s initial ways of understanding, followed by his initial ways of thinking. I then present changes in Austin’s ways of understanding and thinking during the ten-week teaching experiment. The changes identified are similar to those of Franjelica.

**Austin’s Initial Ways of Understanding**

Austin’s initial interview and the first two class sessions reveal that he had naïve ways of understanding biological processes such as decomposition, respiration and photosynthesis, and he conflated matter with energy. Furthermore, his statements did not suggest that he made any connections between these processes.

**Initial Ways of Understanding Matter and Energy Transformation.** Austin held the common misunderstanding that plants can change energy into matter, rather than use energy to convert matter into different forms of matter. During his interview, Austin mentioned energy only when explaining photosynthesis. He stated that the sun provides the plant with energy “and then somehow they make it into sugar.” He was unsure, however, what the plant did with those sugars.

When asked about the composition of animals, Austin stated that they were made of “carbon and lots of stuff. Ah, meat, I don’t know.” When pressed further, Austin added that there were six elements that humans “really” needed and that “made up most of our bodies.” He named carbon, oxygen, nitrogen, hydrogen, and phosphorus and suggested that humans get these elements from eating and from our
surroundings. During these discussions Austin focused primarily on humans; it was not clear if he associated these elements with other animals and plants as well.

**Initial Ways of Understanding Photosynthesis and Respiration.** When asked in the interview what plants need to survive, Austin cited sunlight, water, and soil, and a few moments later added oxygen. It was not until later in the discussion that Austin changed his mind and stated that plants needed carbon dioxide and released oxygen (see “Example 3” below in “Initial Ways of Thinking”). Later, when the interviewer asked why plants need carbon dioxide, Austin admitted that he did not know: “I don’t know, they just absorb it and use it.”

Austin understood that plants obtained their mass to grow from soil, water, and sugars made from the sun. As mentioned earlier, the sun provided the plant with energy and the plants converted that energy into sugars.

Instructor: What do [plants] do with the sugars? How do they help the plant? Like why would the plant make sugars? Do you have any idea?

Austin: I forgot what it was for.

... Austin: I think it’s also for animals when they make their fruits and stuff, animals like it. They can spread the seeds other places.

After a period of uncertainty, Austin concluded that the plant made sugars to provide something that animals needed. This response reflects teleological reasoning.

Austin had a naïve understanding of respiration. He stated several times that humans need oxygen; however, he did not reveal an understanding of the connection between the intake of oxygen and the break down of glucose or the degradation of energy. Austin concluded that if an organism needed oxygen, the byproduct was
carbon dioxide. His statements revealed that he understood the production of oxygen as a gas exchange cycle, rather than as a byproduct of photosynthesis.

**Initial Ways of Understanding Decomposition.** Austin did not attribute decomposition to the decomposers (for example, bacteria). Rather, he believed organisms decomposed, and then this “decomposed stuff” constituted food for the bacteria.

Austin: The algae. It decomposes and then the bacteria either, yeah the bacteria, either the bacteria or yeah, it just becomes, cause it says here, organic nitrogen eventually breaks down into oxides of nitrogen.

... Instructor: How does the plant breakdown.
Austin: Over time I guess. Or with the help of the bacteria.

There are numerous statements in which Austin refers to organisms decomposing and then the bacteria using the decomposed debris.

**Austin’s Initial Ways of Thinking**

Austin’s statements during his interview and his first two lessons provide evidence that Austin’s reasoning can be characterized as perception-based. His statements suggest that he considered only one dimension when trying to account for the functioning of closed systems, and his explanations reflect a focus on the needs of each object in the system. Furthermore, there is evidence to support the notion that Austin harbored teleological reasoning.

**Example 1: One-dimensional relating.** Austin revealed during his interview his understanding that living organisms are composed of elements; however, he did not make any connections between the interrelationships of organisms in a system and
their constitutive elements. For example, Austin stated that plants were necessary for humans. When asked what humans gain from eating plants, he cited vitamins and minerals. He seemed unsure when pressed further, adding antioxidants and fiber, and concluded with the statement that plants keep us healthy. There was no suggestion of any elements being transferred from plants to animals.

Similarly, in the third lesson, the class was trying to account for why the sphere community survived without brine shrimp. When looking at the data, Austin was surprised to discover that the levels of ammonia decreased to zero. His statements suggest that he assumed that, with no ammonia, there was no nitrogen in the system. Austin considered this “weird” because he believed that other species in the sphere would need nitrogen. Austin reasoned that, because there was no ammonia in the water, other organisms would not have access to nitrogen. Austin did not make connections between the composition of organisms, the consumption of organisms, and the transformation of elements, even though he demonstrated an understanding that organisms were composed of “CHONP” (carbon, hydrogen, oxygen, nitrogen, phosphorus). Austin instead concluded that without ammonia, the organisms would not have access to nitrogen.

Example 2: Ad hoc explanations. Austin’s accounts were constrained only by what made sense to him at the time. At one point, his partner, Franjelica, suggested that if there was no ammonia in the water, then the heterotrophic bacteria must not be making it. Austin insisted that they could:

Franjelica: Um. But if we lose ammonia, then they can't be making ammonia for the nitrifying bacteria.
Austin: Yes they can.
Franjelica: How?
Austin: Like, they make it.
Franjelica: But if there is no ammonia in the water-
Austin: -there is organic nitrogen.

Here, Austin argues for ammonia production because he needed ammonia to be in the system in order for his explanation to make sense. His explanation was not constrained by the data, which specifically listed ammonia concentration in the water as zero.

Similarly, during his interview, while discussing how waste cycles on earth,

Austin offered ad hoc explanations for what might happen to urine on earth:

Austin: Well there's the plants that filter it, I think. There is plants in the water so they filter that. And they, I know in the ocean, the salt kind of cancels it out or something.
Instructor: So you said the plants filter, what do you mean by filter? …
Austin: They probably use some of the nutrients. The, the like nitrogen in, probably in the pee. Or something like- they use that. And so they take it out of the system, put that inside themselves, they use it, and then take something out. I think that's what it is, I'm not exactly sure.

When pressed, Austin added a statement about something being transferred between animal waste and plants; however, he was not confident about his claim. Furthermore, Austin did not seem to connect plants’ need for soil with the feces of organisms in a community. These statements indicate that his explanations were constrained only by what made sense to him at a particular point in time.

Example 3: Focus on objects. During his interview, as Austin discussed how each entity in the space station (humans, plants, animals) would survive, he proposed either bringing the necessary supplies up to the station or a machine that would supply what was needed. For instance, when asked about the needs of plants, Austin stated
that plants needed sunlight, water, and soil. He then noted that they would also need oxygen, and he suggested that large tanks of oxygen be brought to the station.

Austin: … There is no oxygen up there, is there? So they’re going to have to take huge tanks.
Instructor: Okay, so if they take tanks up, will they have to take 15 years worth of tanks?
Austin: That’s a lot. I don’t know, I guess they can do that.
Instructor: Is there any other way, um, they could get oxygen.
Austin: Well, recycle the ones they have. Like people who are carbon monoxide, yeah, whatever we expel, they could recycle that. So they don’t have to take that much.
Instructor: So would they do that mechanically or is there another way they might be able to recycle?
Austin: Mechanically, (shakes head) I don’t know how.

Here Austin proposed that something could be used to convert what humans expel back into oxygen. The idea that plants can play this role did not occur to him yet. Only later when Austin was asked about how the oxygen on earth is recycled did he change his mind:

Instructor: Okay. How does that happen on earth?
Austin: Ohhh, humans. We expel- oh. [plants] don’t need oxygen. WE need oxygen. They need carbon monoxide. I think that’s what it is. Carbon dioxide? Carbon dioxide!

…
Austin: So yeah, we use oxygen that the plants bring out, and then we expel carbon dioxide and then (they) use that. So humans and the plants all work together.

In these explanations, Austin focused on the objects he could “see” to account for the functioning of the sphere. Austin’s references to oxygen suggest that he understood oxygen as an input for an organism, rather than as an element cycling within a system.

Similarly, during lesson two, while Austin and his group discussed why the Ecosphere was able to function for a long period of time, Austin focused primarily on
accounting for how each organism was able to stay alive and what each organism contributed.

Austin: Okay, right now the only thing that is not benefiting is the algae. So they need some how to keep living. Bacteria probably does that somehow. I don't know.

Austin was interested in figuring out what each species did for the other organisms in the sphere. He offered various ideas to account for the role of the bacteria, for example, keeping the sphere clean/clear by neutralizing the waste of the brine shrimp, or providing nutrients for the algae; however, he was not confident about any of the roles he suggested. After offering one idea, he added, “I don't know, the bacteria have to do something.” By the end of the lesson, Austin concluded that the role of bacteria was to keep the sphere clean. Austin accounted for the role of each entity in terms of how it helped another species survive, as opposed to considering processes within the system.

**Summary of Austin’s Initial Way of Thinking.** Much like Franjelica, Austin’s explanations of phenomena focused on accounting for the objects he observed. His focus on what each object did within the sphere reflects teleological reasoning. His explanations suggest that he viewed each species as having a purpose—to provide other species with something they needed. For instance, it was unclear from one discussion whether Austin believed that the bacteria became cleaners because the algae and shrimp needed a clean sphere to survive; or whether bacteria were placed in the sphere because they were good cleaners. In either case, there was no evidence to
suggest that Austin understood bacteria as having evolved the ability to decompose waste because it benefited the bacteria.

Also like Franjelica, Austin reasoned at only one level most of the time. He did not make connections between the composition of organisms and what they consumed when accounting for the functioning of the system. This lack of connections between molecular composition of living things and their interrelationships resulted in ad hoc explanations to account for observations.

A unique aspect of Austin’s way of thinking was revealed during his interview when he discussed and explained the functioning of a self sustaining space station. Austin suggested that all the resources, including gases, be shipped to the station. His explanation did not incorporate ideas about the cycling of anything in the station. When asked to consider these resources on earth, it became clear that Austin had gaps in his ways of understanding many of the matter cycling processes on earth.

Finally, several of Austin’s statements reveal that he relied on recall to generate explanations. For example, when asked where plants get their energy from, Austin replied with sun, soil, oxygen, and water, then later admitted that he could not remember what he had previously learned: “It’s all just diagrams somewhere. … But I forgot it” (interview). Later, the interviewer asked why plants need carbon dioxide: “I don’t know, they just absorb it and use it.” These statements indicate that Austin was relying on recall rather than an understanding of the relationship between the composition of a plant and gases such as carbon dioxide. Figure 15 provides a summary of Austin’s initial ways of understanding and thinking.
INITIAL WAYS OF UNDERSTANDING

*Energy converts to matter
*Organic matter decomposes spontaneously
*Plant mass comes from soil, water & sun
*Respiration is the exchange of oxygen and carbon dioxide
*Humans comprised of six elements

INITIAL WAYS OF THINKING

*Focus on inputs and products of organisms
*Ad hoc explanations
*One-dimensional relating
*Simple linear relating
*Teleological reasoning

Developmentally Interdependent

Figure 15: Austin’s initial ways of understanding and thinking

Changes in Austin’s Ways of Understanding

Changes in WoU Matter and Energy Transformation. Initially Austin did not appear to understand the distinction between matter and energy. In lesson five, Austin began discussing different forms of energy. At one point, Franjelica suggested that energy was lost when transferred, and Austin added that it was lost as heat. Later, when questioned by the instructor, he identified heat as an unusable form of energy.

Instructor: Okay, I take the plant, I put it in the sun for two weeks, I take it out of the sun, I put it in the box and I put a heater in the box with it. In ten years, will it be alive.
Austin: Heat. No. Because that heat doesn't spontaneously turn into energy I think. Its just heat, you can't do anything with that.

By lesson six, Austin demonstrated an understanding of the distinction between matter and energy. He stated that matter cycles but energy does not. According to Austin, bacteria convert one form of matter to another form of matter.
Franjelica: So bacteria, bacteria are happy little matter converters, aren't they?
Austin: Oh yeah, they convert from one form to another form of matter.

Austin reiterated several times his understanding that bacteria converts matter.

When a group member suggested wind power converting to electrical energy as an analogy for bacteria, Austin disagreed because “these are different kinds of energy” and bacteria convert matter to matter. Austin later suggested that the wind power analogy would be an appropriate analogy for algae, instead of bacteria, and suggested an oil refinery as the analogy for bacteria.

Austin: Okay, for our bacteria, we said that an oil refinery would be a good example because you have the petroleum from the fossil fuels. One huge form of energy, lots and lots of energy, but its not exactly usable in cars or whatever. So an oil refinery converts the petroleum into gasoline, or diesel, or oil, or whatever it needs. Which is the same as the bacteria. They get either organic or inorganic and then converts it into another form, and also chemical energy that can be used in whatever (?). And yeah, that's bacteria. (5/4)

When Austin mentioned chemical energy, he was likely referring to a change in chemical forms because he later stated that “for bacteria, we said [a good analogy] was the factory because (pause) it converts one form of chemical into another form of chemical.”

In a subsequent lesson, Austin identified and labeled the arrows in a food web as “transfer of energy”. When he drew a diagram of the transfer of energy, Austin created boxes that decreased in size to represent the loss of energy in the transfer. Austin stated that the arrows represented transfer of energy and the squares were
blocks of energy. The group defined food as “energy in packages,” and later Austin wrote on his paper, “food is a usable source of energy and nutrients.”

Changes in WoU Photosynthesis and Respiration. In lessons six and seven, Austin began to develop an understanding of respiration. He defined aerobic respiration for the class as “using oxygen to break down glucose.” He later added that plants get their energy by breaking down glucose. This contrasts with his initial way of understanding because he originally stated that he did not know what plants did with the sugars they created. Austin also understood that some bacteria respired for their energy needs.

It was difficult to determine whether Austin’s way of understanding photosynthesis had changed by the end of the course. Austin had not demonstrated an understanding that the mass of a producer comes primarily from carbon dioxide; however, he did seem to understand that plants use the sun to create sugars, and that these sugars were broken down to provide energy for the plant.

Changes in Ways of Understanding Decomposition. When Austin began the teaching experiment, he viewed bacteria as cleaners of the sphere and believed that organisms would first decompose and then be consumed by the decomposers. Austin made several statements throughout the last five lessons that suggest he changed his way of understanding decomposition. By the end of the teaching experiment, Austin understood bacteria as both consumers and recyclers in a system. For example, in lesson ten Austin stated: “And then the organic molecules go to the decomposers who turn them into inorganic molecules through decomposition. And then they provide that
for the photosynthesis.” Austin understood that the decomposers did the actual decomposing of the organic waste. Furthermore, he understood bacteria as transformers of matter.

**Analysis of Changes in Ways of Understanding.** The changes in Austin’s ways of understanding are summarized in Figure 16. Over the course of the ten week teaching experiment Austin developed a way of understanding the distinction between matter and energy; he understood that matter cycled and that energy flowed through systems. He identified organisms as matter converters. He also understood decomposition as the breakdown of organic matter into elements and he identified the role of decomposers in this process. Austin developed an understanding that respiration involved the use of oxygen to breakdown glucose. Finally, he understood photosynthesis as the process of plants using sunlight to create glucose that is then broken down by the plant to release energy.

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**Figure 16:** Austin’s ways of understanding before and after instruction
Changes in Austin’s Ways of Thinking

Identifying changes in the ways of thinking that governed Austin’s accounts of phenomena was more difficult then for Franjelica for two reasons: 1) Austin did not speak during group discussions as often as Franjelica, and 2) Austin’s ways of thinking did not appear to reflect as many characteristics of model-based reasoning as Franjelica’s had. The characteristics exemplifying Austin’s early explanations included an object oriented focus, ad hoc explanations, one-dimensional connections, and teleological reasoning. Additionally, the cycling of resources (solids, liquids, or gases) was noticeably absent from his account of a self sustaining system. I provide evidence of a change in his way of thinking associated with explaining over the span of three lessons below.

Example 1: Cyclical causal relating. During the third lesson, Austin and Franjelica were trying to account for the source of nitrogen in a sphere with no brine shrimp.

Austin: Decomposing organic debris. No, well yeah. [Heterotrophic bacteria eat] the decomposing algae, and then, I'm sure they are the ones who make, nitrifying bacteria makes the oxides, cool. Okay.
Franjelica: Yeah, well like once, yeah, once, if this decomposes the algae, which is the carb- eh, bad, it will make it into ammonia, nitrifying gets it back into NOx, which-
Austin: Is what we are saying.
Franjelica: -this uses again.
Austin: Yeah. So there we go. That's a cycle.

Although they came to an incorrect conclusion, Austin seemed pleased that they had created a cycle and later referred to this conclusion as the nitrogen cycle. Once Austin
identified that more than one species had a need for an element, he appeared to change his focus from what the object in the sphere did for the other objects, to how the element was recycled in the community.

Later in the same lesson, Franjelica and Austin began to consider tracing elements through the entities in the system as they tried to account for the inputs of each species.

Austin: Um, so we should do it molecule by molecule? Like element by element? Okay?
Franjelica: Or we can just do like,
Austin: System by system. Bacteria did this.

Here, Austin considers the different ways to account for each species and each element. Later he summed up the group’s explanation:

Austin: Okay, without the shrimp…. Okay, so first we should say, okay, if the shrimp dies, there is, the, um, ammonia is going to lower. And therefore the nitrifying bacteria will die, because they need it for energy. So that is the first thing before we even establish the others.

…

Austin: Okay. And, okay, so now we have that. And we are just going to say that nitrifying bacteria is not necessary because we still have heterotrophic bacteria. Okay. So that's that. Okay, so now we have to do the cycle. Okay. Mmm (pause) so the algae decomposes into oxides of nitrogen, NOx. Ah, the, what does heterotrophic bacteria use? (Looks in handout). Nutrients from decomposing or- Okay so, "they generally obtain their nutrients from decomposing organic debris." So heterotrophic bacteria get their nutrients from this decomposing algae. So that's how they live. Um, okay. And then, what's the other thing we are missing? We have bacteria, what else are we missing?

Austin concluded by stating that the two species, heterotrophic bacteria and algae, “keep supplying each other forever.” Austin was considering the need for the nutrients to cycle through the organisms in the sphere, indicating that he was beginning to
consider cycling and recycling as an important process in the functioning of the sphere.

**Example 2: Multi-dimensional relating.** Austin was the first group member to introduce “CHONPS” as the six essential elements humans need (carbon, hydrogen, oxygen, nitrogen, phosphorus, and sulfur). In lesson five, when the group tried to account for what happened to the bacteria after they died, Austin proposed that bacteria was probably also made of “CHONP.” This statement reveals that Austin was beginning to consider interactions between organisms at the level of elements, rather than the exchange of food or nutrients.

Also in lesson five, as the group was diagramming the role of light in the sphere, Austin and Franjelica began to discuss the conversion of matter.

Austin: And then the shrimp goes to the nitrifying. (pause) From the shrimp to the nitrifying is it organic to inorganic?
Franjelica: It’s um, inorganic, then nitrifying makes it organic, so the heterotrophic can make it inorganic again.
Austin: But from here to here it’s organic?
Franjelica: Its inorganic, its ammonia.
Austin: It’s inorganic? Okay.
Franjelica: Like, ’cause it’s waste.

Although Austin was incorrect about the shrimp waste being organic, he considered matter conversions rather that just inputs and products of species. (The confusion about the roles of the two types of bacteria was cleared up later in the lesson.) After Austin and Franjelica further discussed the role of each bacteria species, Austin added, “so here we are providing what each one provides for the environment. Or for the next step in the ladder, in the cycle?” Such a statement confirms that Austin was beginning to consider processes in the system and cyclical relationships.
Summary of Changes in Austin’s Ways of Thinking. Figure 17 provides a summary of the changes in Austin’s ways of understanding and thinking. The transition from a focus on what each species does for the sphere, to the cycling of matter in the system, was markedly observable in Austin’s explanations throughout the teaching experiment. The two examples above provide some insight into the evolution of this transition. Recall that during his initial interview, Austin did not consider cycles of any type in his discussion about how a closed system should be designed (see Example 3 in “Initial Ways of Thinking”). The evidence provided here shows that Austin was beginning to view the relationships among species through the context of the cycling of elements. In addition, there were several instances when Austin stated the importance of decomposers in the conversion of matter, exemplifying his understanding of the importance of the cycling of matter in the functioning of a biological system. These statements suggest that the transformation of matter may have been a lens that Austin was beginning to develop to make sense of the functioning of a biological community.
Figure 17: Changes in Austin’s ways of understanding and thinking

Nevertheless, when Austin presented his explanation and diagram of the functioning of a typical marine community to the class during lesson ten, his statements reflected some persistent naïve ways of understanding.

Austin: Okay, for the first one we called it photosynthesis system, or normal. I guess. Just outside.
Instructor: Okay.
Austin: So first the sun is a source of energy and it provides all the energy needed for the plants, the producers to produce the, in photosynthesis, whatever that the consumers are going to eat.

... Austin: So then the consumers use (?) produce glucose, whatever, and then through respiration they produce organic molecules.
Instructor: Okay.
Austin: And then the organic molecules go to the decomposers who turn them into inorganic molecules through decomposition. And then they provide that for the photosynthesis.
Instructor: So the consumers produce organic molecules. Do the producers produce organic molecules also?
Austin: I would think so, yeah.

Several statements in this excerpt suggest that Austin still harbored naïve understandings. He attributed respiration to consumers only, and asserted, “Through respiration they produce organic molecules.” He also stated, “Organic molecules go to decomposers.” The instructor interpreted this phrase to mean organic debris but that may not be what Austin intended. He may have thought that the consumer rather than the producer, constructs organic molecules. Austin did mention, however, that the byproduct of the decomposer does return to plants for photosynthesis, representing a slight change in his initial way of thinking, as described earlier.

**Student 3: Analysis of the Evolution of Rachel’s Ways of Understanding and Thinking**

Of the three students observed in the teaching experiment, Rachel participated the least. There were several lessons in which she contributed significantly less than Franjelica or Austin. As a result, it was more difficult to identify changes in her ways of understanding and infer changes in her ways of thinking. Nevertheless, many of the changes I identified in Franjelica and Austin’s ways of understanding and thinking were also evident in Rachel’s statements.

