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GAPS IN COLLEGE BIOLOGY STUDENTS' UNDERSTANDING OF PHOTOSYNTHESIS: IMPLICATIONS FOR HUMAN CONSTRUCTIVIST LEARNING THEORY AND COLLEGE CLASSROOM PRACTICE

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Curriculum and Instruction

by

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December, 1999
ACKNOWLEDGMENTS

A friend, himself a holder of an advanced degree, told me of his respect for anyone who earns a doctorate because “it is the most optional thing in the world.” My motivation for seeing this optional experience through was the commitment to improve the educational experience of college science students. This effort was the enjoyable, satisfying, challenging experience it was because of my mentor, Dr. Jim Wandersee, who has been more than generous with his time, attention and excellent advice during this phase of my academic and professional development. I hope I am able in my professional life to develop and sustain the academic focus, caring attitude, and good humor that he modeled throughout our years of work together.

I am indebted as well to my committee members, professors and colleagues who together made this doctoral experience such a positive one. Dr. Ron Good provided valuable intellectual stimulation and advice in and outside of our courses together, as well as encouragement to formally enter science education’s academic arena. Dr. Catherine Cummins always welcomed our interactions and provided clear and supportive feedback. Dr. Charles Teddlie gave me an excellent background in qualitative methods that paved