**Rachel’s Initial Ways of Understanding**

Initial Ways of Understanding Matter and Energy. Rachel’s initial ways of understanding matter and energy were difficult to discern because Rachel rarely
referred to any form of matter or energy when explaining the functioning of a biological system. Rachel introduced energy during the interview in the context of food for humans. For Rachel, food provided “nutrition, energy, to go about and function.” She added later that fats and carbohydrates provide basic energy for humans, and that plants produce energy for themselves.

Rachel interpreted cycles in nature as who eats whom, or as the gas exchange of carbon dioxide and oxygen between plants and animals. Rachel responded with embarrassment when asked to talk about the cycling of oxygen and carbon dioxide on earth: “Um (pause) oh god, there's like cycles they go through and I can't remember a single one of them [uncomfortable laugh].” Rachel’s statements during the interview and the first two lessons suggest that she did not have a clear understanding of the cycling of elements on earth, but she acknowledged that they were recycled.

When discussing the composition of animals, Rachel mentioned carbon, but only after the interviewer pressed her to articulate what fats, carbohydrates, and proteins were composed of.

Instructor: So fats, carbs, and proteins. What are those made up of? Any idea?
Rachel: Ah, god they all (pause) carbon chains (laughs). Oh my gosh. Um, ah, let’s see. Carbohydrates. Ah, I guess sugars for carbohydrates. I would say lipase but I think that is an enzyme for fats. Um, lipids I guess would be more carbons, I don't know. But they’re all organic molecules? That's pretty much all I know.

Rachel added that organic molecules were carbon chains and “whatever group is attached to it.”
Initial Ways of Understanding Photosynthesis and Respiration. During the interview, Rachel was asked what plants need to survive (see chapter 1, first example). She responded first with sunlight and then with nitrogen fixing bacteria; however, she could not explain what these bacteria did for the plant. Rachel later added that plants also need gravity “because of the xylem and phloem,” water, and fertilizer. Rachel described fertilizer as nutrients for plants, but, when considering the space station, she stated that fertilizer had to be shipped in. She did not make a connection between the waste available from humans and the plants’ need for fertilizer.

Rachel’s understanding of photosynthesis was also limited:

Instructor: So if I throw out the word photosynthesis, what does that mean to you?
Rachel: It’s just scary for me that I don’t know because I just learned it last year.

…
Rachel: Um, gosh. Okay, so let’s see. They go through like cycles produce energy for themselves. There’s glycolysis and the Krebs cycle I think. Good god. It’s really sad. I have to read my book. (laughs) Um, okay, so…

Rachel continued by describing photosynthesis as the process by which plants take in sunlight, it travels to the chloroplasts and chlorophyll, gives the plant ATP, and oxygen is released as the end product. She added that plants need carbon dioxide, but understood the intake of carbon dioxide as a different process from the one she had just described:

Rachel: Um (pause) so okay, so [plants] take in our carbon dioxide too. And somewhere in there is the same thing. They take in the carbon dioxide and they get the energy they need and they give off oxygen.
Note that in this process oxygen is also released, but from her description, it is a different process from photosynthesis. When asked why the plant might need carbon dioxide, she responded with, “I wish I remembered. I really do.”

Rachel did not relate the breaking down of food with respiration. While trying to account for the source of carbon dioxide in lesson two, Rachel decided that carbon dioxide must come from the shrimp because the shrimp “inhaled” oxygen. She understood oxygen and carbon dioxide exchange in animals and plants as respiration, but did not associate this with the breakdown of “food”.

Initial Ways of Understanding Decomposition. Just as with Franjelica and Austin, for Rachel, organic objects decompose, but it is not specifically the bacteria that do the decomposing. For instance, in lesson three, Rachel claimed that bacteria clean up the sphere—that is why it is not cloudy. There was no mention of bacteria as the decomposer. Rachel stated only that organisms in the sphere decompose: “[Algae] decomposes. It gives off nitrous oxides. And the organic debris is food for heterotrophic bacteria.” Note that Rachel says, “[algae] decomposes” rather than clarify that the bacteria decomposes the algae. Her follow up statements suggest that she believes that once the algae decompose, the debris then provides food for the heterotrophic bacteria. This idea that organic material decomposes and then the bacteria consume them is reiterated several times.

At one point in the interview, Rachel proposed the idea that bacteria might play a role in replenishing soil after the nutrients are used up by crop plants. She introduced a compost pile as an example.
Rachel: I'm pretty sure that's the bacteria. Not THE bacteria but some sort of bacteria. Like you put in like banana peel. You put it into your compost pile. And then eventually the bacteria gets to it and it decomposes into whatever it decomposes into. Whatever the basic state is. And it goes back into the soil and I guess that’s where it provides the nutrients and it helps.

She defined biodegradable as something that gets decomposed and goes back into the earth. Again she added that bacteria play a role.

**Rachel’s Initial Ways of Thinking**

Of the three students analyzed in the teaching experiment, Rachel’s initial ways of thinking were the most difficult to infer because they were inconsistent. For instance, in one context she revealed multidimensional relating, where in other contexts she seemed only to be able to consider the organismal level. Her accounts tended to focus on objects she observed, and she identified only linear causal relationships.

**Example 1: Focus on objects.** Rachel explained the functioning of a self-sustaining space station by considering each entity in the system separately. She began by discussing the “machines” that would be required to meet the needs of humans on the station. She focused on meeting those needs technologically, rather than creating a self-sustaining system. Rachel suggested that the station would need an air filtration system (described as a way to convert carbon dioxide to oxygen), a machine to recycle urine, and a sanitation system for waste. Rachel’s focus on “mechanical” ways to recycle reflected a focus on macro-level events (for example, providing for the needs of plants and humans), rather than a focus on the processes that maintain a self-sustaining system.
While discussing the purpose of plants on the station, for example, Rachel deemphasized their role in the recycling of gases.

Rachel: No, well, I guess [plants] would also be part of the um system in providing oxygen I suppose, depending on how many you have and how big they are and how efficient they are at converting carbon dioxide to oxygen. But,
Instructor: Okay.
Rachel: Um, possibly primarily they might be used for space study but the secondary reason would be to provide this oxygen….

For Rachel, plants on the space station were primarily used for research, and only secondarily for gas exchange purposes. According to Rachel, a machine would be required to convert carbon dioxide into oxygen, and to extract oxygen from other materials in the station, in order to meet the demand for oxygen.

Example 2: One-dimensional relating. Rachel’s accounts reveal that she primarily focused on macro-level events, as in the example above, yet in one specific context she made connections to underlying micro-level interactions. During the interview, she began discussing how the nutrients in the soil of crop plants could be replenished. In this context, she was “pretty sure” that bacteria break down “compost” into its “basic state.” Her statements imply that she understood that organic compounds break down into elemental forms; however, when asked later in the interview about the composition of plants, she only mentioned cells. In fact, she seemed embarrassed that she did not know the composition of plants. Only when she discussed the composition of humans did she mention elements such as calcium and carbon, but then, only after she was pressed to consider the composition of fats, proteins, and carbohydrates. These statements indicate that Rachel reasoned primarily
at the organismal level. The exception in this case was when she discussed crop rotations. It is plausible to conjecture that her way of understanding within that context allowed her to make connections to microscopic level interactions.

**Example 3: Simple linear relating.** As previously stated, when Rachel and her group developed an explanation for the functioning of the Ecosphere, they considered each entity in the sphere separately. The entire group tried to account for the role of each species by considering what it “does.” Early in the discussion Rachel specifically asked, “What does algae do?” and “What eats algae?” As the group discussed the role of the shrimp in the sphere, Rachel asked if the shrimp affected the algae at all. Her inquiry suggests that she was focused on accounting for each individual species’ needs, not the interrelationships among all of the species.

Near the end of lesson two, the group discussed what would happen if the algae were removed from the sphere.

Rachel: Okay, so the nitrifying bacteria would not function. What about the heterotrophic? They need oxygen too. Well [nitrifying bacteria] can't reproduce without oxygen. [Heterotrophic bacteria] can't decompose. So, so if [nitrifying bacteria] needs carbon, do they get it from [heterotrophic bacteria]? Cause [heterotrophic bacteria] reproduce every twenty minutes. So, would, you said they probably had a short life span. And so these nitrifying would probably eat the dead heterotrophic.

Again Rachel considered each species separately and how each would be affected by a loss of oxygen. Her simple linear causal reasoning about the effect of a loss of oxygen led her to incorrectly conclude that the nitrifying bacteria would consume the dead heterotrophic bacteria, even though she had previously discussed nitrifying bacteria’s
source of carbon. Further, the fact sheet to which she referred specifically stated that the nitrifying bacteria cannot breakdown organic material.

**Summary of Rachel’s Initial Ways of Thinking.** Rachel tended to focus on macro-level phenomena such as waste accumulation and the need for water and oxygen when explaining the functioning of a self-sustaining system. During her interview, Rachel’s approach to providing for the needs of plants and animals with mechanical systems revealed that she was not thinking about molecular level processes such as matter cycling and energy flow in systems, nor was she considering the interrelationship between all the entities present.

Rachel’s statements reflected limitations in her ways of understanding the relationship between the needs of organisms and molecular level processes. For example, it is likely that she did not make the connection that the wastes from humans could be used as fertilizer to replenish the soil for plants because she did not understand that plants and animals were composed of similar elements. Nevertheless, when she introduced the topic of crop rotation, Rachel discussed the need for organic compounds to break down in order to replenish the soil. She attributed the recycling of nutrients in soil to bacteria, demonstrating some understanding that bacteria convert matter into a usable form for another species. More importantly, in this context she considered the cycling of matter as an important process to explain the functioning of crop-land, indicating that she had made connections between the organismal level and the underlying micro-level interactions. In this case, the context of the discussion
greatly influenced the connections she made between different levels of organization and biological processes.

Finally, Rachel’s accounts indicate that she applied simple linear causal reasoning to explain relationships between species. Figure 18 provides a diagram summarizing Rachel’s initial ways of understanding and thinking.

![Diagram](image)

**Figure 18:** Rachel’s initial ways of understanding and thinking

**Changes in Rachel’s Ways of Understanding**

Changes in Ways of Understanding Matter and Energy. Evidence from the last five lessons indicates that Rachel developed an understanding of the difference
between matter and energy. For instance, in lesson five Rachel stated that when bacteria converted matter from one form to another, this process provided energy for the bacteria. Later, as the group tried to identify an analogy for bacteria, she objected to the analogy the group had developed because it represented energy changing form instead of matter:

Rachel: Yeah, those are, well, one is electric energy, and one is wind pow- wind.
Franjelica: Yeah, that's, you take it can convert wind energy into mechanical energy.
Rachel: We are not having conversion from energy to energy, are we? We are talking about conversion from matter.

As the group discussed the car as an analogy for bacteria, Rachel again discussed matter as something that changed form.

Rachel: Well if you just look at the products and the reactants, it takes the hydrocarbons and just switches it to carbon monoxide and water, or whatever. So yeah, like you are essentially taking matter, changing it to..
Austin: ..matter also.
Rachel: another form of matter. Like you are taking the liquid hydrocarbon and changing it to [a] gas or whatever.

Rachel’s comments imply that she was differentiating matter from energy.

Interestingly, Rachel appeared to have some difficulty discussing sources of energy. Several times during lesson seven Rachel stated that the producer “created” energy, including during the class discussion: “Well we said that [sunlight, nutrients and carbon dioxide] fuel the process by which phytoplankton create energy.” Yet, during this same class discussion, Rachel also stated that energy can be neither created nor destroyed. Thus, it appeared to be difficult for Rachel to discuss the process of energy transformation in terms of producers and photosynthesis.
Changes in WoU Photosynthesis and Respiration. Rachel’s development of a biological understanding of photosynthesis was gradual. By lesson five Rachel demonstrated an understanding that the plant *used* energy from sunlight rather than gained energy directly. Yet, it was unclear if she understood that the energy the plant used came from the breaking down of glucose—that sunlight provides the energy needed to produce glucose. For example, during the fifth lesson, the group was considering the car analogy for the algae:

Rachel: As far as the algae goes, um (long pause) I suppose the algae could work as. Well, not really because we are not looking at the hydrocarbons as a form of energy, right? We are looking at it as a source of energy. So two different things. So not quite like-
Austin: So the hydrocarbons are comparable to light?
Rachel: the sun.
Austin: The sun yeah.
Rachel: The sun. And then the energy that they get, is, its, well. I guess the light because the light helps produce energy. Not, it doesn't actually give (pause) /energy.
Austin: It helps (pause)
Rachel: It helps produce the energy, right?
Austin: Yeah.
Rachel: It doesn't actually give the energy?
Austin: No, no. /They don't use (?)
Rachel: Okay so then it can be comparable to light.

Rachel’s comments signify that she was confusing sunlight with a source of energy for the producer. Note that Rachel began by making a correlation between the sun as a source of energy for the producer and the hydrocarbons as a source of energy for the car. At that point, she recognized her error: “It doesn't actually give (pause) energy,” a statement she followed with a question to her group to help confirm her suspicion that the sun does not actually give the energy to the producer. She incorrectly concluded, however, that the sun can be correlated with the hydrocarbons in the car.
Her confusion suggests she had not yet developed a biological understanding of respiration in producers. From a scientific standpoint, hydrocarbons can be correlated with glucose in the analogy: they are broken down by the producer for energy. But for Rachel, hydrocarbons provide a source of energy for the car just as light is a source of energy for the plant. Sunlight, however, only provides the energy to produce glucose. If the plant cannot make glucose, the plant will not have energy to sustain itself, regardless of how much sunlight is available. Rachel’s way of understanding sunlight as energy directly for the plant prevailed throughout the lesson. At the end of the lesson, during the class discussion, Rachel again made a correlation between the sunlight and the gasoline much to the frustration of one of her group members.

By the sixth lesson there was evidence that Rachel was further developing her understanding of the process of photosynthesis. One of her group members proposed to the instructor that carbon dioxide provided energy for phytoplankton. Rachel disagreed:

Instructor: Carbon dioxide provides energy for phytoplankton. Is that true?
Austin: Kind of.
Rachel: No.
Franjelica: Carbon dioxide is- Rachel: -a key element in creating energy.

Rachel rejected the idea that carbon dioxide provided energy directly for the plant. Several times Rachel used the phrase “fuels the process” to describe the role of the sun, yet followed those statements with comments such as, “[carbon dioxide] is the basic building block of its energy source.” These and other statements from Rachel
indicate that she was developing an understanding that carbon dioxide and nutrients are used by producers to make something that the plant uses for energy. Yet her statements did not demonstrate an understanding that producers use carbon dioxide, water, and sunlight to create glucose, and that glucose would be broken down by the plant to release energy.

**Changes in Ways of Understanding Decomposition.** Initially, in the context of explaining the functioning of a closed system, Rachel did not associate decomposition with organisms. By the fifth lesson, however, Rachel had developed an understanding that bacteria were the organisms that did the decomposing:

Rachel: The decomposition releases the nitrous oxides and then whatever nutrients the bacteria takes from the dead algae is the food for this bacteria. Um, it requires the [oxygen] to be decomposed and the [oxygen] comes from the algae.

Here, Rachel refers to the action of the bacteria as the decomposers. The algae do not decompose to then be consumed by bacteria, but rather, Rachel states that nutrients are taken during the decomposition of the algae by the bacteria. There were several subsequent statements in which Rachel associated bacteria with the act of decomposing.

**Analysis of Changes in Ways of Understanding.** Initially, Rachel revealed limited understanding of how elements cycle on earth. However, when explaining the functioning of a biological system, she did not refer to matter cycles or energy. By the seventh lesson, Rachel had developed an understanding of the differences between matter and energy, and that, as an organism changes matter from one form to another, this releases energy for the organism.
Rachel did not appear to understand the relationship between a plant’s need for carbon dioxide, the process of photosynthesis, and the cycling of gases between plants and animals during the interview or first two lessons. Instead, she relied on recall to remember the role of different biological processes and mechanisms, and expressed embarrassment that she could not remember things she knew she had learned previously. During the teaching experiment, Rachel developed an understanding that photosynthesis involves the process of using sunlight and carbon dioxide to create something the plant uses for energy. There is no evidence, however, to suggest that she had developed an understanding that glucose is the product produced and broken down by the plant. It was also unclear from the data if Rachel developed a biological understanding of respiration.

During the interview, Rachel revealed two different ways of understanding decomposition. When discussing crop rotations, she stated that the bacteria play a role in recycling nutrients. When discussing closed systems, such as the Ecosphere and the space station, her statements imply that she believed that organisms decompose, and then this decomposed “stuff” provides food for the decomposer. The different contexts resulted in access to different schemes for decomposition and the role of bacteria. By the sixth lesson, Rachel developed a way of understanding decomposition as the breakdown of organic matter into elements and the role of decomposers in this process.

The changes in Rachel’s ways of understanding are summarized in Figure 19.
**Figure 19:** Rachel’s ways of understanding before and after instruction

**Changes in Rachel’s Ways of Thinking**

The characteristics of Rachel’s initial explanations included an object oriented focus, simple linear causal relations, and, in the context of closed systems, one-dimensional relating. Rachel discussed the cycling of elements only in the context of crop-lands. I provide below evidence of certain changes in her ways of thinking from lessons four, five, and ten.

**Example 1.** Throughout lessons four and five, Rachel’s explanations suggest that she was beginning to consider matter cycling as a process underlying the functioning of a closed system. For instance, during lesson four, Rachel began theorizing how the needs of bacteria and algae in the Ecosphere were met as a result of the cycling of matter in the system:

Rachel: Um, we said that when the heterotrophic bacteria decompose it produced carbon dioxide and that’s what the algae use as part of the photosynthesis in um, addition to the sunlight, [to] produce the [oxygen]. Which the heterotrophic bacteria use to help
Rachel’s statement reveals that she was thinking about the cycling of matter in the system: “…other nutrients that eventually went back to the heterotrophic bacteria.” Note also that Rachel referred to the interrelationship between the bacteria and the algae.

Although Rachel was beginning to make connections between the needs of organisms and the cycling of matter in a closed system, these relationships were still developing. Near the end of this fourth lesson, the group was trying to determine why replacing the bacteria with snails caused the system to fail. In this segment, the group had told the instructor that phosphates were part of the problem.

Instructor: So how does shrimp get phosphate?
Austin: From the water? I’m not sure exactly.
Instructor: How do the shrimp get phosphate?
Rachel: I really don’t know.

Earlier, the group had decided that the algae were made up of elements (CHONPS) and that these elements provided the shrimp with what they needed to survive. When asked the question in a slightly different context, however, this understanding was not applied.

Example 2. In lesson five, the students were first asked to consider the car as an analogy for the consumer and then to create analogies to represent the bacteria and the algae. Rachel’s statements suggest that she considered cyclical relationships as she tried to make sense of the car as an analogy for a consumer.
Rachel: Wait, what, okay. So we still put out hydrocarbons, okay, in the car. But how are they used up again? Like we know that energy that we put out is used up in like other forms. Like bacteria decomposes or whatever, but how do the hydrocarbons in the air, how do they [get] used up again.

According to Rachel, the waste from a consumer is recycled back into the system and reused, and bacteria play a role in this cycling. Yet she questioned whether or not car emissions were recycled. Her attention to the differences between the car and a consumer suggests that she was considering the relationships between entities in the system at a microscopic level: consumers’ waste is composed of elements that cycle through other organisms. Rachel asked if the emissions from the car were also recycled. Notably, Rachel used the term energy here instead of matter: “Like we know that energy that we put out is used up in like other forms.” Here, Rachel made the common mistake of assuming that matter is transformed into energy (Anderson, Mohan and Sharma, 2005).

The connections that Rachel made between processes at the organismic scale (consuming food) and the molecular scale (matter cycling and energy flowing) are reflected near the end of lesson five when she shared her group’s idea that the car provides a productive analogy for the consumer.

Rachel: So we eat our food, but we don't use up all our energy that we gain from the food. Say that's what you are eating, five calories, right? But you’re not going to use all those five calories. You are going to lose like maybe three. It’s going to [become waste]. But in um, the biological system, that, those three calories that comes out as waste, its going to get used by bacteria or whatever, and its gonna be used, continue to be used, until it’s used up? Right? But since the car in not 100 percent efficient, it’s gonna give off the hydrocarbons in the end, the hydrocarbons are not going be used
by anything here. So that's why it's not the best analogy, but it also sort of is.

Rachel’s argument, that the consumer’s waste was used by some other organism, indicates that her account was constrained by the principle that matter needs to cycle in a system. Her explanation focused on the cyclical relationships.

Nevertheless, several aspects of Rachel’s accounts reveal that she still held several undesirable ways of understanding. First, although Rachel viewed the consumer as a participant in the cycling of matter, her statements demonstrate that she was only considering the liquid and solid waste of the consumer rather than the gases the consumer expelled. If this is the case, she was not viewing carbon dioxide as a waste product of consumers. This raises the question of whether she understood that the elements in carbon dioxide are used to make up the mass of plants and animals.

Second, the emissions of the car are composed of elements that can be converted to another form of matter. Rachel’s explanation, however, did not suggest that she recognized these gases as elements that are part of the matter cycling. She stated that the emissions of the car “are not going to be used by anything here.” So, although she was beginning to make connections between consumers and matter cycling, she still needed to develop the understanding that gases are also part of matter cycling, a common difficulty for students (Leach, Driver, Scott, and Wood-Robinson, 1996a; Wood-Robinson, 1991).

Finally, her statements cited above reflect a belief that matter gets “used up.” Consumption is a common misconception among learners (Carlsson, 2002a; Reiner and Eilam, 2001). It is unclear whether she thought that the waste used by another
organism is then lost from the system, or whether she thought that it is eventually recycled back into the system.

**Example 3.** In the tenth lesson, when the group members were sharing their understanding of the differences between the hydrothermal vent community and a typical marine community, Rachel demonstrated some understanding that elements within a system cycle.

Rachel: Sun, light, algae, photosynthesis, provides O₂, goes to the little fishy thing which ah, excrete the stuff that the bacteria decomposes and also dying.
Austin: And the bacteria
Rachel: And then the O₂ is also present in the water. And um, the algae dies too and all that marine snow, new word, new phrase, um,
Austin: becomes food for the
Rachel: Bacteria. Becomes food for the bacteria. And um, it decomposes into certain nutrients that the algae needs.
Austin: Yeah. And then that becomes for the plants again.
Rachel: Yeah.

The diagram she created to share with the class included arrows representing the cycling of elements; however, her homework diagram did not reflect any cycling of elements through decomposers.

**Summary of the Development of Rachel’s Ways of Thinking.** Figure 20 provides a summary of the changes in Rachel’s ways of thinking and understanding. The evidence from lessons four, five, and ten demonstrates that Rachel was beginning to make connections between the needs of organisms and the cycling of matter when trying to account for the functioning of a biological system. Recognition of the cycling of elements between organisms in a system implies a consideration of cyclical causal relations. There is insufficient evidence, however, to make any claims about other
characteristics of Rachel’s accounts, primarily because she did not share her ideas to the same extent as Franjelica and Austin during the group discussions. Without multiple comments, statements, and solutions, it is difficult to infer the particular characteristics of her explanations of the various biological phenomena.

Figure 20: Changes in Rachel’s ways of understanding and thinking

Summary of Evidence from the Teaching Experiment regarding Students’ Ways of Thinking and Understanding

Within the current chapter, I have presented the results from one of the aims of the teaching experiment: to determine if building on students’ existing ways of
understanding in ecology leads to development of a desirable way of thinking. More specifically, I sought to determine if helping students develop (a) a way of understanding biologically mediated processes such as energy and material flows, respiration, photosynthesis, decomposition, and (b) a way of understanding the interrelationships among these processes, would lead to the development of characteristics associated with model-based reasoning.

Substantial evidence has been offered to support the claim that the three students developed several of the intended ways of understanding. All three students demonstrated an understanding of decomposers as both “doing” the decomposing and as participants in the recycling of matter, reflecting a change in their ways of understanding decomposition. Furthermore, all three students developed an understanding of the distinction between matter and energy—that matter cycles and energy flows through systems. None of the students demonstrated these ways of understanding in their interviews or during the first two lessons. Explication of the types of situations that created an intellectual need in students to develop these ways of understanding is discussed in chapter 7.

There were differences, however, in the three students’ ways of understanding photosynthesis and respiration at the end of the teaching experiment. Franjelica demonstrated an understanding that carbon dioxide and water were the source of elements for the production of glucose in a plant. She also understood that producers must breakdown glucose in order to gain usable energy just as animals do. Neither Rachel nor Austin demonstrated this same level of understanding photosynthesis or
respiration. Austin understood that plants use the sun to create sugars and these sugars were broken down to provide energy for the plant, but he did not demonstrate an understanding that the mass of the producer came primarily from carbon dioxide. Rachel, on the other hand, understood that carbon dioxide and nutrients are used by producers to make something that the plant then breaks down for energy. Yet her statements did not demonstrate an understanding that producers specifically create glucose or that glucose is broken down by the plant to release energy. I attribute the differences in their ways of understanding photosynthesis to a poorly designed problem situation that I discuss in chapter 8.

Although I did not expect students’ ways of thinking to change from perception-based reasoning to model-based reasoning in the course of ten weeks, I did recognize a number of changes in the characteristics of students’ reasoning as they tried to explain ecological phenomena. By the end of the ten weeks, all three students’ accounts reflected multidimensional relating. The students were making connections between the phenomena of a functioning system, the processes within that system, and matter and energy flow. Franjelica discussed consumers, producers, and decomposers as matter-processing systems. In addition, both Austin and Rachel, who had not considered cycles in their discussions about how a closed system should be designed during their interviews, made connections between the needs of organisms and the cycling of matter when explaining the functioning of hydrothermal vent communities and typical marine communities during lesson ten.
The students’ discussions about the cycling of matter suggest that they were considering processes within a biological system in addition to the objects they could see. They were thus beginning to make connections between macro-level properties and micro-level interactions (Jacobson and Wilensky, in press). Furthermore, attention to matter cycling indicates consideration of cyclical causal relating (Grotzer and Basca, 2003), another characteristic of model-based reasoning. Finally, the students’ explanations of the functioning of a hydrothermal vent community were constrained by a need to account for the cycling of elements (constraint-based reasoning).

This evidence provides support for the assertion that helping students develop ways of understanding biological processes and the relationships between processes at various scales can contribute to students’ development of model-based reasoning. It is important, however, to keep in mind the robustness of students’ initial ways of thinking. Although the students in this experiment began to develop some characteristics of model-based reasoning, several more opportunities for them to reason about the relationship between scientific theoretical models and phenomena would be necessary for these characteristics to govern their accounts of biological phenomena.
CHAPTER 7: RESULTS ON WHAT CONSTITUTES INTELLECTUAL NECESSITY FOR ECOLOGY INSTRUCTION

In DNR in mathematics, problem situations are used to create in students intellectual need. Only through problems can the instructor hope to “stimulate a desire within to search for a resolution or a solution, whereby they might construct new knowledge” (Harel, in press, p. 3). It follows that the only way to create intellectual need in biology learners would be to use problem situations in which the students identify inconsistencies or incompatibilities in their existing understanding, thus creating cognitive disequilibrium and stimulating a desire for resolution. This proposition offers a unique approach to instruction in biology. Problems in biology lessons are usually used only for students to repeat information to which they have already been introduced (see chapter 5). Therefore, what is the nature of biology problem situations that create intellectual need? Furthermore, what does learning look like in an ecology context when instruction is based on the Necessity Principle? This chapter is devoted to answering these two questions.

Development and Implementation of Problem Situations

In the first phase of my research, I constructed models of my students’ current knowledge and conjectured about the types of situations that would help the students see a need for a way of understanding they had not yet formed. Chapter 5 provided data on the models of students’ initial ways of understanding and thinking for the students interviewed. I used these models to develop and refine problem situations to use in the final teaching experiment. An example of the implementation of three of these problem situations and the students’ development of solutions is provided below,
followed by an analysis of the characteristics that likely contributed to the success of these problems in helping students refine or modify their ways of understanding.

In the sections that follow, I present analyses of the students’ interpretations of, and solution processes for, three different problem situations used in the teaching experiment designed to create in students an intellectual need. I include (a) how the problem situation built on my model of students’ biology; (b) evidence to show that the problem was intrinsic to the students; and (c) the students’ solution path to resolve the problem. I chose to present these three situations because the data suggests that, in these particular cases, the students refined or advanced their ways of understanding to be more closely aligned with those held by the biology community. Based on one of the premises of DNR-based instruction, one can only determine if intellectual need was created by observing whether or not the learner refined or developed a way of understanding. The evidence from the experiment reveals that for the three problems discussed below, the students in the teaching experiment developed some of the intended ways of understanding. For this reason, I was able to posit that intellectual need was created.

**Example One: Understanding Organisms as Matter Transforming Systems**

As stated in previous chapters, one of the cognitive objectives for the students was to help them develop multi-dimensional relating—explaining phenomena by relating macro-level properties and micro-level interactions. I conjectured that one way of understanding that might contribute to the development of this way of thinking
is to understand living organisms as matter transforming systems (see chapter 5). Developing this way of understanding was the goal of Problem 1C.

Setting the Stage

The problems given to students prior to Problem 1C were essential in preparing the students cognitively for this problem to create cognitive puzzlement. In Problem 1A, the students were introduced to the Ecosphere and were asked to create an explanation and diagram for why this biological system was able to function for a long period of time (in some cases, over 20 years). All five groups of students in the class primarily accounted for the functioning of the Ecosphere system by focusing on the feeding and gas exchange relationships between the species. For example, the video group claimed that the algae were necessary because they provided oxygen and food for the shrimp. The shrimp, in turn, were necessary because they provided food for the bacteria and carbon dioxide for the algae. Finally, the bacteria were necessary because they provided food for the shrimp. As predicted from my model of students’ ideas about biological systems, all of the groups in the teaching experiment created a cycle to diagram the relationships between species.

After each group shared their diagram with the class, they were given the following question:

**Problem 1B:** A student analyzing the sphere hypothesized that if the algae, or the bacteria, or the brine shrimp were removed from the sphere, the other organisms in the sphere would not survive. Do you agree with this? Why or why not? Explain.

Figure 21: Problems statement 1B
After sufficient time to discuss this question in their respective groups, the students shared their opinions with the entire class. In the case of a sphere with no shrimp (bacteria and algae only), 15 of the 16 students created explanations stating that, in a sphere without shrimp, all the other organisms would die.

These introductory problem situations served several purposes. First, a norm was established in the class such that the students began to understand that they were responsible for their solutions. The instructor did not give the students any feedback as to whether or not their cycles were accurate representations, but rather, she allowed each group to discuss and create their own explanation. Each group was then asked to share their ideas with the entire class and provide some justification for their conclusions. Second, the students gained more confidence in their own conclusions because each group constructed diagrams and explanations concluding that bacteria, algae, and shrimp were all essential to the functioning of the sphere. This provided the opportunity for Problem 1C to create perturbation—brine shrimp are not necessary for the sphere to function. Third, these two problems allowed the instructor to verify her initial model of students’ ways of understanding and thinking. The students did in fact conclude that the shrimp were an essential component of the sphere because they provided the carbon dioxide needed by the algae. Furthermore, the students did not consider decomposers as participants in gas exchange in the Ecosphere. Finally, the problems provided an opportunity for the students to become familiar with the species in the Ecosphere and hypothesize about their relationships. Without this familiarity, the students would not have been able to assimilate Problem 1C.
Problem Statement 1C

As stated earlier, the students brought to the situation an understanding that “things” cycle in a biological system, and the model of students’ biology revealed that the students had a limited understanding that living organisms were comprised of carbon and various other elements. The students, however, did not make the connection that the organisms were participants in the cycling of elements within the sphere. Problem statement 1C was designed to create in the students a need to understand bacteria and the other organisms in the sphere as matter-transforming systems.

Problem 1C: When the algae or the bacteria are removed from the sphere, all the organisms in the sphere do indeed die. However, when the shrimp are removed from the sphere, the sphere is still able to survive indefinitely. The algae and bacteria continue to grow and thrive. Explain why or how this is possible. Be specific.

[Hint: Data on the composition of the sea water over time can be useful.]

Figure 22: Problem statement 1C

Recall that the students had previously decided that the shrimp were a necessary component for the functioning of the sphere. Here they were asked to explain how it was possible for the sphere to function without shrimp. The intent of the problem statement was to cause initial surprise and puzzlement, and then to create a need to understand how the algae and bacteria’s needs were met. Ultimately, the entire situation was designed to create a need in the students to understand bacteria as a converter of matter, rather than just a consumer.
The students were given several data tables to accompany this problem. The data tables provided the water composition measurements over a 100 day period. The first table provided data for an Ecosphere with all of the species included (see Table 3).

Table 3: Ecosphere water composition data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Acceptable Range</th>
<th>Day 1</th>
<th>Day 10</th>
<th>Day 20</th>
<th>Day 30</th>
<th>Day 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>10 - 25 NTU</td>
<td>10</td>
<td>11</td>
<td>13</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>&gt; 5.0 mg/L</td>
<td>6.3</td>
<td>6.6</td>
<td>6.4</td>
<td>6.5</td>
<td>6.4</td>
</tr>
<tr>
<td>Carbon Dioxide</td>
<td>&gt; 2.5 mg/L</td>
<td>3.1</td>
<td>3.5</td>
<td>3.2</td>
<td>3.6</td>
<td>3.1</td>
</tr>
<tr>
<td>Oxides of Nitrogen (NOx)</td>
<td>0.05 - 0.09 mg/L</td>
<td>0.06</td>
<td>0.06</td>
<td>0.07</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>Ammonia (NHx)</td>
<td>0.02 - 0.05 mg/L</td>
<td>0.03</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Organic Phosphorus (P)</td>
<td>0.010 - 0.05 mg/L</td>
<td>0.015</td>
<td>0.02</td>
<td>0.017</td>
<td>0.015</td>
<td>0.018</td>
</tr>
<tr>
<td>Dissolved Phosphates (POx)</td>
<td>0.02 - 0.09 mg/L</td>
<td>0.05</td>
<td>0.05</td>
<td>0.06</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Three other data tables were also provided: water composition data for a sphere with no algae; water composition data for a sphere with no bacteria; and water composition data for a sphere with no shrimp (see Appendix 7). The data for the sphere with no shrimp showed a significant decrease in ammonia over 100 days, while all other measurements were within acceptable ranges. The intent was for the students to use the data to deduce the role of one type of bacteria in the sphere—heterotrophic bacteria. In the following sections, I discuss how the students interpreted the problem and how they came to resolve their cognitive puzzlement.

Students’ Interpretation of Problem 1C

A problem has the potential to create intellectual need in a learner if the learner assimilates the problem, and upon assimilation, he or she experiences a state of perturbation (Harel, 2006). In other words, the learner can form a goal, but is unable to
achieve it. There is evidence to suggest that the students in the video group assimilated Problem 1C. Just a few minutes after reading the problem, Austin restated it: “Wait, the whole point of what we are doing now is to find out why shrimp don't matter?” He then recalled for the group their original conclusions that specified why the shrimp were necessary for the sphere to function. Finally, at the end of the lesson when the group was preparing to present their ideas to the class, the group again restated their goal:

Austin: Okay, so are we going to write this down? So, um, let's see, so we should start with, what are we asking right now?
(Rachel laughs)
Austin: If, how it survives.
Rachel: Yeah, how it survives without the shrimp.
Austin: Okay, without the shrimp.

These statements demonstrate that the students formed a propositional representation for the problem text and situated the problem in a familiar context; thus, they assimilated the problem.

The students’ statements and actions suggest that initially, they could not solve the problem with their current knowledge. The students approached the problem by trying to identify what each species still in the sphere needed to survive. The students’ actions indicate that the obstacle they encountered was an inability to identify where the nutrients that allowed the algae and bacteria to survive came from if the shrimp were absent. The students had not yet deduced that each species must be “recycling” what the other needed if the organisms in the sphere continued to thrive without shrimp.
The Development of a Solution—Developing a Way of Understanding

Several factors contributed to the students’ development of an explanation for how the sphere was able to function without brine shrimp and, ultimately, an understanding of living organisms as matter transformers. In the sections that follow, I identify certain key contributors by summarizing the video group’s learning as they developed a solution.

Appropriate intervention by the instructor. Early in their solution process, the video group began discussing the source of some of the compounds on the data sheets. Rachel decided that she would graph the data while Franjelica and Austin began recording their ideas. The instructor approached the group as they were discussing the source of nitrogen oxides and carbon dioxide.

Franjelica: Okay, we thought that the shrimp gave up carbon dioxide, now we know that there is carbon dioxide in sea water.
Austin: Yeah. (?) in the sea water.

At this point, the group concluded that the shrimp were not necessary as a source of carbon dioxide or nitrogen because these compounds were in the water. The instructor interrupted the group and questioned their conclusion:

Instructor: You said the NO\textsubscript{X} was in the sea water. So if the algae needed the NO\textsubscript{X} and they were taking it out of the seawater, or using it, do you think that the seawater has a never ending source of NO\textsubscript{X}?
Franjelica: Not unless something else is replenishing it.
Austin: Yeah.
Instructor: So then it would die eventually. Cause it would use up the NO\textsubscript{X}. But it doesn't die. It lasts for [let’s say] 1000 years. Explain how.
Austin: So what makes it?
(Instructor walks away)
After the instructor left the group, the students began re-reading aloud some of the information sheets on each species, searching for information to help them identify “what makes” the carbon dioxide and nitrogen oxides.

Discussion. This intervention by the instructor was important and necessary because the students had begun to conclude that the algae and bacteria could obtain the nutrients they needed from the sea water. If the students found this solution satisfying, then they would not have seen the need for bacteria to transform matter and, therefore, would not have developed the intended way of understanding. The instructor’s intervention helped the students to recognize the need to account for a source. Thus, the role of the instructor was important in guiding the learner to understand the insufficiency of their initial solution.

It is also important to note here that the students used the reading as a source of information to help them solve the problem. In this instance, the problem was figuring out where nitrogen oxides might come from. This use of written information to help solve a problem is distinctly different from more traditional reading assignments in biology courses where the students are expected to read for the purpose of recording and memorizing concepts. Here the reading was purposeful for the student because it served as a source of the information sought by the student. The solution however, could not be found within the information sheets.

Building on Existing Ways of Understanding and Thinking. Franjelica and Austin spent a long time trying to discover the source of nitrogen oxides (NOX) in the sphere. They began by recording information about the bacteria and algae from the
information sheets. Through her search, Franjelica realized that both the algae and the bacteria needed similar elements. Austin, on the other hand, could not be distracted from his goal.

Franjelica: Okay, so algae needs light, water, carbon, oxygen, nitrogen and phosphorus. And these guys both all need carbon, oxygen, phosphorus, and nitrogen. So they all need the same stuff. Except for the, yeah, they all need the same stuff.

Austin: Well, yeah, okay. Um. What was the question she asked us? The one, where does the nitrogen, how does it decompose? Was that the question?

Franjelica: How does it renew.

Austin: How does it renew. So /the plants-

Franjelica: /there is some in the water already.

Austin: Yeah.

Franjelica: But if they take it out, then obviously its-

Austin: And we said the plant decomposes. But how does it decompose?

Franjelica: Yeah.

Austin: And we said, was it through the bacteria? Or was it over time? Where is algae? Does it not say?

At this point, it appeared that Austin had more questions than answers. He and Franjelica continued by exchanging ideas in hopes of making sense of the relationships between the species.

Franjelica: Heterotrophic has carbon, all that stuff. And then it says heterotrophic needs organic carbon source, which this is?

Austin: Which one?

Franjelica: Algae.

Austin: Oh, the algae is.


Austin: (Looking at the information sheet) Decomposing organic debris. No, well yeah. [Heterotrophic bacteria] take the decomposing algae, and then, I'm sure they are the ones who make, nitrifying bacteria makes the oxides, cool. Okay.

Franjelica: Yeah, well like once, yeah, once, if [heterotrophic bacteria] decomposes the algae, which is the carb- eh, bad, it will make it into ammonia, nitrifying gets it back into NOx, which-

Austin: Is what we are saying.

Franjelica: -this uses again.
Austin: Yeah. So there we go. That's a cycle.
Franjelica: New cycle.

Here, Franjelica and Austin decided that the algae, which they had earlier agreed was composed of carbon, hydrogen, oxygen, nitrogen, and phosphorus (CHONP), decomposed and provided nitrogen to the heterotrophic bacteria. The heterotrophic bacteria produced ammonia, and the nitrifying bacteria converted ammonia into nitrogen oxide that could be used by the algae. Both Franjelica and Austin seemed pleased to have developed a cycle to describe the relationship between the species; however the resulting cycle was biologically incorrect.

Discussion. As mentioned earlier, the students came to the lesson with the inclination to create a cycle to account for the relationships between species in a functioning biological system. At first glance, it would appear that the students’ desire to create a cycle to explain the survival of the organisms in the sphere was impeding their development of a biological explanation. However, on further inspection, it becomes clear that the students’ desire to create a cycle played a critical role in their development of the desired understanding.

Once the students recognized that both algae and bacteria required similar elements for survival, they began to account for the exchange of these elements between the organisms. In other words, their desire to create a cycle led the students to consider the cycling of the elements between organisms. This was an important step in the process of developing an understanding of bacteria as matter converters. If the students had not come to the problem with a way of understanding that the relationships between organisms are cyclical, the problem may not have led to them to
consider the cycling of elements. So, although the students had not created a biological explanation, they were considering the cycling of elements between organisms, including decomposers. As the students continued to pursue their solution, they became dissatisfied with their new cycle. After sharing ideas with other groups, they eventually created a biologically acceptable explanation.

Presenting and Comparing Solutions. Franjelica and Austin spent much of their time trying to account for the inputs and products of the algae and bacteria. Approximately fifty minutes into the lesson, the instructor asked groups to pair up and share their current solutions. Group one merged with the video group, and together, they began to discuss their ideas. One student shared that her group had been trying to account for the source of phosphorus for the algae. After some debate, Franjelica offered a summary of her understanding.

Franjelica: Yeah (pause), cause we have the, algae is an organic carbon source. And the heterotrophic bacteria decomposes algae. Like we know that part. But um, and so we are just trying to figure out what exactly it decomposes it to. We know it kicks out N, ah, nitrogen oxide. And we know it uses, um, we know it uses the, al- the decomposed algae and the oxygen. And we know it kicks out ATP to fuel itself. And then, more of itself. And also NOx. They're- we're also trying to figure if it kicks out anything else too.

Her final statement suggests that Franjelica and her group members had not yet created an explanation that satisfied all of their questions.

The instructor interrupted the class at this point, and another group paired up with the video group. This second group presented to the video group the manner in which they approached a solution:
Scott: We just decided what were the bare necessities needed for the algae and the bacteria to live, right? And then we just ah, went through all the information we had, and figured out how it can just recirculate among the two organisms.

Scott continued by stating that algae required water, carbon dioxide, nitrogen, and phosphorus; heterotrophic bacteria required organic carbon sources and oxygen; and nitrifying bacteria required ammonia and carbon dioxide. “And then we just figured out ah, how things could ah, recirculate among each other.” At this point, Franjelica posed a question:

Franjelica: How does it recirculate ammonia, if ammonia goes to zero?
Scott: If ammonia goes to zero?
Jan: Only the nitrifying need ammonia to survive. And so, if there is no ammonia, then they don't, we figured that the nitrifying bacteria would die. While the heterotrophic bacteria would continue to live.

... 
Jan: Cause there isn't an abundance of ammonia that needs to be taken care of any more. So if there is no ammonia then there is no need for it.

Jan had proposed a theory that the video group had not considered. Franjelica continued her questioning:

Franjelica: Doesn't the algae need, can nitrifying go the other way? Cause doesn't algae need the nitrogen back?
Scott: Right, right. The thing is that Franjelica: /cause it needs to be ammonia for algae to use it.
Scott: Look at the molecular formula of the algae. It has nitrogen, it has oxygen in it. When it is decomposed by bacteria, all these organic compounds are released. Right? So it’s just like, if something dies in the forest, they tell you about bacteria, they breakdown the body, everything gets put back into the soil (Jan moving her hands around during this explanation mimicking cycling.) Right. So it’s the same thing with this. So what's going to happen is the-
Austin: Once it decomposes?
Jan: Yeah.
Scott: Recirculate back to the algae.

Scott continued by stating that the data table showed ammonia decreasing to zero, but added that nitrifying bacteria required ammonia to survive. On hearing this, Austin interjected:

Austin: If there's no ammonia, then they are gonna die.
Scott: Right.
Austin: And [the sphere] still survives. We know that, so okay.
Scott Yeah, so nitrifying bacteria, um, they die off but you still have your-
Austin: -heterotrophic. That, that makes sense. Okay.
Jan: And that's the like pair that can use the decomposing matter.
Austin: Yeah. That's pretty good. They can be converted to algae.

At this point, the visiting group left, and the video group discussed the plausibility of this new theory (see Authoritative Approval below). Eventually, both Franjelica and Austin adopted the theory that the nitrifying bacteria “die off” and used it in their account of the functioning of the system without shrimp.

Discussion. Franjelica and Austin spent almost an hour trying to make sense of the relationships between the algae and the two kinds of bacteria. The various explanations they proposed accounted for only part of the data. For this reason, they were never satisfied with their account of why the Ecosphere system was able to function. For instance, the information sheet stated that nitrifying bacteria converted ammonia to nitrogen oxides to meet its energy needs; however, the data sheet for the Ecosystem with no shrimp showed that the ammonia levels decreased to zero. The group created a cycle to show how nitrogen moved between the bacteria and algae, but their cycle included ammonia as one of the products. The fact that ammonia decreased to zero presented an obstacle that the group could not resolve.
When the second group shared their solution, Franjelica and Austin were cognitively ready for a theory that allowed them to reconcile the ammonia and nitrifying bacteria issue. Jan’s suggestion that the nitrifying bacteria died out presented a solution that allowed Franjelica and Austin to achieve their goal—to create a cycle to account for the conversion of elements between the bacteria and algae in the sphere without conflicting with the data. The cycle they developed was an acceptable biological explanation that identified bacteria and algae as matter transforming systems.

One week later, during the fourth lesson, the groups were asked to reconstruct their solution to Problem 1C and to share it with the whole class. The video group effortlessly recreated their explanation to account for how the needs of each species were cycled in a sphere without brine shrimp, suggesting that they had been cognitively ready for the information Jan and Scott had offered near the end of the previous lesson that resulted in the reorganization of their schemes.

**Franjelica’s need for authoritative approval.** As the video group discussed the theory proposed by the visiting group, Franjelica was hesitant to accept the notion that the nitrifying bacteria died without authoritative verification, despite her ability to restate the impossibility of any other solution. At first, Franjelica questioned whether or not the nitrifying bacteria actually die:

Franjelica: Are we sure it dies?
Austin: It has to because apparently, where was it, this one, this one (looking for a handout), nitrogen, nitrifying bacteria-
Franjelica: I wish we knew if it could go backwards. I want it to go backwards.
Austin: So they convert Ammonia?! to nitro-oxides of nitrogen for their energy needs. So if they don't have any ammonia, they can't survive.

Franjelica was not satisfied with Austin’s argument and continued to search for another solution. Only after questioning the instructor did Franjelica choose to accept that the nitrifying bacteria must indeed die.

Franjelica: We are trying to figure out whether or not the nitrifying bacteria dies because there is no ammonia in the water.
Instructor: Okay, so then what did you just say?
Franjelica: Are we absolutely positive that when the, that when, cause algae is decomposed by the heterotrophic. And it uses it.
Instructor: Okay.
Franjelica: And anything that is not used by heterotrophic gets kicked back into the water for algae to pick up again. But are we absolutely certain that the nitrogen that gets kicked out into the water doesn’t come out as ammonia?
Instructor: Are we absolutely certain that the nitrogen doesn't come out as ammonia?
Austin: Yeah, well it says right here.
Instructor: Can it be coming out [as] ammonia? Do you have any ammonia in your water?

... 
Austin: No.
Instructor: If it was coming out as ammonia and you did a water quality test, would there be ammonia in your water.
Franjelica: Yes.
Instructor: And do you have any ammonia in your water.
Franjelica: No.
Instructor: So your data proves that idea wrong.
Franjelica: So there is no ammonia. So the nitrifying does die.
Austin: Yes. It has to. Thank you.
Instructor: Just telling you what your data says.

Subsequent to this discussion, Franjelica accepted the theory that the nitrifying bacteria died, and as a result, she was able to move forward and create an explanation for the functioning of the sphere without shrimp.
**Discussion.** I had not anticipated Franjelica’s need for authoritative approval, and this need could have impeded her learning. I, as the instructor, chose to lead Franjelica to a logical interpretation of the data because I was confident that if she concluded that nitrifying bacteria died, she could progress in her learning. I conjectured that she would deduce that bacteria decomposed algae and, in the process, converted the elements in algae into another form that would eventually be returned to the water and taken back up by the algae. Franjelica did indeed come to this conclusion and, in later lessons, actually referred to bacteria as “matter converters” when she could not remember the term “decomposers.”

**Follow-up Problem.** After each group presented their solution to Problem 1C, they were given a follow-up problem. The goal of the follow-up problem was to provide the students an opportunity to apply their newly developed understanding of bacteria as matter transformers.

![Figure 23: Problem statement 1D](image)

Problem 1D: One of the functional roles of the bacteria is to keep the sphere clean by removing the shrimp waste. In the first trials to create a functioning sphere, the researchers used small snails similar to those in a fish tank. These snails are known to eat the waste of fish, brine shrimp and other marine organisms. Although the snails were able to keep the sphere “clean” the brine shrimp and algae did not survive for a long period of time. Explain why the snails were not able to keep the sphere alive.

[Hint: Data on the composition of the sea water over time can be useful.]

The video group began by reading the information sheet about the Nassarius Snail and reviewing the water composition data for a sphere with algae, brine shrimp, and snails.
They concluded that there would be fewer available nutrients for the algae if the snails replaced the bacteria.

After giving the students time to create an explanation, the instructor asked one group to present their solution to the class.

Instructor: If you could, tell us why the sphere doesn't survive with the snails?
Student: Um, snails can't convert phosphorus in like shrimp, to the inorganic forms. To usable forms the algae can use.

...  
Instructor: And how do you know that this isn't happening?
Student: Because you have the data table for the water with no bacteria, but with snails. (pause) The numbers drop off? Um, yeah the numbers of the POX and NOX drop off.

Another student added that without POX and NOX, the algae would die, after which the other organisms in the sphere would also die.

Discussion. It is important to point out here that Problem 1D was fundamentally different from Problem 1C in that 1D did not necessitate a specific way of understanding for the students. Instead, 1D provided an opportunity for the students to solidify and appreciate the way of understanding they had recently formed. Both types of problems are important for learning. I include the example of Problem 1D here to help distinguish between Problem 1C—designed to create in the student a need for a particular way of understanding not yet formed—and the follow-up problem that provided the student an opportunity to apply his or her newly developed or refined way of understanding.
**Analysis of Example One**

From the DNR perspective, learning grows out of problems intrinsic to the students, problems that pose for them an intellectual need. Problems 1A and 1B were essential for creating the context for Problem 1C, affording 1C the potential to create cognitive disequilibrium. Analysis of the students’ solution process for Problem 1C indicates that the students assimilated the problem and took responsibility for the solution. The task proved to be sufficiently challenging and, because the students were asked to present their group solution to the class, it promoted the need for the students to communicate with each other. As they shared their ideas, they were compelled to resolve differences in both their interpretations of the situation and their ways of understanding. While the group members questioned and challenged each other, they clarified their own understanding.

The intent of the problem was to help students develop an understanding that living organisms transform matter. As anticipated, the students drew on their desire to create a cycle to represent relationships between species, and this existing knowledge played a key role in helping the students develop an awareness and, subsequently, an understanding of organisms’ participation in the cycling of elements.

The students’ struggle to reconcile their desire for a cycle with the data to account for the transfer of various elements between species created in them a “readiness” to assimilate a hypothesis presented by another group. In the end, their assimilation of this hypothesis led the students to a solution that satisfied their puzzlement and restored equilibrium. While developing an explanation to account for
why the organisms could survive in a sphere without shrimp, the students gained an understanding of living organisms as matter transformers.

It should be noted, however, that once the visiting group presented their theory, an acceptance of the theory did not proceed smoothly. Although Problem 1C was designed to create intellectual need, the additional need for authoritative approval emerged, and until resolved, impeded Franjelica’s learning.

Example Two: Differentiating between Matter and Energy

I conjectured that helping students refine their understanding of the distinction between matter and energy would contribute further to the development of characteristics associated with model-based reasoning. Interviews with students revealed multiple and sometimes incompatible schemes of matter and energy that varied depending on the context (see chapter 5). If students were to consider matter cycling and energy flowing as micro-level processes essential to the functioning of a biological system, then they needed to reorganize their schemes about matter and energy to include an understanding that (a) matter and energy are not the same; (b) matter cycles and energy flows through a system; and (c) energy degrades in a system and therefore there must be a constant input of energy. Helping students develop these ways of understanding was the goal of Problem Situation 1E and 1E Supplemental.

Setting the Stage

The students were given Problem 1E and asked to work independently for several minutes.
Problem 1E: If the sphere is placed in a closed box (a dark environment) after a period of weeks everything in the sphere dies. What role does light play in keeping each of the organisms alive? Create a diagram to represent your ideas.

Figure 24: Problem statement 1E

After approximately ten minutes of independent work, Franjelica and Austin shared with each other their ideas and, together, created a diagram to share with the class. (Rachel was absent during this lesson.)

In the following segment, the video group shared their diagram with the instructor.

Instructor: Can you guys tell me where you are at?
Austin: Um, I think we’ve completed our cycle. (pause) From the sun it provides light for algae, so they can produce photosynthesis and survive, because it needs energy. And then the energy um, well, the algae provides energy for the shrimp through food because they eat the algae, the shrimp do. So then the shrimp expels all these-
Instructor: So energy is going from here to here? (Instructor points from algae to shrimp)
Austin: Mmhmm.
Franjelica: Yeah.
Instructor: Okay, can you write energy?
Austin: Well, isn't energy going, well all the arrows represent energy.
Instructor: Okay, can you write that on there?

All five groups created a diagram that closely resembled their diagram from the previous lesson that represented the cycling of nutrients in the sphere. All of the groups included arrows representing energy flowing from the bacteria and shrimp back to the algae.

This initial problem served the purpose of providing a context for perturbation. Based on my model of the students’ biology, I conjectured that the students would
represent energy traveling from the sun to the algae, and then cycling through all the organisms back to the algae. All five groups did in fact create such a diagram.

Problem Statement 1E Supplemental

After surveying all five groups’ diagrams, the instructor brought one of the diagrams to the front of the class. After briefly summarizing the diagram for the class, she stated that this diagram was representative of the other four diagrams in the class. She then presented the following question:

Problem 1E Supplemental: Consider the following statement: If energy cycles like matter does, then I should be able to put a plant in the sunlight for a week, then remove it from the light and it should survive in a box (or unlit place) for years because the energy it was supplied with would keep cycling. But we know that this is not true – the plant dies. How can you account for this? If needed, revise your diagram.

Figure 25: Problem statement 1E supplemental

The intent of this problem was to bring to the students’ attention their incompatible schemes: If energy cycles as matter does, the plant would be able to survive for a long period of time in the dark. However, the students knew that a plant would die after days or months in the dark. Once the students were sufficiently puzzled, I hypothesized that this problem would create in them a need to draw upon a different scheme: in food web relationships there is a loss of energy between trophic levels.

Students’ Interpretation of Problem 1E Supplemental

The video group students’ statements suggest that they assimilated Problem 1E Supplemental. Franjelica did not initially interpret the problem as intended; however, Austin explained his interpretation to Franjelica:
Austin: But she, I think she is saying that it’s stored like in the shrimp and stuff, not in the environment. Like the energy that was in the algae is now in the shrimp and the bacterias. She is saying, how come it doesn't continue cycling. Why does the sun need to continue to provide continuously.

Franjelica: So this is our dome. And there is water. Water everywhere.

Austin: So why doesn't it continue to recycle?

Austin was able to restate the problem in such a way that Franjelica could then develop a similar goal. Their subsequent discussion provides evidence that they situated the problem in a familiar context and were able to begin proposing solutions.

Thus, they assimilated the problem and developed a goal, indicating that the problem created the intended puzzlement.

The Development of a Solution—Developing a Way of Understanding

It took only a few minutes after Franjelica interpreted the problem as intended for her to introduce the idea of the transfer of energy in a system:

Franjelica: Okay. Transfer of things, of energy, you always lose something.

Austin: That's true.

Franjelica: Even like batteries. They can only hold a charge for so long.

Austin: Okay, that makes- that's a pretty good start right there.

Franjelica: So every time, every organism, every time it transfers you lose energy.

Austin: Yeah, a lot of energy. /Only 10 percent or something

Franjelica: /so every time. Okay, so while energy does go-

Austin: -it is decreasing.

Franjelica: So while energy goes here, with this arrow (points to arrow between algae and shrimp), it also goes out.

Austin: Yeah.

Franjelica: And so with every transfer /it also leaves

Austin: /heat and stuff.

Franjelica: Yeah.

... Austin: So yeah, and eventually, if it keeps decreasing by 10 percent or something each time, you are gonna reach zero, or something similar to zero.
Franjelica: So every transfer of energy results in a loss of energy. And eventually be it five years or two hours, there won't be enough energy in the system to- Austin: -survive. Or replenish, or sustain the system.

When the instructor later asked about energy transfer, Franjelica and Austin restated that energy was lost in the form of heat as it flowed between organisms, and this energy was thus no longer usable by other organisms. As a result, the sphere needed a constant input of energy; in this case, sunlight.

After the instructor had time to visit each group, the five diagrams were placed around the room for a “gallery walk.” The groups were asked to visit two diagrams (excluding their own) and, by writing comments on post-it notes, judge how well each diagram represented the role light plays in sustaining the organisms in the sphere.

Franjelica and Austin were not satisfied with one of the diagrams:

Franjelica: [They] have no labeled transfer of energy. Cause they-
Austin: Ohhh.
Franjelica: I see the transfer of nutrients; I don't see the transfer of energy.
Austin: Couldn't the nutrients be the energy? 'Cause the nutrients do contain the energy.
Franjelica: But they didn't say that.
Austin: They didn't. You're right. Okay. Specify, because we were supposed to, yeah.
Franjelica: This is my nutrients, it is my energy.
Austin: Yeah. Okay so yeah, that's something that is missing.

Both Franjelica and Austin distinguished between matter and energy in this context.

Discussion. The ease with which Franjelica and Austin developed a solution that satisfied them reveals several things. First, they did indeed have a scheme for the loss of energy between organisms, and they knew that the energy was lost in the form...
of heat. Second, although they had previously developed schemes to account for the energy relationships in a biological system, they had not made the connection between their understanding of the loss of energy between trophic levels and the need for a constant input of energy to keep a system functioning. Third, it is likely that they had never previously experienced the need to distinguish between matter and energy. Since they knew the plant would die in the dark—but also knew matter cycled in the sphere—distinguishing matter from energy became necessary. From this point forward, neither Franjelica nor Austin conflated matter with energy again. In fact, on several occasions, they were almost adamant about not confusing matter with energy (see chapter 6).

Analysis of Example Two

Problem 1E Supplemental created cognitive puzzlement because the problem brought to the students’ attention inconsistencies or incompatibilities in their existing schemes. To resolve these incompatibilities the students needed to reorganize their schemes of matter and energy. Both Franjelica and Austin demonstrated a refinement of their understanding of matter cycling and energy flowing through systems.

This episode provides an efficacious example through which to illustrate the role small groups play in helping create intellectual need. Franjelica did not assimilate Problem 1E when it was first presented. Rather, she assimilated the problem only after Austin stated the problem in a new way. Thus, the interaction between the students led to the assimilation of the problem situation. Moreover, because the problem required that students present their solution to their classmates, it was necessary that they share
their ideas to ensure they were working toward the same goal and that their understandings were compatible with each other. The problem situation, then, required Franjelica and Austin to articulate their thoughts so that they could be formulated into an idea that could be communicated to the class. As a result, ideas surfaced during their discussion that may not have been considered had they worked independently.

For instance, as Franjelica and Austin began discussing Problem 1E Supplemental, Franjelica raised the idea that energy is lost: “Transfer of things, of energy, you always lose something.” As a result of this new idea, Austin proposed “heat” as the form of energy lost. Had they worked independently, Austin may not have considered the loss of energy, and Franjelica may not have identified the energy as heat. Together, however, they were able to develop a biological explanation to account for the role light plays in keeping each of the organisms in the sphere alive.

**Example Three: The Dead Zone**

Both of the previous examples provided problem situations intended to create a need for a specific way of understanding in biology: living organisms as matter transforming systems, and matter cycles and energy flows in a biological system. Sometimes, however, the goal of a lesson is to help students develop a characteristic of a way of thinking. In the following case, the problem situation was designed to create a need in the student to make a connection between cellular level processes and macro-level properties.
Problem Situation: The Dead Zone

This problem situation was introduced at the start of the seventh lesson. At this point in the teaching experiment, the students had begun to develop a biological understanding of (a) decomposition and the role of decomposers in the cycling of matter, (b) photosynthesis as a process in which plants create sugars, (c) respiration as a process in which sugars are broken down to release energy and in which oxygen plays a role, and (d) matter cycling and energy flowing in biological systems. The Dead Zone problem was designed to create in the students the need to identify the relationship between elements in a biological system, trophic interactions, the process of respiration in decomposers, and the health of an ecological system. More generally, the goal was to create a need in the student to connect molecular processes, cellular processes, and organismal processes in order to explain an ecological process—eutrophication.

Students had not solved any problems related to the Gulf of Mexico prior to this problem situation, and therefore, a short introduction precedes the actual problem statement.

Problem 3A: “It can stretch for 7,000 square miles off the coast of Louisiana, a vast expanse of ocean devoid of the region’s usual rich bounty of fish and shrimp, its bottom littered with the remains of crabs and worms unable to flee its suffocating grasp. This is the Gulf of Mexico’s "dead zone," which last summer reached the size of the state of New Jersey.” (The New York Times, 1998)

The Gulf of Mexico “dead zone” is a seasonal phenomenon occurring in the northern Gulf of Mexico, from the mouth of the Mississippi River to beyond the Texas border. Scientists have identified the cause of the dead zone as an oxygen deficiency in the water; oxygen levels within the zone fall...
below 2 milligrams per liter of water - too low to support marine life. Those organisms that can swim leave the area, but organisms such as crabs and worms are trapped in these suffocating waters. The oxygen depletion, referred to as hypoxia, begins in late spring, reaches a maximum in midsummer, and disappears in the fall. Hypoxic waters appear normal on the surface, but on the bottom, they are covered with dead and distressed animal life. The Dead Zone was first recorded in the early 1970's. It originally occurred every two to three years, but now occurs annually. In the summer of 1999 the Dead Zone reached its peak, encompassing 7,728 square miles.

Use what you know about functioning ecosystems to develop an explanation for what might be causing the hypoxic conditions each summer in the Gulf of Mexico ecosystem.

(Hint: Attached is a map of the region, dissolved oxygen contour maps for July 1990, 1993, 1997, and information about the waters that flow into the Gulf of Mexico. Use the simulator and these resources to help you develop an explanation for what might be causing the oxygen to be depleted in these waters each year during the summer months.)

Figure 26: continued. Problem statement 3A – The Dead Zone

The information sheet (see Appendix 7) included two maps of the Mississippi drainage area and the following statement:

**Information about the waters flowing into the dead zone:**
The Mississippi River Basin covers forty-one percent of the continental United States, contains forty-seven percent of the nation’s rural population, and fifty-two percent of U.S. farms. The waste from this entire area drains into the Gulf of Mexico through the Mississippi River. Included in this agricultural waste are phosphorus and nitrogen, which were first used in fertilizers in the United States in the 1930s. By the 1960’s, fertilizer use increased by over two million metric tons per year. Since then, concentrations of nitrate and phosphate in the lower Mississippi have increased proportionately to levels of fertilizer use by agriculture. Overall, nitrogen input to the Gulf from the Mississippi River Basin has increased between two and seven times over the past century. In addition to agricultural waste, inadequately treated or untreated sewage and other urban pollution is also dumped into these waters.

Figure 27: Information sheet accompanying Problem 3A
The students worked in pairs or groups of three and had access to the Ecobeaker simulator program “Sewage” (Meir, 1999). The sewage program simulates a lake containing phytoplankton, zooplankton, and fish. The phytoplankton grow in proportion to the phosphorus concentration. This graphical simulator allowed the students to vary phosphorus inputs and record the resulting algal and oxygen levels in the lake. As the students increased the levels of phosphorus in the simulator, this led to algal blooms, which ultimately resulted in an increase in decomposers. The increase in decomposers caused a decrease in oxygen levels within the lake. Decomposers, however, were not represented on the simulator. The only evidence for the existence of decomposers was the decrease in oxygen.

In this problem situation, the students were asked to develop an explanation to account for the decrease in oxygen levels in the Gulf of Mexico during spring and summer. The simulator provides an opportunity for students to explore the relationships between the nutrient levels and oxygen in a lake ecosystem; however, the simulator does not explain the cause of the decrease in oxygen. This is where the need for making connections between the various processes acting within a biological system is created.

Students’ Interpretation of The Dead Zone Problem

Rachel and Franjelica’s statements suggest that they assimilated The Dead Zone Problem. As soon as they were presented with the problem statement, they began familiarizing themselves with the simulator. After spending time manipulating the
parameters, Rachel indirectly verbalized that her goal was to figure out why the dead zone occurs.

Rachel: You think that’s what it is? Like the dead zone is, that's what this suffocating is?

... 
Franjelica: I don't get what you just meant. 
Rachel: I’m talking about the phytoplankton is building up so much that it is actually like choking the fish, like literally? It’s not letting anything get in.

Rachel’s hypothesis indicates that she had assimilated the problem and set a goal of explaining why the organisms in the dead zone die.

Later, Rachel restated her question aloud to no one in particular: “Okay, the fish level doesn't seem to be changing. So what’s with the dead and distressed marine life in the bottom of the bay?” This statement provides further support that this problem situation was intrinsic for Rachel. Although Franjelica did not restate her interpretation of the problem, her conversations early in the lesson suggest she had also set the goal of explaining why the organisms died in the spring and summer in the Gulf of Mexico.

The Development of a Solution—Developing Connections between One’s Ways of Understanding

Similar to Problem 1C in Example One, the solution for this problem developed gradually. In the sections that follow, I discuss some of the contributing factors that helped students regain cognitive equilibrium and develop connections between their understandings of biological processes.

The Simulator. After reading the problem, the video group immediately began familiarizing themselves with the simulator. They methodically increased the amount
of phosphorus in the system and recorded the changes. In a relatively short period of
time, Rachel concluded that the increase in phosphorus led to an increase in
phytoplankton and zooplankton while oxygen levels decreased. At this point, Rachel
asked why the phytoplankton increased:

Rachel: Oh, wow, look at that. Why do think the phytoplankton goes up
so much?
Franjelica: The phytoplankton?
Rachel: Mmhmm.
Franjelica: Well it does need phosphorus, so there is like, just a massive-
[phytoplankton] is mostly self sufficient, with just a couple [of
other needs]. And it brings nitrogen and phosphorus in the
environment and if those are just being pumped in, [the
phytoplankton] probably just sky rockets.
Rachel: You think that's what it is? Like the Dead Zone is, that's what
this suffocating is?

Shortly after, Franjelica and Rachel restated for the instructor their conclusion that the
phytoplankton increased because phosphorus acted as a fertilizer that facilitated
growth. They also concluded that oxygen levels decreased as the phytoplankton
increased.

Discussion. Observations about the relationship between phosphorus and
plankton led Rachel to offer her initial hypothesis to account for why the organisms in
the dead zone die—the plankton “chokes” the fish. Although this hypothesis later
proved to be unsatisfactory for her, the identification of the relationship between the
phosphorus, plankton, and oxygen provided the groundwork for developing an
explanation. If the students had been told that increasing phosphorus led to an increase
in plankton, it is likely they would not have considered why; and without considering
why, they may never have developed the need to make a connection between the
process of decomposition and the decrease in oxygen. Therefore, the simulator played an important role in providing an opportunity for the students to develop questions that were intrinsic for them.

**Instructor Intervention.** Several times throughout the solution process, the instructor visited the video group to answer questions and gauge their progress.

Experience from the pilot teaching experiment indicated that the students could spend the entire lesson manipulating the parameters of the simulator without progressing to the development of a solution. Therefore, after providing sufficient time to experiment with the parameters in the simulation and observe the outcome, the instructor gave each group a list of questions to prompt them to develop some conclusions from the simulator:

i. How does phytoplankton population size relate to phosphorus level? Provide a biological explanation for your answer.

ii. What is the relationship between phytoplankton population size and oxygen at the bottom of the lake? Provide a biological explanation for your answer.

iii. How does phytoplankton population size relate to toxin level? Provide a biological explanation for your answer.

After visiting Franjelica and Rachel, and recognizing that they responded to these prompts with observations only, the instructor followed up with more probing questions:

Instructor: So what do you have, what are you answering?
Rachel: So we are looking at the first question and we are looking at the trends and we saw that as phosphorus increased the population of phytoplankton increased as well.
Instructor: Okay
Rachel: And as phosphorus increased, oxygen levels were decreasing.
Instructor: Okay. And were you able to think of why for either one? Why that might happen?

To account for the increase in phytoplankton, they proposed that the increase in phosphorus provided the “nutrients” or fertilizer that the phytoplankton needed to grow. For the decrease in oxygen, Rachel advanced her theory about the overgrowth of phytoplankton “literally choking” the fish. After unsuccessful efforts to help Rachel and Franjelica articulate the “choking” hypothesis in hopes that they might see its insufficiency in explaining the decrease in oxygen, the instructor left the group.

Within five minutes, the instructor addressed the entire class and reminded them that the simulator does not simulate the Gulf of Mexico, but merely a hypothetical lake. She then asked the students to think about whether all living things necessary for an ecosystem to function are represented in the simulator. This question prompted Franjelica and Rachel, along with several other groups, to include decomposers in their discussions. Nevertheless, neither Franjelica nor Rachel made the connection between decomposers and oxygen levels at this time.

Discussion. The instructor did not intervene by providing evaluations of the students’ explanations, but rather, her prompts helped the students advance. It is likely that the students would have spent the majority of the lesson manipulating parameters on the simulation if the instructor had not intervened and offered guided questions followed by probing questions. The instructor consistently asked the students how they would account for the changes they observed and recorded. These questions contributed to helping the students redirect their focus and use their time more efficiently.
One of the key steps in developing a solution was the transition from focusing on why the organisms die to focusing on why the oxygen decreases. Getting the students to make this transition proved challenging. The problem clearly stated that the oxygen levels in the dead zone were too low to support life. Yet Rachel initially concentrated on explaining why the organisms in the dead zone die. It is not obvious what prompted Rachel to change her focus, but, once the instructor stated that the simulator did not simulate the Gulf of Mexico, Rachel began to focus on explaining why the oxygen levels decrease. Accounting for the oxygen decrease puzzled both Rachel and Franjelica.

Cognitive “Readiness”. Once Franjelica and Rachel set a goal to explain the decrease in oxygen, they proceeded by offering random hypotheses, and then debated the plausibility of these hypotheses.

Rachel: Why is your oxygen going away? (Directed to no one in particular.) Oh, my god (hands rubbing face). Okay, all I picture is like, this phytoplankton is growing and growing and this place is literally becoming darker and darker because it is growing so much. And-

Franjelica: You would need one hell of a lot of that to /cover the Gulf of Mexico.
Rachel: /But look at/ look at that area. That area was pretty large. They called it dead zone.
Franjelica: I mean you would need a hell of a lot of plankton to fill an area that big.

After rejecting this hypothesis, several other hypotheses were offered. For instance, Rachel asked about the cause of the red tide and tried to make a connection between the red tide phenomenon and the decrease in oxygen levels.
At one point, Franjelica introduced cellular processes into the discussion:

“We’ve done respiration. We’ve done photosynthesis, basically. Photosynthesis and respiration, which is the breakdown of glucose.” Franjelica did not follow through with this thought, however. Instead, she began discussing the increase in phytoplankton again:

Rachel: Yeah. So we get that, we understand that the nutrients of fertilizer help cause this algal bloom, or whatever, planktonian bloom, but, why does it suck up-
Franjelica: Okay, it used to happen every other year or so. Now it happens every year.
Rachel: More run off.
Franjelica: More run off?
Rachel: Accumulation of whatever? I swear, it’s in there and it’s just taunting me.
Franjelica: (laugh) I get that feeling.

Franjelica and Rachel could account for the increase in plankton in the spring and summer, but were searching fervently for a way to account for the decrease in oxygen.

On a number of occasions, Rachel became outwardly frustrated that she could not determine why the oxygen decreased, as evidenced by the following three segments.

Rachel: And I’m like, I’ve heard of this concept before, not like the word, like the phrase dead zone, but, (?) it was red algae. Oh, my god. Why does the oxygen go away (exasperated tone)?!

***

Rachel: What would it do? It would just reverse-
Franjelica: -it screws with the oxygen somehow.
Rachel: Ah! (exasperated tone)
Franjelica: This is fun in a frustrating way.
Rachel: Do algae blooms and- fricken a.,

***
Franjelica: Autotrophic, the additives seep into the water, basically miracle grow.
(Rachel’s hands covering her face)
Franjelica: This is so scientific.
Rachel: I pulled an all nighter and I can’t frigen think of what, god dammit. I get to the part where it blooms but I don’t know. I lose, I lose the train after that.

At one point Rachel asked, “Can I look it up on the internet? This is driving me crazy.” In contrast to Rachel’s frustration, Franjelica seemed to enjoy the perplexity. She continuously offered ideas for them to consider. Both students’ puzzlement was resolved during the class discussion at the end of the lesson.

Discussion. There were numerous statements throughout the lesson to indicate that Rachel and Franjelica were cognitively puzzled. Rachel’s outward frustration suggests that she was cognitively ready to accept a solution that accounted for the decrease in oxygen. Although neither Franjelica nor Rachel made connections between their ways of understanding biological processes on their own, they had an internal desire to resolve the problem. This cognitive “readiness” helps explain why, after developing a solution in the class discussion, both Franjelica and Rachel were able to effortlessly explain the decrease in oxygen in the subsequent two lessons.

Class Discussion. With only a few minutes remaining in class, the instructor addressed the class as a whole, restated her interpretation of the progress of each group, and concluded by asking questions. Prior to this class discussion, Franjelica and Rachel had not yet been able to account for the decrease in oxygen.

Instructor: If you had a bacteria image on there, what would your bacteria do? If my phosphorus went up, if my zooplankton went
up, my phytoplankton went up, what do you think my bacteria would do?
Student: Increase.
Instructor: She said increase. What do you think?
Student: Goes up.

... 
Instructor: Okay, why would my bacteria increase? Four groups said bacteria would increase. Why?
Student: It’s a cycle. If one part goes up, the rest (?) .
Instructor: ... If I have more zooplankton, why would my bacteria increase?
Rachel: Is there more food for it?
Student: (?) more nitrogen in the water.
Instructor: So her argument is for nitrifying bacteria, there is more nitrogen. What did you say?
Student: (cannot hear)
Instructor: [Student] said more plants, then more plants die and then more bacteria to break them down. So she took care of heterotrophic bacteria, you took care of nitrifying bacteria. More animals, more ammonia. (pause) Okay, so now you have bacteria going up. What would happen to my oxygen levels if my bacteria goes up? What did you guys just say?
Student: It would go down.
Instructor: Why would it go down?
Student: Cause they use oxygen.
Instructor: So they use oxygen. So I have high bacteria numbers, my oxygen levels go down. What do you guys think?
Student: We agree with that.
Instructor: They agree with that.

After additional student responses, Franjelica raised her hand:

Franjelica: The oxygen level would go down, because the more bacteria there is- the bacteria needs oxygen for respiration and bacteria multiply like crazy, like even exponentially. So the more bacteria there is, the more oxygen is being used. And so, and there is more plants, more surface area, a lot more bacteria, more oxygen is being used, and eventually the plankton, there is just not, produce enough oxygen for everything there.

Rachel did not contribute to the class discussion before the class ended. The class met again one week later, and Franjelica was absent from this particular session.
Because Austin had been absent from the previous lesson, Rachel summarized for Austin the initial problem and her solution. In a very short period of time, Rachel had explained to Austin that the increase in phosphorus led to an increase in phytoplankton, which in turn led to an increase in bacteria, which caused a decrease in oxygen. Later in the lesson, she provided a more formal explanation for the Dead Zone:

Rachel: As the phosphorus increases each summer because of rain and irrigation run off, the phytoplankton increases. This provides more food for the bacteria, then that would decompose it and use that for nutrients or whatever, which consumes the $O_2$ to function. Because they are obligate aerobes. More food means more bacteria, which means less $O_2$.

Rachel thus provided a biological explanation for the decrease in oxygen levels in the dead zone.

Discussion. Prior to the class discussion on the day the Dead Zone Problem was introduced, Rachel and Franjelica had been struggling to account for the decrease in oxygen. Conducting a short class discussion was not part of the original schedule for the lesson. Due to time constraints, however, the instructor felt the need to provide a degree of closure before the students left for the day. At the time, the instructor was concerned about leading the students to the solution; however, in retrospect, at least for the video group, the students were cognitively ready for a way to resolve their puzzlement. I submit that had the class ended without the discussion, Rachel may have resorted to the internet to uncover the cause of the dead zone. Regardless, Rachel and Franjelica had an intellectual need for a way to make sense of the decrease in oxygen, and when the idea was proposed that bacteria increase
resulted in a greater demand for oxygen, both Franjelica and Rachel assimilated this idea.

The subsequent lessons illustrate that both students had modified their schemes by making connections between elements involved in the process of cellular respiration, organismal processes and interactions, and the functioning of an ecological system. Although Rachel had spent a substantial part of the lesson in frustration—she could not account for the decrease in oxygen—she came to the next lesson, a week later, with a solution for the dead zone problem that revealed that she had made connections between various biological processes, connections she shared with Austin. Likewise, Franjelica came to class two weeks later and readily explained the decrease in oxygen in a completely different problem situation involving a lake: “Well the (run off means) a lot of phytoplankton. That increases bacteria and less oxygen and da da da. So its, it um, upsets homeostasis.” Both Franjelica and Rachel had been ready to resolve the cognitive puzzlement created by the Dead Zone Problem, and as a result of this need, they made connections between their ways of understanding different levels of biological processes.

Analysis of Example Three

The goal of Example Three was to create a need in the students to make connections between the different levels of biological processes. None of the students from the pilot teaching experiment or the final teaching experiment, including Rachel and Franjelica, approached the problem by considering the cycling of oxygen in the system—tracing the oxygen through the various trophic levels to
identify why it might decrease—or by considering the cellular processes within organisms that utilize oxygen and how these processes contribute to the functioning of an ecosystem. Either approach would have pointed to multi-dimensional relating, a characteristic of model-based reasoning.

Instead, the students offered ad hoc explanations. Rachel initially accounted for the problem by assuming that the phytoplankton “choked” the fish, and later, suggested that the phytoplankton covered the top of the water, preventing the plants below from photosynthesizing, resulting in a decrease in oxygen (a conception held by many students). Franjelica also offered various hypotheses to account for the death of the animals in the water and the decrease in oxygen. Although the students came to this lesson with a biological way of understanding the cycling of elements in organisms, a basic understanding of the processes of photosynthesis and respiration, and an understanding of the role of decomposers and decomposition in a biological community, they did not initially make connections between these ways of understanding when trying to make sense of the dead zone. Thus, it was necessary to create a problem situation that provoked in the students a need to develop these connections.

I chose to use the simulator to provide an opportunity for the students to identify for themselves the relationship between runoff, plankton levels, and oxygen levels. Identifying these relationships led the video group to investigate why they occurred. This inquiry ultimately led to a desire to account for the decrease in oxygen. Norms had been established in the classroom by this time such that the
students knew they were responsible for developing an explanation based on the data and their own intellectual resources. This norm likely contributed to the success of the problem. As mentioned previously, Rachel was visibly annoyed that she could not account for the decrease in oxygen while Franjelica seemed to enjoy the search for a solution. The discussion and debate among the pair contributed to their rejection of potential explanations. By the end of class, Franjelica and Rachel were cognitively ready for the class discussion, which eventually led them to develop connections between their understandings of biological processes.

**Analysis of the Tasks**

In this teaching experiment, I developed two types of problems: problems designed to necessitate for the students a specific way of understanding and problems that provided an opportunity for the students to apply their newly developed way of understanding. In my analysis, I was primarily interested in describing those problems that created in students an intellectual need to learn what I intended for them to learn. In the three examples presented here, the students demonstrated that they had developed the desired ways of understanding. By analyzing the students’ engagement with the problems and their solution paths, I propose that these problems were successful for the following reasons: each problem built on students’ existing knowledge; the problems were sufficiently challenging for the students; the students took responsibility for the solution; and each task required the students to present their solution to the class. This list does not claim to be exhaustive or to establish causality,
but rather, it provides a vision of what intellectual necessity in an ecology context looks like.

**Building on Models of Students’ Biology.** One premise underlying the design of the problems used in this experiment is that when a learner encounters a situation that is incompatible with, or presents a problem that is unsolvable by, his or her existing knowledge, cognitive perturbation results. Examples One and Two describe problems that were constructed to lead students to confront the insufficiency of their initial ideas. For instance, interviews prior to the teaching experiment revealed a common conception among this population of students that autotrophs are dependent on animals for their carbon dioxide needs. Furthermore, the interviews revealed that the students did not consider decomposers as participants in the cycling of carbon dioxide, oxygen, or other elements. Based on these findings, I designed the problems that preceded 1C to build on this model of students’ understanding. I conjectured that the students would conclude that the brine shrimp were essential for the sphere to function, and, as discussed in Example 1 (see Setting the Stage), the students came to that conclusion. By eliciting their existing knowledge with preliminary problems, Problem 1C was able to create puzzlement in the student because the sphere could in fact survive without the brine shrimp. Creating this cognitive disequilibrium contributed to the students constructing an understanding of bacteria as participants in the exchange of elements in the sphere.

For Problem 1E, the interview data had indicated that the students did not distinguish between matter and energy when considering ecosystem functioning. Thus,
I theorized that the students would create a diagram representing energy cycling through the species in the Ecosphere. As anticipated, they created a cycle to explain the role of light in the functioning of the system. Creating a diagram that represented energy cycling through the system provided a context for the students to be perturbed. The follow up question, 1E Supplemental, elicited students’ knowledge that plants must have a constant input of light or they will die. These two schemes are incompatible, and the recognition of this fact led students to develop a new way of understanding. Thus, knowledge of the students’ existing ways of understanding allowed me to develop problems that led them to confront the incompatibility of their two schemes.

**Challenging Problems.** If one intends to create intellectual need with problem situations, the problems must challenge the students. Typical problems in biology, such as “What is the difference between respiration and photosynthesis?” do not generate in students an appreciation for the knowledge we intend for them to learn. These typical problem tasks are often viewed as inconsequential to the student and, as a result, leave the student intellectually aimless. Since the goal of instruction is for the learner to refine and advance their ways of understanding, the problem must be challenging enough to serve as a stimulus for the student. If so, the student develops an intellectual appreciation for the problem, and solving the problem becomes purposeful.

The problems presented in the three examples proved challenging for the students. The students’ engagement in solving the problems and the refinement of
their ways of understanding confirm that the problems were intellectually stimulating. Unlike traditional problem tasks, in the three problems presented here, the students were not provided the information to solve the task ahead of time, nor were they given text in which they could read and locate the answer. Rather the problems required the student to reason and synthesize information to create a solution.

Devolution of the Problem. After the first few class sessions, a norm became established in the classroom such that the students did not expect the instructor to provide the answer to the problems either verbally or in a written document. Instead, the students knew they were expected to generate solutions in conjunction with their group members, utilizing data, fact sheets, and their own deductive reasoning. Furthermore, the students knew they could not rely on the teacher to validate their solution. With the exception of a few specific instances —such as Franjelica’s reluctance to accept the death of nitrifying bacteria—the instructor allowed the students to develop solutions that were not scientifically accurate. For example, in the problems prior to Problem 1C and 1E, the students generated and shared aloud explanations and diagrams that later proved to be biologically incorrect. Over time, the students began to understand that the instructor would not validate their solutions, thus “passing down” the responsibility for the solution to the students.

The “passing down” of the problem to the students is based on Brousseau’s theory of didactique (1997). According to Brousseau, for a problem to foster learning, the students must accept the problem as their problem (a process referred to as “devolution”). If the students can rely on the teacher to validate their solution, then
they see no need to engage in the solving process, other than to please the teacher. As Simon (1995) argues, “A teacher may pose a task. However, it is what the students make of that task and their experience with it that determines the potential for learning” (p.133). In the three problem situations exemplified here, there is substantial evidence to confirm that the responsibility for the problem was passed down from the teacher to the students. It was through the development of solutions that students constructed new knowledge.

Presenting Solutions. For the problem situations described in this chapter, and most of the other problems assigned in the teaching experiment, the students were aware that they would be expected to share their solutions with the whole class. Knowing they would have to communicate their solutions to others prompted individual group members to share and discuss their ideas with each other to ensure that their ways of understanding were compatible. This articulation of ideas by each group member allowed the students to refine their own understanding and, eventually, develop a shared understanding of their solution. In some cases, the sharing of ideas within the group led to dissonant interchanges. According to Lumpe and Staver (1995), these types in interchanges are important components of rich, provocative dialogue. Such dialogue “pushes” students to evaluate the strength of their own understandings (Southerland, Kittleson, Settlage, and Lanier, 2005). Thus, in these problem situations, the task of presenting the group’s solution to others facilitated the development and refinement of ideas.
It is necessary at this point to clarify how social interaction among students can lead to creating intellectual need, since the necessity principle clearly states that students are most likely to learn when they see an *intellectual* need for what we intend to teach them, as opposed to a *social* need. From the DNR perspective, learning is defined as “a continuum of disequilibrium-equilibrium phases together with (a) the ways of understanding and ways of thinking that are utilized or newly constructed during the various phases and (b) the cognitive, social, and affective stimuli that result from or instigate these phases” (Harel, 2006). Assigning students to present their solutions to the whole class provides a “social stimuli” to instigate disequilibrium-equilibrium phases, however, the interactions within the small group often led to an *intellectual* need to formulate or formalize an idea.

For instance, as Franjelica and Austin developed a solution to Supplemental Problem 1E (see “Example Two: Differentiating between Matter and Energy” above), the students’ intuitive ideas about energy flow in trophic relationships emerged as a result of their discussion and interaction. In their attempt to reconcile the cycling of energy with the death of the plant in a box, the students began to formulate certain agreements about the flow of energy in a biological system. Franjelica suggested that energy was always lost when transferred, and Austin added that the energy lost was in the form of heat. Thus, in their efforts to create a solution to share with the class, the students realized the need to formulate statements to which they both agreed. In this way, the small group interactions instigated by the structure of the learning environment facilitated the emergence of ways of understanding and I account for this
emergence as the need for communication. This need for communication is an intellectual need, not a social need.

**Learning in a Biology Context when Instruction is based on Creating Intellectual Need**

Helping students develop the intended ways of understanding goes beyond developing appropriate problem tasks. Two additional factors contributed to students constructing the desired ways of understanding in this experiment. First, the instructor frequently interacted with the group throughout their development of a solution, questioning their progress and helping them to confront inconsistencies in their conclusions. As a result, the students developed explanations that were compatible with those institutionalized in biology. For this reason, it is essential for the instructor to *guide* the learners in order to increase the likelihood that they will resolve their conflict by constructing knowledge structures consistent with domain principles (Harel, in press).

Second, the students worked collaboratively to solve the three problem situations described above. Not only did their conversations help students to assimilate and agree upon an interpretation of the problem (as described above), but their continued interaction facilitated the development of a solution. Zaslavsky (in press) reported that social interaction during mathematical problem solving played a central role in creating uncertainty as well as in leading to resolving uncertainties. The transcript data from the teaching experiment provided in the three examples above demonstrate that the students consistently proposed hypotheses and exchanged ideas. At various times, the students completed each other’s statements, encouraged
articulation of a thought, rejected proposed hypotheses, and kept each other on task. As a result, the group configuration promoted communication that contributed to exploiting the potential of the problem tasks. Without this social interaction, it is unlikely that the desired solutions would have been reached by one individual alone.

It should be noted here that the problem tasks and the group interaction contributed to the learner’s cognitive “readiness” for an intrinsic piece of knowledge. For example, while engaged in the Dead Zone problem, the video group students became eager for a solution, and, upon hearing another group’s solution during the class discussion, they assimilated this solution. In the end, they constructed the desired way of understanding. This line of reasoning supports the assertion that—as long as students are cognitively “ready” for a piece of knowledge—an instructor or written information can serve the same purpose as abstracting a solution from interaction with material objects. Thus, lecture and text reading can be valuable tools for learning if the students are intellectually stimulated and see the need for the knowledge it provides (see Lobato, Clarke and Ellis, 2004; and Schwartz and Bransford, 1998).

Summary

DNR based instruction is concerned with how instruction can be designed and implemented so that students see a mathematical need for desirable or institutionalized ways of understanding. One of the goals of this teaching experiment was to determine what constitutes intellectual necessity for ecology learning. I chose to use problem situations to create cognitive puzzlement because it is only during attempts to resolve the problem that the student will recognize inconsistencies or incompatibilities in his
or her understandings. This recognition leads to cognitive disequilibrium, and students’ desire to regain equilibrium constitutes the basis of the Necessity Principle.

In this chapter, I presented three problem situations that created an intellectual need in the students for a particular way of understanding or thinking. After developing solutions, the students revealed new ways of understanding that were more closely aligned with those accepted in the biological community. The first problem situation was designed to help the students develop an understanding of living organisms as matter transforming systems. Problem 1C built on the students’ solutions to two preceding problems. The initial problems set the context and the foreground for students to be cognitively perturbed. Problem 1E supplemental also caused students to confront their existing understanding by helping them recognize their conflicting schemes: energy cycles in a system and a constant input of energy is needed for a biological system to function. From these two problems, the students developed an understanding that living organisms act as matter transforming systems and an understanding of the distinction between matter and energy in a biological system.

The third problem example, The Dead Zone Problem, was designed to stimulate in students the need to make connections between their ways of understanding different levels of biological processes. The problem utilized a lake ecosystem simulation to help students identify the relationship between the phosphorus, the plankton, and the oxygen levels, thus providing the groundwork for perturbation.
Each of these problem situations were successful at creating intellectual need because each built on a model of students’ existing knowledge, were challenging for the students, required the students to present their solution to the class, and exploited the norms previously established in the classroom. The intervention by the instructor, together with the group configuration, contributed to the students developing the intended ways of understanding.
CHAPTER 8: SUMMARY AND DISCUSSION

Revisiting the Results

The results from this study provide empirical evidence to support the claim that the DNR principles of teaching and learning in mathematics are applicable to the teaching and learning of ecology. With respect to the Duality Principle, results from the teaching experiment reveal that students’ ways of thinking in ecology influence their ways of understanding. Conversely, building on students’ ways of understanding leads to changes in their ways of thinking. In the case of intellectual necessity, the results illuminate how problem situations can be developed for biology learners that create cognitive disequilibrium-equilibrium phases and can thus lead to the modification or refinement of existing schemes.

The Duality Principle in Biology Education

Ways of Thinking. One of the fundamental mental acts in which ecologists engage is accounting for phenomena in the natural world. Ecologists try to explain the death of a “body of water” or the survival of a community of organisms in extreme environments, such as hydrothermal vents, by making connections between various biological processes and principles. To explain the functioning of an ecological system, they draw on their understanding of biologically mediated processes, such as energy and material flows, respiration, photosynthesis, decomposition, and interrelationships among these processes. They consider cyclical and multi-directional causal relationships among all interacting components, and they attend to changes at time scales both short and long term. Furthermore, ecologists’ accounts are
constrained by theoretical models institutionalized in the scientific community, such as conservation of matter. These characteristics associated with accounting for biological phenomena constitute model-based reasoning.

Students, on the other hand, tend to apply perception-based reasoning when explaining phenomena in the natural world. The college level students in this study accounted for ecological phenomena by focusing on the objects and actors in the community observed, and their explanations were constrained only by what made sense to them at the time. The students’ accounts focused primarily on macro-level properties with little, if any, mention of the underlying micro-level interactions. Furthermore, their explanations were ad hoc, as opposed to being grounded in theoretical models, and as a result, they were insufficient to account for all aspects of the phenomena. As the teaching experiment demonstrates, helping students develop model-based reasoning constitutes a valid cognitive objective for instruction.

**Ways of Understanding.** The differences in the ways of thinking of the ecologists and the students are likely the result of differences in their ways of understanding. My interview data revealed that undergraduate university students had unscientific understandings and gaps in their understandings of some of the more fundamental concepts underlying biological systems and they struggled to describe the relationships among these biological concepts. Although the students’ ways of understanding biological processes were varied, nine of the ten students interviewed did not demonstrate a biological understanding of the transformation of matter, the
flow of energy, respiration, photosynthesis, decomposition, or the relationship
between these concepts and a community of organisms.

The purpose of the study, however, was not to document students’ existing
ideas, but rather, to gain insight into their ways of understanding in order to determine
if problem situations that built on students’ ways of understanding in biology led to
changes in their ways of thinking. More specifically, the cognitive objective guiding
the teaching experiment was to help students begin to develop characteristics of
model-based reasoning. I conjectured that if students refined their ways of
understanding metabolic processes in cells (photosynthesis and respiration),
decomposition, and molecular level processes such as matter cycling and energy flow,
and if they developed an understanding of the relationships among these processes,
then they may begin to develop multi-dimensional relating, a system-oriented focus,
and non-linear causal relating, and ultimately, begin to develop accounts of ecological
phenomena constrained by scientific theoretical models.

**Changes in Students’ Ways of Understanding and Thinking.** The data from the
ten-week teaching experiment revealed that the students developed several of the
intended ways of understanding. All three students demonstrated an understanding of
decomposers as both *doing* the decomposing and as participating in the recycling of
matter, a result that reflects a change in their ways of understanding decomposition.
Furthermore, all three students developed an understanding of the distinction between
matter and energy—matter cycles and energy flows through systems. None of the
students demonstrated these ways of understanding in their interviews or during the
first two lessons. There were, however, certain differences in the three students’ ways of understanding photosynthesis and respiration on completion of the teaching experiment. Two of the focus students continued to reveal fragmented understandings. This was likely a result of the ineffectiveness of the problem task that targeted this way of understanding. (I shall return to this point later.) Finally, the data indicates that the students began to develop an understanding of the relationship between different levels of biological processes.

Although I did not expect students’ ways of thinking to change from perception-based reasoning to model-based reasoning in the course of ten weeks, the data reveal distinct changes in the character of students’ reasoning as they accounted for ecological phenomena. By the end of the ten weeks, all three students’ accounts reflected multi-dimensional relating. The students were making connections between the phenomena of a functioning system, the processes within that system, and micro-level interactions such as matter and energy flow. The students discussed the cycling of matter both with respect to organisms’ roles and as a process necessary for a biological system to function. This indicates that they were considering processes rather than just objects. Furthermore, attention to matter cycling suggests consideration of cyclical causal relating, another characteristic of model-based reasoning. Finally, the students’ attention to the cycling of elements in their explanations of the functioning of a hydrothermal vent community signifies that their accounts were constrained by a molecular model of matter cycling and energy flowing in biological systems.
The evidence within this dissertation provides support for the assertion that helping students develop ways of understanding biological processes and the relationships between processes at various scales can contribute to students’ development of characteristics associated with model-based reasoning. It is important, however, to keep in mind the robustness of students’ initial ways of thinking. Although the students in this experiment began to develop certain characteristics of model-based reasoning, several more opportunities for them to reason about the relationship between scientific theoretical models and biological phenomena are necessary for these characteristics to govern their accounts.

**Biology Instruction based on Intellectual Necessity**

The Necessity Principle states that students are more likely to learn when they see a genuine intellectual need. Identifying what constitutes intellectual need within an ecology context and illustrating the resulting learning was the second goal of this study. I developed problem situations to create intellectual need in biology learners to determine whether appropriately designed problem tasks would allow biology learners to identify inconsistencies or incompatibilities in their existing understanding, generate cognitive disequilibrium, and stimulate a desire for resolution.

The results indicate that problem situations that created intellectual need were successful for several reasons. First, most of the problem tasks were constructed to lead students to confront the insufficiency of their initial ideas. I was able to accomplish this because the problems were designed based on the model I developed of undergraduate students’ existing ways of understanding. Second, the problems were
challenging, and therefore served as stimuli for the student. As such, the students
developed an intellectual appreciation for the problems, and solving them became
purposeful. Third, students learned early in the teaching experiment that they could
not rely on the instructor to validate their solution. Thus, a norm was established that
facilitated the devolution of the problem situations to the students, and contributed to
the success of the problems. Finally, the students were expected to share their
solutions with the rest of the class. Knowing they had to communicate their solutions
prompted individual group members to share and discuss their ideas with each other to
ensure that their ways of understanding were compatible. The articulation of their
ideas allowed the students to refine their own understanding and, ultimately, develop a
shared understanding of their solution.

Unsuccessful Problem Tasks. As previously stated, the data show that there
were differences in the three students’ ways of understanding photosynthesis and
respiration at the conclusion of the teaching experiment. Franjelica demonstrated an
understanding that carbon dioxide and water provided the source of elements for the
production of glucose in a plant. She also understood that producers, just as animals,
must breakdown glucose in order to gain usable energy. Neither Rachel nor Austin
demonstrated this same level of understanding photosynthesis or respiration.

I attribute the differences in their ways of understanding to poorly designed
problem tasks. Prior to the teaching experiment, I did not know the features of
problem tasks that would create intellectual need. I therefore developed several
different types of tasks from which to draw. For example, as I considered how to
design a task that created a need in students to understand photosynthesis, I reviewed the literature on the history of biologists’ understanding of photosynthesis. I quickly became aware that helping students recognize that plant mass does not come from soil or water would take several sessions, more time than I had intended to spend on this way of understanding. Therefore, I chose to assign the students the task of going to an interactive internet site to learn about the development of biologists’ understanding of photosynthesis as a homework assignment. The web site (NSTA, 1998) presented questions for the students to consider, along with the scientist’s initial ideas prior to presenting the scientists’ experiment and conclusions. At the time, I considered this website activity well designed and sufficient to help students think about their own ideas and contemplate the scientists’ results. The data from the teaching experiment, however, reveal that the students did not develop the way of understanding I had intended.

Although the questions presented in the internet activity built on students’ initial ways of understanding (for example, plant mass comes from water or soil), the assignment was not challenging for the students. I inferred from the lack of change in the students’ ways of understanding photosynthesis that the activity did not create cognitive puzzlement. Furthermore, because the activity was completed as an independent homework assignment, the students lacked the opportunity, and the need, to discuss and challenge each other’s ideas as they engaged in developing solutions. Rather, as they proceeded through the site, their initial ideas were proven incorrect without creating an intellectual stimulus for resolution. This activity, then, turned out
to not only violate the didactical contract previously established, but denied the students an opportunity to be intellectually challenged. Although I presented a problem task in the lesson following the homework assignment that provided the students with an opportunity to apply their understanding of photosynthesis, the students had not developed the intended ways of understanding from the original activity. As a result, the students continued to demonstrate a fragmented understanding of photosynthesis at the conclusion of the teaching experiment. This finding emphasizes the importance and difficulties in designing problem situations that create intellectual need in the students for the knowledge we intend for them to learn.

**Repeated Reasoning.** Although I did not set out to explore the application of the repeated reasoning principle in this research study, I did apply this principle to the instructional design. While designing problem situations, I began to consider different contexts in which I could provide students with an opportunity to develop explanations constrained by models of matter and energy transformations, or to make connections between the cellular, molecular, and organismal levels, both characteristics of model-based reasoning. For instance, the final problem situation presented in the teaching experiment asked students to account for the functioning of a hydrothermal vent community. The purpose was for the students to have an additional opportunity to consider matter cycling, energy flow, and cellular level processes as the underlying mechanisms that help to explain the functioning of this atypical biological system. The students were required to investigate the hydrothermal vent organisms and chemosynthesis independently, synthesize their findings, and present their
explanation for the functioning of the system to their group members during the final class session. My goal was not for the students to develop an understanding of chemosynthesis, although this may have occurred, but rather, I intended for the students to struggle to make sense of the various processes occurring in this community that facilitated the flow of energy and cycling of matter. In other words, I wanted the students to gain further experience reasoning about the micro-level processes that underlie macro-level properties in biological systems in a different context.

Therefore, although I did not set out to study repeated reasoning in biology instruction, the principle informed the design of the teaching experiment. The three different problem sets used in the teaching experiment provided an opportunity for the students to practice their reasoning so as to help them internalize and interiorize the ways of understanding and thinking targeted in this study. This repeated reasoning helped students to develop characteristics of model-based reasoning. I conjecture that, through more opportunities to reason in different contexts, the characteristics of model-based reasoning would become more robust.

**What Do These Results Tell Us About Biology Instruction?**

Within biology education it is widely accepted that students are not developing biological ways of understanding through coverage-oriented lecture and memorization (AAAS Project 2061, 1990; Christianson and Fisher, 1999; Okebukola, 1990; Osborne and Wittrock, 1983; Leach, Driver, Scott and Wood-Robinson, 1996a; Lin and Hu, 2003; Wandersee, Mintzes and Novak, 1994). Although the field of biology education
is aware that traditional approaches to biology instruction are not effective at helping students develop desirable ways of understanding, many biology teachers continue to focus on biological facts, definitions, and processes, ignoring the broader conceptual tools that govern students’ understanding of the subject matter, such as justification schemes, problem solving approaches, and beliefs about biology. My research provides an alternative way to think about biology instruction.

**Concepts Driving Instruction versus Ways of Thinking.** For the most part, biology instructors design lessons based on the biology content they want the students to acquire, for example, the steps in meiosis and mitosis, the parts of the cell and their function, or the organ systems. My research suggests that, at least in ecology, objectives for instruction can be focused not on acquiring content knowledge, but on helping students develop the ways of thinking of biologists. In other words, in this alternative approach, the goal for a unit in biology would be to help students develop a desirable way of thinking (multi-dimensional relating, for instance) rather than focus on a compartmentalized topic (for example, the parts of a cell and their function). This does not mean that, in this alternative approach, teaching is devoid of content. On the contrary; helping students develop ways of understanding different biological concepts is the only way to help students develop desirable ways of thinking. But, in this rethinking of instruction, the content is selected specifically because of the developmental interdependency between one’s ways of understanding and a particular way of thinking.
Consider, for example, my teaching experiment unit. The cognitive objective for instruction was to help students develop characteristics of model-based reasoning: multi-dimensional relating, non-linear causal reasoning, and a system-oriented perspective. I chose ecosystem functioning as the context for students to develop explanations based on particular scientific models, such as matter and energy transformations, energy degradation, and conservation of mass. I designed problem tasks to help students develop a basic understanding of cellular processes and matter and energy flow within the context of an ecological system because these processes contribute to explaining the functioning of a biological system. Therefore, my objectives were hierarchical. In order for students to develop multi-dimensional relating, they needed to understand, for example, that plants and animals are composed of similar elements that cycle within a system. To develop this understanding, the students also needed to understand, in a general sense, what the organisms did with the elements they consumed and what they produced. If the students understood organisms as matter transforming systems, and cellular processes of organisms as mediating matter cycling, then this provided an opportunity for them to think multi-dimensionally about the functioning of a system, rather than considering only the organismic level. So, although one of my tasks was designed to help students develop a basic understanding of photosynthesis and respiration, developing this understanding served a larger purpose—to help students begin to reason multi-dimensionally.

Helping students develop a way of thinking about the provisional nature of ecology knowledge is another valid cognitive objective for guiding instruction from a
DNR perspective. The theories developed in ecology change frequently and have a low level of generality (Pickett, Kolasa and Jones, 1994). In fact, scientific theories in general cannot be definitively established. However, in biology courses, ecological theories are frequently taught as if they were facts: “Thus, a sort of freezing befalls scientific knowledge, which is regarded then almost as a thing instead of a conceptual system” (Del Solar and Marone, 2001, p.684). Students develop a belief that biology is a set of truths. From a DNR perspective, instruction could be designed to help students develop their interpretation of biology to include an understanding of the provisional nature of scientific theories. Problem tasks would be designed to provide opportunities for students to consider two or more competing conjectures as explanations of biological phenomena. For example, through problem situations, students would consider how the assumption of ecological equilibrium versus its nonexistence affects model development. Students would be given opportunities to reason about how each assumption influences the interpretation of the data collected. This alternative focus for instruction differs dramatically from the more traditional focus in which teachers design instructional units based on specific sub-domains: genetics, organ systems, cell structure and function, and so forth.

Rethinking biology instruction as being organized around helping students develop ways of thinking could begin as early as elementary school. Students develop many undesirable ways of thinking during these early years, such as teleological reasoning, simple-linear causal relating, and a belief that biology is comprised of an established set of facts. With a focus on students’ ways of thinking, rather than
compartmentalized content knowledge, the curriculum could help *desirable* ways of thinking become robust throughout the schooling years.

**Presenting Concepts versus Concepts Emerging.** In most biology classrooms, the teachers present the students with the concepts they are going to be learning prior to the actual instruction. Instruction then proceeds by lecture, reading, or a laboratory activity intended to explain and demonstrate the concepts (Johnson and Lawson, 1998). My research study presents an alternative way to help students develop desired understanding in biology: problem situations designed to create intellectual need. The students in the teaching experiment were not privy to the problem learning objectives prior to the presentation of the problem tasks. Rather, they were given challenging tasks and, through the development of solutions, biological concepts emerged. In some cases, the students’ existing ways of understanding were refined or modified; in other cases, new ways of understanding were developed. In all cases, biological concepts were introduced only after the students had an opportunity to reason about the situation. In this way, the biological concepts were *a posteriori* to the students’ intellectual stimulation and desire for resolution.

Long-term instruction, in which the biological concepts emerge from engagement in biological situations, has the potential to not only lead students to develop desirable ways of understandings but also to develop desirable beliefs about biology. As students engage in the formulation and justification of their ideas, they may develop a belief that biology is a problem solving science. For example, biology involves making sense of observations and patterns in nature. Biologists engage in
developing and applying theoretical models to explain or predict these observations and patterns (Giere, 1991). With multiple courses designed to flow the biology concepts to emerge from the solution process, students may begin to develop an intellectual appreciation for the interrelationship between biological phenomena and the related concepts and processes courses typically “cover.”

**What Makes Implementation of DNR Difficult within the Current Situation?**

There exist several elements that could make the implementation of DNR-based instruction in biology difficult. These can be arranged into four categories: (a) the structure of the discipline of biology, (b) the influence of the teacher on enacting the instructional approach, (c) the research on students’ biology, and (d) the context of biology education. The generation of these categories was influenced by Fey’s (1994) discussion of four factors that influence the development and implementation of any mathematics or science curriculum in the U.S.

**Difficulty #1: The Discipline of Biology**

As mentioned in chapter 1, the field of biology is partitioned into several different domains, including microbiology, molecular biology, ecology, bioinformatics, evolution, and biochemistry. The separation of biology into distinct domains derives from a necessity to specialize and focus on a manageable amount of information at one time in order to advance the field. To a practicing biologist, the interrelationship between these different domains is understood.

The traditional philosophical approach to instruction in biology has been to conform to this same compartmentalized approach, with concepts apportioned into
manageable chunks of subject matter, both for the learners and the instructors. Accordingly, many biology textbooks present information segregated into separate domains. Designing biology education around these domains, however, may not be the best way for students to develop ways of understanding and thinking institutionalized in the field. In this compartmentalized approach, students are presented with biological concepts and processes in isolation and are expected to learn them in a given sequence without developing a way of understanding the relationship between these concepts. As a result, students develop a belief that biology is an assemblage of unrelated facts that must be memorized. This way of thinking about biology can then influence students’ interpretation of new information. Rather than try to identify connections and relationships between biological concepts, students are content to simply memorize facts and engage in rote learning.

Alternatively, designing instruction based on ways of thinking requires helping students to develop the conceptual tools that govern biologists’ activity. “Ways of thinking”, however, is an educational researcher’s construct. Among the community of biologists, the focus of their daily activity is the generation of new knowledge—developing, revising, or applying biological concepts and models to explain natural phenomena. Biologists’ activity involves the application of their existing understanding of biological concepts and models to interpret and make sense of new situations. Thus, college and secondary level instructors focus on helping students acquire a vast number of concepts in introductory classes, presumably because they
believe that the students do not have enough content knowledge to reason about biological phenomena.

The research, however, reveals that the amount of previous biology instruction one has does not improve performance on pre-tests or post-tests (Anderson, Sheldon, and Dubay, 1986; Johnson and Lawson, 1998; McAdaragh, 1981). In other words, students are not “retaining” what they are taught. These findings problematize the current focus of introductory biology courses; instructors worry about course prerequisites and “covering” topics to make certain that students are adequately prepared for upper-level courses. Notably, Johnson and Lawson (1998) found that reasoning ability was the better predictor of final examination scores in both inquiry and traditional classes.

Reorganizing biology instruction around anything other than the acquisition of biological concepts would mean developing a new way of thinking, or “paradigm”, with respect to biology education, a challenging task. The ways of thinking of biologists are essentially the characteristics reflective of their mental acts as they practice biology. School science does not often focus on what scientists do, but rather, focuses only on helping students acquire what biologists know. Helping students develop the mental acts of predicting, synthesizing, modeling, and explaining would require thinking differently about the objective of biology instruction.

Difficulty #2: The Influence of Teachers

Teachers’ beliefs have been shown to directly influence their motivation, intentions, and behaviors in the classroom (Czerniak and Lumpe, 1996; Haney,
Czerniak, and Lumpe, 1996; Pajares, 1992). One foundational aspect of teachers’ beliefs that would influence the implementation of DNR-based instruction is their beliefs about student learning. One’s philosophical perspective on learning influences how one structures lessons, designs curriculum, and interacts with students.

**Structuring lessons and designing curriculum.** In my experience working with high school biology teachers, many of them believe that the best way to help students “learn” biology is to offer them multiple opportunities to re-present biological concepts. They begin a unit with explicit instruction of a set of concepts, and then offer activities to either demonstrate the science ideas or reproduce them. For example, one high school biology teacher began a unit she titled “building knowledge on photosynthesis” by first lecturing to the students about what photosynthesis is and where it occurs, after which she outlined the steps involved. The following day she assigned students to create a power point presentation of the steps involved in photosynthesis. During an informal discussion after this class, the teacher shared that she believed that providing students with multiple opportunities to reproduce information was the best way for them to learn. She suggested that students could take notes on the steps of a biological process for one lesson, act out the steps in another lesson, and draw them for a third lesson. She added that the students needed an opportunity to experience the concepts visually, kinesthetically, and traditionally (for her, traditionally meant note taking). She stated that her photosynthesis unit was one of her best units because she provided multiple activities that complemented the material presented in lecture.
This teacher believed that the students would retain the information if they had enough opportunities to re-present the information, and these beliefs directly influenced her lesson design. In this instructional approach, the students perform their tasks solely because they are asked to do so; not because the activities hold intrinsic value or provide intellectual stimulation. Although this teacher explicitly stated that she created an environment in which the students are “actively learning” (for example, creating power point presentations), the students are not afforded opportunities to enter into cognitive disequilibrium-equilibrium phases and reorganize their schemes.

Similarly, in a typical undergraduate college level biology course, fast-paced, fact-packed, coverage-oriented lectures characterize the instructional approach (Christianson and Fisher, 1999; Klionsky, 2004; Powell, 2004). The students are passive recipients as the instructor transmits knowledge as a finished product. A belief that the best way to help students learn is for them to record information and memorize it underlies this lecture-based approach. In fact, some instructors intentionally do not post their lecture notes on the internet and explicitly tell their students that the process of writing the information during lecture will help them to remember it. In this passive learning format, the instructor conveys knowledge to the students, and they, in turn, are expected to memorize it “with a tacit understanding that cramming for the exams is accepted” (Klionsky, 2004). Consequently, students develop an undesirable way of thinking about the nature of biology. Furthermore, much research has been published that suggests that these teacher centered approaches to instruction do not help most students internalize and interiorize biological concepts,
(Klionsky, 2004; Johnson and Lawson, 1998; Lord, 1994; National Research Council, 1999; Powell, 2003). My findings from the student interviews conducted in the first phase of this study concur.

The DNR perspective proposes a distinctly different way to think about teaching and learning. For learning to occur, students must see a need for what we intend to teach them. As stated earlier, this means that concepts emerge from engagement in intrinsic and challenging tasks. In my implementation, problem situations provoked students’ intrinsic motivation to search for a solution, and constraints added to the tasks were designed to perturb students’ equilibrium. From this perspective on learning, the students’ knowledge guided the direction of instruction and the design and development of classroom tasks.

Helping teachers develop these ways of thinking about pedagogy necessarily means assisting them to develop new ways of understanding both learning and instruction. Not only would teachers need to reorganize their schemes of how students learn, but they would also need to develop knowledge about how to access students’ existing ways of understanding and value this information for designing tasks. Extensive professional development would be needed to aid teachers in the development of these ways of thinking. Furthermore, in the event that teachers develop an understanding of a social-constructivist perspective on learning and agree that the DNR approach to instruction is effective, they may still decide that this approach is not practical or plausible in the classroom, or requires too much time and effort.
Interactions with students. Another way teachers’ beliefs would influence the implementation of DNR-based instruction is through their interaction with students during classroom activities. As the teacher and students interact together, negotiation of expectations occurs (Brosseau, 1997). This negotiation results in a relationship that forms between the teacher and the students—a “didactical contract.” In most biology classrooms—secondary and college level—a didactical contract is established in which the students expect the teacher to convey the biological concepts they need to learn in a clear and organized manner. Likewise, the students are expected to reproduce this knowledge in examinations, and in some cases, apply it to answer questions from the text or to observe and make sense of experimental results. From the DNR perspective, instruction should be designed to promote personal knowledge construction. This means that students take responsibility for their learning, and the teacher passes down this responsibility to the students. In this alternative approach to instruction, tension can develop between a teacher’s desire not to intervene in the students’ solution process and her desire for closure, a phenomenon referred to as the teacher’s “epistemological responsibility” (Balacheff, 1991).

For example, in a study by Balacheff (1991), the author set out to explore the benefits and limits of the use of social interaction in the mathematics classroom within the context of teaching and learning mathematical proof. One of his goals was to design a situation in which the responsibility for the validity of the problem’s solution was passed down from the teacher to the student (devolution). The teacher was provided with a well-designed problem that would engage students—one that the
students could accept and act on. An agreement was made between the teacher and researcher that once the students accepted the problem as their own, the teacher was not to intervene until the students presented a solution.

Balacheff (1991) described the manner in which the teacher established a unique social setting for the students; however, the interventions of the teacher led the students to perceive this learning situation as a typical lesson, in which the role of the student was to rely on the teacher for the solution process. Through what appeared to be innocuous comments and questions, the teacher led the students to believe that their solution would be validated by the teacher, rather than each other, and the necessity to engage in ways of understanding proof were extinguished. The students no longer saw the problem as an opportunity to discover a solution, but rather, as another exercise where they would rely on the teacher’s evaluation of their solutions. Thus, the interventions of the teacher changed the didactical contract for the students, and the intended learning was averted. Lotan, Cohen, and Holthuis (1994) also found that a teacher’s interference in small group activities decreased the degree to which the group members interacted: “When a teacher facilitates, disciplines, or provides direct instruction, it has the effect of shutting down the student talk” (p. 23).

According to Brosseau (1997), a tension exists when the teacher tries to place responsibility for learning on the student. The teacher is responsible for providing situations and activities for the students that help the students develop scientific understanding without telling the students everything they need to know. This requires formulating a method for making the answer explicit for the student: “How to answer
with the help of previous knowledge, how to understand and build new knowledge, how to ‘apply’ previous lessons, how to recognize questions, how to learn, guess, solve, etc.” (Brosseau, 1997, p.35). The students, on the other hand, want to know what it is that the teacher wants them to learn so they can be successful. If a student struggles with or avoids the problem, then the teacher “has the social obligation to help [the student] and sometimes to justify herself for having given a question that is too difficult” (Brousseau, 1997, p. 31). Often this creates a tension between the teacher’s responsibility and the students’ expectations (Balacheff, 1991; Herbst, 2002).

In DNR-based instruction, the responsibility for learning must be passed onto the students. The students must be intellectually stimulated to engage in a problem situation and develop a solution. A teacher’s inappropriate interaction with the students can thwart the devolution of a problem solution and result in a teaching situation that does not progress into the modification of a way of understanding or thinking. Nevertheless, as seen from the analysis of the implementation of the problem tasks in my teaching experiment (chapter 7), the teacher’s guidance is needed at times to help shape ideas and observations if we are to help students develop scientific understandings (Ball, 1992). Thus, a teacher’s actions must be guided by an understanding of the tension between facilitating personal knowledge construction and the teacher’s desire to guide the students. Applying DNR-based instruction, then, requires that the teacher develop a new way of thinking about instruction and her role in the classroom.
It is challenging to reconstruct one’s conceptual scheme of the practice of teaching (Haney, Czerniak, and Lumpe, 1996; Lloyd, 1993; Munby, 1984; Richardson, Anders, Tidwell, and Lloyd, 1991). The most immediate challenge in this process is helping teachers recognize the need to consider how their students are interpreting situations and constructing knowledge. Just as students should have various opportunities to reason, teachers would need repeated opportunities to reason and reflect about their students’ learning and their own teaching. Furthermore, it is important for teachers to have a deep and broad understanding of biology in order to recognize changes in students’ ideas and modify instruction accordingly.

**Difficulty #3: The Research on Students’ Biology**

Designing problem tasks that lead students to cognitive puzzlement and, through conflict resolution, result in the emergence of the intended biology concepts, necessitates building on models of students’ biology. It follows that research must provide teachers with information about students’ typical ways of understanding and thinking in biology, the origin of this knowledge, and how students apply their knowledge in problem situations. Although there exists some research on students’ existing ways of understanding biology, there is a paucity of information about students’ *learning*: what students pay attention to in different biology situations, how students interpret these situations, what relationships the students draw on to solve biology problem tasks, and what types of situations cause the most difficulty for students and why. Since the goal of DNR-based instruction is to help students develop biological ways of understanding and thinking, it is essential that educational
researchers continue to examine students’ development of biological knowledge and identify obstacles to learning.

Distinguishing different types of problem situations in biology instruction would allow researchers and teachers to examine the methods students employ to solve different classes of problems. If we find that one class presents more difficulty for students, studies can help identify the cause of these difficulties, and teaching experiments can be administered to see if recommended remedies are effective and can guide the direction of instruction in the classroom. Thus, identifying where students have conceptual difficulties can lead to developing more coherent instructional tasks (Greer, 1992).

Although a complete analysis of the tasks for a specific conceptual domain would be beneficial for distinguishing where students have difficulties, once these difficulties are identified, it is necessary to determine whether these difficulties are the result of epistemological or didactical obstacles. Epistemological obstacles have roots in the historical pathway of mathematics and science. These obstacles are due to the nature of the development of human knowledge (Brousseau, 1997) and are often inevitable. Didactical obstacles are the result of narrow or faulty instruction. Many didactical obstacles are the result of teachers’ beliefs and are difficult to overcome. For this reason, explorations into the variety of ways in which students interpret and solve different types of problems in biology are needed in order to minimize didactical obstacles and help students overcome epistemological obstacles. Such studies are almost nonexistent in biology education.
Difficulty #4: The Context of Biology Education

The *National Science Education Standards* (National Research Council, 1995) and AAAS *Benchmarks for Science Literacy* (1993) promote conceptual understanding and application in science. Many teachers, however, feel pressured to “cover” large amounts of material in biology because their students’ learning is measured by an external fact-oriented standardized test. In fact, there has been a movement in many states in the U.S. to resort back to “basic skills” science instruction. For example, in contrast to the *National Science Education Standards*, the *California State Science Standards* (California State Board of Education, 1998), adopted in 1999, reflect a substantial increase in specific factual content to be acquired at each grade level (American Physical Society, 1998; Bianchini and Kelly, 2003; Lopez, 1998).

Parents and other community members place pressure on schools and teachers to prepare their students to perform well on standardized tests. With these external pressures, teachers find it difficult to balance their desire to help students develop an *understanding* of biology concepts with their responsibility to “cover” a wide range of specific biology topics. Implementation of DNR-based instruction in biology would result in teachers “covering” less material. Teachers may be more inclined to consistently apply DNR-based instruction if empirical evidence showed that this instructional approach can at least match the performance on standardized tests of current approaches in biology education.
Comments Regarding the Difficulties of Implementing Harel’s DNR in Biology Education

The difficulties outlined above suggest that the implementation of Harel’s DNR-based instruction within the current state of biology education is a formidable task. This in no way means that we should reject the DNR instructional approach. A multitude of studies exist reporting the insufficiency of the current teacher- and concept-centered approach in helping students internalize and interiorize biology knowledge. After successfully completing multiple biology courses, studies report that students are unable to demonstrate a biological understanding of some of the more basic biological concepts and processes. Therefore, a reconceptualization of biology teaching and learning is exigent. The implementation of DNR-based instruction and the identification of difficulties inherent in its implementation represent the first step in learning how to effect change, and provides an awareness of the challenges involved.

Directions for Future Research

The preceding discussion of the difficulties of implementing DNR-based instruction in the current educational environment pointed towards several areas of future research, including approaches that effectively help teachers modify their ways of understanding both learning and instruction, varied investigations of student learning in biology, identification of didactical and epistemological obstacles to learning, and standardized test performance of students participating in instruction based on the DNR perspective. There are, however, more immediate areas of research directly related to this study of the application of DNR-based instruction to biology.
My study was limited to only one domain of biology—ecology. Future studies are needed to address the extent to which DNR-based instruction applies to other domains of biology. Although I submit that model-based reasoning is a way of thinking that characterizes biologists’ acts as they account for biological phenomena in a variety of fields of biology, this study was limited to interviewing and interacting with practicing ecologists only. Further studies are needed to identify and explicate the ways of thinking and interdependent ways of understanding of biologists in multiple domains of biology before one can generalize that DNR-based instruction is applicable to biology education.

Another direction for future research is the implementation of problem situations based on the necessity principle at varying academic levels. More specifically, studies are needed to identify those features of problem situations that create intellectual need among high school or middle school biology students. Are there features unique to the secondary level? Furthermore, what are the specific challenges inherent in the implementation of DNR in biology instruction at the secondary level? For instance, how do secondary level group dynamics influence the devolution of problems? Answers to these types of questions are needed to determine how best to support the introduction of DNR-based instruction into the secondary level.

A third direction for research would be to identify the categories of experiences that constitute intellectual need in biological practice. The problem situations designed for this study created a need in students to understand why a
particular phenomenon occurred. They sought to explain a phenomenon in depth. Thus, these problems likely created a *need for causality*. What other experiences constitute intellectual need in biology? Furthermore, what roles do other types of necessity play in biology students’ scheme reorganization? In other words, how do social, political, altruistic, and emotional needs influence students’ engagement in problem situations or contribute to or hinder efforts to create cognitive puzzlement? If we can better understand both intellectual need and the influence of other needs in biology learning environments, we have a better chance of designing coherent problem tasks and learning experiences for students.
APPENDIX 1: PILOT INTERVIEW PROTOCOL

Name.
Year in college.
Major.
What biology courses have you taken?
Do you think you understood the material pretty well?
“There are no right answers to these questions. I am interested in your thinking as you answer them – not the answer but the thought process behind the answer.”

1) Share any relationships you can find between these items. (Present the individual intertidal task cards slowly.)

2) Mexicanthina Lugubris is a non-native mollusc that feeds on barnacles. (Present card.) What could possibly happen to this ecosystem (point to the system the student created/described in #1) if this species were introduced into this ecosystem?

2b) What other information might you need or want to know to determine what could happen?

3) Imagine the water temperature of the ocean increased by two degrees over the next 100 years as a result of global warming. Do you think this would affect this ecosystem? If yes, how? If no, why not?

4) (Present biology concept/process cards one at a time.) What relationship if any can you identify between these concepts and the elements presented for the intertidal ecosystem you have described?

5) (Begin by explaining how samples of plants and animals are taken at a particular site.) Here is some hypothetical data taken over a fifty year period from an intertidal ecosystem. (Present data cards.) Can you identify any changes in this ecosystem over this time period? If yes, what might be possible causes of these changes?
**Intertidal Task Cards:**

Present students with index cards with the following words and picture:

<table>
<thead>
<tr>
<th>Sand</th>
<th>Seagrass – A marine plant that grows in the sand in the intertidal zone.</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Sand Image]</td>
<td>![Seagrass Image]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Native Mollusc – Acanthina punctualata. A marine gastropod (snail) that lives on and around the rocks in the intertidal zone. This snail preys on littorines (other small snails) and barnacles.</th>
<th>The Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Native Mollusc Image]</td>
<td>![Ocean Image]</td>
</tr>
</tbody>
</table>

© Guido T. PUP-Hls
The Sun

Rocks

Turf Algae – green, brown, and red algae that grow on the rocks and sand in the intertidal zone.

Climate (temperature, rain, wind)
<table>
<thead>
<tr>
<th>Western Sandpiper – a small shore bird that forages on the intertidal zone. The Sandpiper feeds on insects, small crustaceans (like barnacles) and molluscs (snails).</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Microfauna: the marine animal population too small to be clearly distinguished without the use of a microscope. It includes protozoa, small nematodes, small unsegmented worms, and arthropods. Many of these organisms live in and feed on the algae.</th>
</tr>
</thead>
</table>
Mexicanthina – A marine gastropod (snail) that lives on and around the rocks in the intertidal zone. This snail preys on other small snails and barnacles.

Barnacles – animals that live in marine environments. These barnacles attach to rocks on the intertidal area and filter feed when the tide is high enough to reach them. They provide shelter for other intertidal organisms.
Biology concept/process cards:

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>PHOTOSYNTHESIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATTER</td>
<td>DECAY</td>
</tr>
<tr>
<td>CO₂</td>
<td>NITROGEN</td>
</tr>
<tr>
<td>OXYGEN</td>
<td>RESPIRATION</td>
</tr>
</tbody>
</table>
### Data cards:

<table>
<thead>
<tr>
<th>Avg temp of water in deg.</th>
<th># of Acanthina (mollusc)</th>
<th>Year</th>
<th># of humans observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>57</td>
<td>118</td>
<td>1955</td>
<td>2</td>
</tr>
<tr>
<td>58</td>
<td>136</td>
<td>1960</td>
<td>1</td>
</tr>
<tr>
<td>61</td>
<td>121</td>
<td>1965</td>
<td>2</td>
</tr>
<tr>
<td>59</td>
<td>126</td>
<td>1970</td>
<td>4</td>
</tr>
<tr>
<td>60</td>
<td>118</td>
<td>1975</td>
<td>5</td>
</tr>
<tr>
<td>61</td>
<td>105</td>
<td>1980</td>
<td>12</td>
</tr>
<tr>
<td>61</td>
<td>110</td>
<td>1985</td>
<td>18</td>
</tr>
<tr>
<td>62</td>
<td>63</td>
<td>1990</td>
<td>22</td>
</tr>
<tr>
<td>61</td>
<td>96</td>
<td>1995</td>
<td>31</td>
</tr>
<tr>
<td>63</td>
<td>101</td>
<td>2000</td>
<td>37</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>% coverage of Seagrass</th>
<th>% cover of algal turf</th>
<th># of Mexicanthina</th>
<th># of Western Sandpipers observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>35%</td>
<td>55%</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>37%</td>
<td>50%</td>
<td>10</td>
<td>18</td>
</tr>
<tr>
<td>34%</td>
<td>56%</td>
<td>7</td>
<td>16</td>
</tr>
<tr>
<td>33%</td>
<td>58%</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>31%</td>
<td>54%</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>32%</td>
<td>53%</td>
<td>22</td>
<td>17</td>
</tr>
<tr>
<td>30%</td>
<td>61%</td>
<td>31</td>
<td>15</td>
</tr>
<tr>
<td>31%</td>
<td>63%</td>
<td>35</td>
<td>17</td>
</tr>
<tr>
<td>29%</td>
<td>67%</td>
<td>47</td>
<td>17</td>
</tr>
<tr>
<td>30%</td>
<td>66%</td>
<td>54</td>
<td>18</td>
</tr>
</tbody>
</table>
APPENDIX 2: LIST OF BIOLOGY TEXTS

To develop a pragmatic list of history and philosophy texts, I contacted professors from the science studies department at the University of California, San Diego and asked for recommendations of resources that address the growth of biological thought over time. I also considered texts included on the recommended reading list of the SHiPS (Sociology, History, and Philosophy of Science) Resource Center Web Site (http://www1.umn.edu/ships/).

1. *The Structure of Scientific Revolutions* by Thomas Kuhn
2. *The Growth of Biological Thought: Diversity, Evolution, and Inheritance* by Ernst Mayr
3. *Ecological Understanding* by Pickett, Kolasa, and Jones
4. *Doing Biology* by Hagen, Allchin and Singer
5. *The Order of Things: An Archaeology of the Human Sciences*, by Michel Foucault

Each of these texts has components that discuss some aspect of the development of biological thought over time.
APPENDIX 3: INTERVIEW TASKS

Fall 2004 Interview Protocol

Introduction:
My name is April Maskiewicz and I am a PhD student in the Math and Science Education Program here at UCSD. For my dissertation research I am studying students’ learning in ecology. The purpose of this study is to determine ways to better help students develop ways of understanding ecology.

During this interview you will be asked to respond to questions or problem situations related to ecology phenomena. There is no obligation to participate in this study. Your participation will in no way impact your grade in this course. The instructor will not know the identity of those students participating in the study. Information obtained in this study will not be shared with the instructor of this course or with the TA(s) of the sections that the study participants attend. Participation is strictly voluntary and you can withdraw from the study at any time.”

(Describe for the student the Ecosphere.)

1. Have you ever heard of or seen one of these spheres? If yes, what do they know about them? If no, describe the sphere: “This is a self-contained and self-sustaining miniature ecosystem encased in glass. Inside each Ecosphere are microorganisms, red brine shrimp, algae, and filtered seawater. The Ecosphere is a self-sustaining ecosystem, so you never have to feed the life within. The spheres can survive for more than eight years.”

2. The Situation: Consider that you have been hired to teach a summer session for high school students here at UCSD. The first activity you will lead for the session is to have students create their own Ecospheres. The coordinator for the program has told you that although the students really enjoy this activity, many of them create spheres that die before the summer session even ends. She would like you to help the students understand how the Ecospheres work so that the students have a better chance of creating a sphere that will last a long time.

3. What ideas do you have about why this Ecosphere works? In other words, why is it able to survive for so long?
   a. If the student has difficulty starting – ask: What can you identify as the components of this system?

4. What do these organisms need to survive? Where do they get these things?
5. Why don’t you ever need to empty out the sphere? Or add anything to the sphere?
6. Producers versus consumers:
   a. What would happen if you didn’t have algae in the sphere?
b. If you didn’t have the micro-organisms such as bacteria in the sphere?
c. If you didn’t have shrimp in the sphere?
d. Can the algae survive without the shrimp? Can the shrimp survive without the algae? Why or why not?

7. Matter
   a. Where do these organisms get their nutrients for growth and survival
   b. What does the new alga need to grow? Where does it get this from?
   c. If there is no soil, where does the alga get its “stuff” from to grow?
      Where does the producer get its nutrients for growth and survival? (If they use CO2 in the air to make sugars, then why doesn’t the air run out of CO2? It comes from shrimps breathing. Then where does the shrimp continue to get the CO2? From eating. Then the CO2 comes from the plant even though the plant takes it in. How could you explain this to a student?)

8. Why do the shrimp die when the oxygen is too low?

9. Energy:
   a. Where do these organisms get their energy?
   b. What do plants use the energy in sunlight for?
   c. How do the consumers release energy from food?
   d. How do the producers release energy from food?
   e. Why does the sphere need light but not direct sunlight - What will happen?

10. Decomposition
    a. What happens to the organisms when they die?
    b. Why doesn’t the sphere fill up with dead organisms?
    c. How do decomposers get their energy from dead organisms? (If stuck ask, how do other organisms get their energy from eating?).
    d. If there were no decomposers in this system, what would happen?
    e. What would happen if the decayed material disappeared?
    f. When decomposers breakdown the dead organisms, what happens to the materials in the dead plants or animals?

11. If you were to create a visual diagram to help the students understand the relationships that result in this functional ecosystem, what might this diagram look like? (Provide paper and marker to create a diagram.)

12. One of your students finds that his system has an overgrowth of green algae. Why might this have happened? What do you think you should do to help the system recover? (If the student has no idea, ask what they would suggest to do if the green algae were disappearing at a rapid rate.)
APPENDIX 4: VOLUNTEER INFORMATION SHEET

Request for Interview Subjects

Research Project: Rethinking Biology Learning and Teaching: Applying DNR-based Instruction to Biology Education

Researcher: April Maskiewicz, PhD student in Math and Science Education
Contact information: amaskiewicz@ucsd.edu

Brief Overview of Research: For my dissertation research I am studying students’ learning in biology. The purpose of this study is to determine ways to better help students develop ways of understanding biology. I am here to ask for students to volunteer to participate in my study.

I am looking for students for individual interviews (approx. 1 hour) and also for students to participate in a short series of interviews (two or three interviews). During these interviews you will be asked to respond to questions or problem situations related to biology phenomena. Through these interviews you may gain insight into various biology topics.

There is no obligation to participate in this study. Whether you choose to participate or not will in no way impact your grade in this course. The instructor will not know the identity of those students participating in the study. Information obtained in this study will not be shared with the instructor of this course or with the TA(s) of the sections that the study participants attend. Participation is strictly voluntary and you can withdraw from the study at any time.

If you have any questions at all, please contact me at the e-mail address above.

Name: __________________________________________________________

Contact information

Phone #: ________________________________________________________

e-mail address: ________________________________________________
APPENDIX 5: E-MAIL RECRUITMENT LETTER

This e-mail is intended for students in the following MAJORS in WI05:
BI28 Animal Physiology & Neurosci
BI29 Biochemistry and Cell Biology
BI30 Ecology, Behavior & Evolution
BI31 General Biology
BI32 Microbiology
BI33 Molecular Biology
BI35 Human Biology
UNBS Undeclared-Biological Sciences

Living Organisms are connected to each other in the CYCLE OF LIFE.

Enroll in Biology Workshop (BILD 95) Spring Quarter and develop a better understanding of how the cycle is a delicate equilibrium.

Experience a FUN, HIGHLY INTERACTIVE, problem-solving approach to learning biology.

Wednesdays 3:00-4:20pm
Section ID: 534201

This course is restricted to Lower-Division Undergraduate students only.

------------------------------------------------------------------------
Sent via StudentLink
http://studentlink.ucsd.edu/
APPENDIX 6: PROBLEM TASK DAY 1—SELECTING GROUP TO RECORD

The table below lists important historical, archeological, geological, and astronomical events—but not in chronological order. Once you have organized the data, create an analogy that you could use if you were a TA to help your students understand how long humans have been on earth relative to the earth’s age.

<table>
<thead>
<tr>
<th>HISTORICAL</th>
<th>ARCHAEOLOGICAL</th>
<th>GEOLOGICAL</th>
<th>ASTRONOMICAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beginning of dark ages in Europe</td>
<td>Evidence of stone ground tools</td>
<td>Marine and invertebrates</td>
<td>Probable origin of our galaxy</td>
</tr>
<tr>
<td>500AD</td>
<td>10,000 B.C.</td>
<td>abundant 500 million</td>
<td>5.5 billion</td>
</tr>
<tr>
<td>Discovery of America 1492</td>
<td>Evidence of permanent dwellings</td>
<td>Age of Fishes 420-360 million</td>
<td>Probable origin of life 4.0-3.6 billion</td>
</tr>
<tr>
<td></td>
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APPENDIX 7: FINAL TEACHING EXPERIMENT PROBLEM TASKS

Problem Set One

Question 1A:
The Ecosphere is a self-contained miniature ecosystem encased in glass. Inside each Ecosphere are micro-organisms (bacteria), red brine shrimp, algae, and filtered sea water. The Ecosphere is a self-sustaining ecosystem, so you never have to feed the life within. These small spheres can survive for more than eight years. The large spheres have been known to last for over 20 years.

The Ecosphere will thrive for over eight years without the owner having to add or remove anything from the sphere. However, this is not the case with any combination of organisms in a closed container. The company that created these spheres had to find the right combination of organisms that would survive together for an indefinite period of time. Explain why this combination of organisms allows this sphere to survive for such a long time? Be specific. Provide a diagram to represent your ideas.

Question 1B:
A student analyzing the sphere hypothesized that if the algae, or the bacteria, or the brine shrimp were removed from the sphere, the other organisms in the sphere would not survive. Do you agree with this? Why or why not? Explain.

Question 1C:
When the algae or the bacteria are removed from the sphere, all the organisms in the sphere do indeed die. However, when the shrimp are removed from the sphere, the sphere is still able to survive indefinitely. The algae and bacteria continue to grow and survive. Explain why or how this is possible. Be specific.

[Hint: Data on the composition of the sea water over time can be useful.]
Data for Question 1C

Page 1:

**Ecosphere Water Quality Data**

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**Turbidity:** measured in Nephelometric Turbidity Units (NTU)

A measurement that provides an estimate of the muddiness or cloudiness of the water due to clay, silt, fine organic and inorganic matter, soluble colored organic compounds, plankton, and microscopic organisms. A nephelometer is used to measure how much light is scattered by suspended particles in the water. The greater the scattering, the higher the turbidity. Therefore, low NTU values indicate high water clarity, while high NTU values indicate low water clarity.

---

**Question 1D:**

One of the functional roles of the bacteria is to keep the sphere clean by removing the shrimp waste. In the first trials to create a functioning sphere, the researchers used small snails similar to those in a fish tank. These snails are known to eat the waste of fish, brine shrimp and other marine organisms. Although the snails were able to keep the sphere “clean” the brine shrimp and algae did not survive for a long period of time. Explain why the snails were not able to keep the sphere alive.

[Hint: Data on the composition of the sea water over time can be useful.]
Data for Question 1D

**Ecosphere Water Quality Data - No Bacteria, With Snails**

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**Turbidity:** measured in Nephelometric Turbidity Units (NTU)
A measurement that provides an estimate of the muddiness or cloudiness of the water due to clay, silt, fine organic and inorganic matter, soluble colored organic compounds, plankton, and microscopic organisms. A nephelometer is used to measure how much light is scattered by suspended particles in the water. The greater the scattering, the higher the turbidity. Therefore, low NTU values indicate high water clarity, while high NTU values indicate low water clarity.

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**Question 1E:**
If the sphere is placed in a closed box (a dark environment) after a period of weeks everything in the sphere dies. What role does light play in keeping each of the organisms alive? Create a diagram to represent your ideas.

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**Question 1E: Supplemental**
Consider the following statement: If energy cycles like matter does, then I should be able to put a plant in the sunlight for a week, then remove it from the light and it should survive in a box (or unlit place) for years because the energy it was supplied with would keep cycling. But we know that this is not true – the plant dies. How can you account for this? If needed, revise your diagram.
Question 1F:
i: The engine of a car is often used as an analogy of how consumers in a system (such as the brine shrimp) are able to survive. Why might this be an appropriate analogy? Why not?

ii. What might be an appropriate analogy for the bacteria?

iii. What might be an appropriate analogy for the algae?

Question 1F: Supplemental
Imagine you are a TA grading students’ answers to this “create an analogy” question. One student writes:

“The car analogy also works well for the bacteria and the algae. However, the algae require two analogies, one is the car and the other is a powerhouse.”

How would you respond to this claim? Explain.
READING ASSIGNMENT 1
DUE 5/4/05

Go to the following website:
http://www2.nsta.org/energy/find/primer/primer2_1.html

You are responsible for reading through “An Energy Primer – Part 2” in its entirety. When you get to the bottom of each page, there is a green arrow that will bring you to the next page in this section. There are 22 pages in this section (Part 2). You are done when the green arrow says “Part 3…”

You should be able to answer the following questions after reading this assignment:

1. A plant grows from a seed into a large tree. Does it get its mass (the matter that makes it a larger heavier plant) from the soil? What is your evidence?

2. Is water “food” for the plant? What is your evidence?

3. What evidence is there that “air” is involved in plant growth and development?

4. What evidence is there for the hypothesis: “plants restore the air somehow”?

5. What experiment can show that light is required for the “replenishment” of the air?

6. Do plants “breathe” like animals? What is your evidence?

7. Where does the oxygen produced by plants come from, the carbon dioxide or the water?

8. What evidence do you have that carbon dioxide is required in order for plant to release oxygen? [Hint: click on the orange writing (“several kinds of experiments”) in the middle of the page titled “Berthollet and Senebier”]

9. What part of the plant is necessary for oxygen to be produced?

10. Where does the mass (the matter) of the plant come from?

11. What does a green plant make specifically?

12. Where does the process of the conversion of CO₂ and H₂O to glucose and O₂ take place?

13. Why would Engelmann expect to see bacteria in the regions of the leaf where light was absorbed the most?

14. What is photosynthesis?

15. What support would you offer to support the claim that photosynthesis is the source of most of the energy on earth today?
Imagine that you are applying for a summer job here at UCSD as a teaching assistant for a three week Summer Science Workshop for high school biology students. Each year the professor teaching these high school students begins the workshop by having students create their own mini Ecospheres. The professor provides various types of plants, animals, and bacteria for the students to choose from. The professor has told you that although the students really enjoy this activity, many of them create spheres that die before the summer session even ends. She would like to hire a teaching assistant that can work closely with the students to help them understand how the Ecospheres work so that the students have a better chance of creating a sphere that will last a long time.

You know from friends who have interviewed before you that the professor asked them the following questions:

a. What would you tell the students to help them understand the needs of living organisms in a closed system? In other words, what is needed in a closed system of living organisms in order to keep the system functioning indefinitely?

b. Because various types of seawater plants, animals, and bacteria are available for the students to choose from to create their spheres, design a general diagram that could be used to help the students choose types of organisms wisely.

Write answers to both of these potential interview questions.
Problem Set Two

Question 2A
The following diagram represents a food web commonly found in lake ecosystems. What do the arrows represent? Label each arrow and be prepared to explain.

Use the diagram for question 2A to answer each of the following questions:

i. What specifically “goes into” each organism? Is your response the same for every organism in the web?

ii. What does each organism gain by consuming this? (In other words, why does each organism take it in?) Is your response the same for every organism in the web?
Question 2B
The diagram in Question 2A is a food web. How could the energy in an ecosystem be represented? Create a drawing of your ideas.

Question 2C
Based on the food web diagram and the energy diagram, how would you define the term “food”?

Question 2D
The following diagram represents the relationship between two different types of diets and how many humans the diets can support:

If there exists a set amount of grain, 10 humans eating only this grain can sustain themselves. However, only one human, eating only cows (beef) that feed on the set amount of grain, can sustain him or herself. Why would this be?
Question 2E
Ecosystems can also be represented by diagramming the BIOMASS (the total dry weight) of the various types of organisms. Biologists have found that in all types of ecosystems the populations of top predators are small compared to other organisms in the system. For example, there are few sharks in the ocean compared to fish or zooplankton. To model this, biologists calculate the biomass (the total dry weight) of all organisms of a particular type and create a diagram to represent or compare these amounts (see below).

![A Hypothetical Biomass Pyramid](image)

i) What explanation(s) might account for why the biomass decreases from herbivores to top carnivores? Be specific.

ii) One student proposed the following explanation for this diagram:

“The producers use the energy from the sun to convert carbon dioxide into glucose. This glucose is eaten by an herbivore and provides the herbivore with energy. Because the herbivore grows and reproduces and moves around, the herbivore loses much of this energy as heat. So there is less energy available for first-level carnivores. There are fewer organisms moving up consumer levels because at each level they need to eat a lot more food to get enough energy to sustain themselves.”

The class seemed to agree with this idea. However a fellow student asked the following question: “If plants (primary producers) create the glucose that provides energy for the other consumers, then why would there be fewer herbivores than primary producers? Wouldn’t the biomass of the herbivores be the same as the biomass of the producers?” How would you respond to this?
Problem Set Three

Question 3A
“IT can stretch for 7,000 square miles off the coast of Louisiana, a vast expanse of ocean devoid of the region's usual rich bounty of fish and shrimp, its bottom littered with the remains of crabs and worms unable to flee its suffocating grasp. This is the Gulf of Mexico's "dead zone," which last summer reached the size of the state of New Jersey.” (The New York Times, 1998)

The Gulf of Mexico “dead zone” is a seasonal phenomena occurring in the northern Gulf of Mexico, from the mouth of the Mississippi River to beyond the Texas border. Scientists have identified the cause of the dead zone as an oxygen deficiency in the water; oxygen levels within the zone fall below 2 milligrams per liter of water - too low to support marine life. Those organisms that can swim leave the area, but organisms such as crabs and worms are trapped in these suffocating waters. The oxygen depletion, referred to as hypoxia, begins in late spring, reaches a maximum in midsummer, and disappears in the fall. Hypoxic waters appear normal on the surface, but on the bottom, they are covered with dead and distressed animal life. The Dead Zone was first recorded in the early 1970's. It originally occurred every two to three years, but now occurs annually. In the summer of 1999 the Dead Zone reached its peak, encompassing 7,728 square miles.

Use what you know about functioning ecosystems to develop an explanation for what might be causing the hypoxic conditions each summer in the Gulf of Mexico ecosystem.

(Hint: Attached is a map of the region, dissolved oxygen contour maps for July 1990, 1993, 1997, and information about the waters that flow into the Gulf of Mexico. Use the simulator and these resources to help you develop an explanation for what might be causing the oxygen to be depleted in these waters each year during the summer months.)
Information about the waters flowing into the dead zone:
The Mississippi River Basin covers forty-one percent of the continental United States, contains forty-seven percent of the nation’s rural population, and fifty-two percent of U.S. farms. The waste from this entire area drains into the Gulf of Mexico through the Mississippi River. Included in this agricultural waste are phosphorus and nitrogen, which were first used in fertilizers in the United States in the 1930s. By the 1960’s, fertilizer use increased by over two million metric tons per year. Since then, concentrations of nitrate and phosphate in the lower Mississippi have increased proportionately to levels of fertilizers use by agriculture. Overall, nitrogen input to the Gulf from the Mississippi River Basin has increased between two and seven times over the past century. In addition to agricultural waste, inadequately treated or untreated sewage and other urban pollution is also dumped into these waters.
Question 3B
You are having a small summer house built on a lake in upstate New York. You have chosen this spot because of its isolation and the beauty of the lake. The lake is active with plant and animal life and covers an area of about 1.5 square miles. On its north side many small streams enter the lake carrying runoff from the area, while on the south side many small streams carry away some of the lake's water. Because of poor drainage in the area, it is necessary to have a septic tank installed. In order to have the septic tank do its job for a longer period of time, it is suggested to you, by the builder, to let all waste water (showers, sinks, garbage disposal, etc.), with the exception of the toilet empty into the lake. Since only you and two or three other people will be using the house and the lake is fairly large, you decide to give it some thought.

Discuss below what you would decide to do and why? Be specific.

HOMEWORK 2
Due 6/1/05

In this class we have learned about the roles of producers, consumers, and decomposers in helping to keep an ecosystem functioning. We have also studied some of the things that can go wrong when one of these ecosystem components is removed or begins to overpopulate. Additionally we have reviewed the biological processes that are essential in keeping an ecosystem functioning.

The hydrothermal vents are thriving ecosystems. The goal of this homework is for you to describe how these vent communities function without utilizing energy from the sun.

a. Who are the producers, consumers and decomposers in these hydrothermal vent ecosystems?

b. What are the biological processes that keep this unique ecosystem functioning?

c. Create a diagram that compares and contrasts the functioning of hydrothermal vent ecosystems with the more typical marine or freshwater ecosystems that we have studied in this class.
APPENDIX 8: HYPOTHETICAL LEARNING TRAJECTORY FOR PROBLEM SET 1

Goal – Problem Set 1:
(a) Students develop a biological way of understanding metabolic processes in cells (photosynthesis, respiration), decomposition, and large scale processes such as matter cycling and energy flowing in a natural system.
(b) These ways of understanding can be used to help student develop an understanding of the relationships among these processes.

Target Ways of Understanding:
Matter and Energy Transformation
- All living organisms are composed of similar elements (CHONPS) that cycle through both the biotic and abiotic factors of an ecosystem
- Living organisms function as matter-transforming systems
- Matter changes to matter. This change can release energy.
- Energy is lost in a biological system as heat

Decomposition
- Bacteria play a role in the cycling of matter
- Materials in one organism become part of another organism
- Decomposers are organisms such as bacteria that actually do the decomposing
- Decomposers respire

Photosynthesis and Respiration
- Plant mass comes primarily from carbon dioxide gas
- Plants use light energy to construct glucose from CO₂
- Plants breakdown glucose for energy and release CO₂
- Animals use oxygen glucose for energy and release CO₂
- Animals use during the breakdown of CHO compounds.

With these Ways of Understanding (WoU) students can begin to make connections between functioning of an organism or system, the common elements of living things, and the role of energy.

Question 1A:
Purpose: To elicit initial ideas. (Do not offer information sheets until students have had 15 minutes or more to discuss own ideas.)

Expected Students WoU that are elicited:
- Circle of Life is why sphere functions.
- Connections are between living organisms, food, CO₂ and O₂ exchange, and space. All at a phenomenological level.
- Focus on gas needs: O₂ and CO₂ cycle to replace each other. Plants need CO₂ – animals need O₂.
Focus on food needs for animals.
Bacteria “cleans” the sphere.
“Stuff” recycles – no mechanism.
Bacteria fixes Nitrogen.
Respiration involves the changing of gases between plants and animals.
There can be no excesses – inputs must equal outputs (in terms of needs of org and wastes).
Sunlight is energy for plant to photosynthesize – to make O2.

Students will create a cycle representing the feeding relationship between the shrimp, algae, and bacteria.

**Question 1B:**
Purpose: To elicit initial ideas about cycling of nutrients at the molecular level (elements).

Expected Students WoU that are elicited:
- “Stuff” recycles – no mechanism.
- Remove Algae – no oxygen
- Remove Shrimp – no CO₂.
- Remove Bacteria – orgs die from toxic waters.

Students will respond that the sphere cannot survive if one of the species is removed from the sphere.

**Question 1C:**
Purpose: To develop… WoU decomposers as organisms that contribute to the cycling of matter; WoU functional role of bacteria – recycle N and P in a form plants can use; WoU bacteria releases CO₂; WoU plants need N and P to survive.

Expected Solution Path:
This question is designed to challenge students’ idea that shrimp are necessary for the recycling of CO₂. First students will try to resolve where the CO₂ comes from. Then they may begin to rely on the data to make sense of why the system functions without shrimp. They will struggle to make sense of the data at first. After some time, they will understand why the system crashes in the first two data sets and this should help the students to identify the functional role of bacteria. The intent is that students conclude that bacteria transform the carbon, oxygen, nitrogen and phosphorus into a form that the plants can use.

Questions to follow up Question 1C: [warm up discussion for next day?]
a) Why is the sphere able to function without shrimp? Be specific.
b) What evidence do you have to support your claims?
c) What is bacteria’s role in this sphere? Is bacteria’s purpose in life to provide algae with its needs? What is bacteria’s purpose? (Targeted at addressing students teleological reasoning.)

**Question 1D:**
Purpose: Repeated reasoning. To develop… WoU the role of decomposers; WoU role of bacteria is to recycle N and P in a form plants need; WoU bacteria releases CO₂; WoU plants need N and P to survive.

Expected Solution Path:
This question is for students to apply their WoU role of bacteria to another situation. At first students may not immediately consider that bacteria convert P and N into usable form for plant. However, after reviewing the data they should conclude that snails do not make this conversion.

**Question 1E:**
Purpose: Develop… WoU that energy does not cycle as matter does; WoU energy lost as heat.

Expected Solution Path:
Students will begin by discussing the role of light in photosynthesis. They will conclude that with no light the plant dies, and then other orgs die. Students will create a diagram of energy that is cyclical – going from bacteria back to plants.

Ask each group to place diagram in front of class. Ask Supplemental question:

**Question 1E: Supplemental**
Purpose: Same as 1E.

Expected Student response:
Students will expect plant to die. They will then need to reconcile diagram with this expectation. Students will try to account for why energy doesn’t cycle. If it does not happen in small groups, class discussion may bring out common understanding that energy is lost as heat when organisms metabolize and grow.

Potential Follow-up Questions: If a plant loses heat, but needs a constant input of sunlight, not a heater, what is the relationship here? So I have a loss of heat and an input of light, how do you make sense of that?
Question 1F:
Purpose: WoU all organisms respire to gain energy – animals, bacteria, and plants. Respiration is taking in oxygen and an organic compound and breaking it down releasing energy and CO₂.

Expected Student Response:
   i. Gasoline is the energy. Car needs oxygen. Car burns gasoline to get energy and releases CO. Similar to animal respiration.
   ii. Recycling factory – converts animal waste into something useful that is recycled in the system.
   iii. Powerhouse – plant makes energy that gets to whole system.

   Students will not likely consider that the car analogy works for all three organisms because all three respire.

Supplemental Question:
Imagine you are a TA grading students’ answers to this question. One student writes: The car analogy also works well for the bacteria and the algae [because they also respire]. However, the algae requires two analogies, one is the car and the other is a powerhouse. How would you respond to this claim? Explain.

   If Needed: Draw diagram on board of a plant in a sealed container. Ask what students would expect the gas concentrations to do during the day and evening. Students will likely state that the oxygen concentration will increase while CO₂ decreases. What will occur at night? The oxygen and CO₂ levels will stay the same. Then draw that the oxygen levels decrease and the CO₂ levels increase during the night. Ask them to make sense of this.

Question 1G: HOMEWORK
Purpose: For students to generalize that a system needs at minimum a producer and decomposers. That a consumer is also supported in a system with the other two elements.

Expected Student Responses: Producer, consumer, decomposer circular diagram
REFERENCES


BIBLIOGRAPHY


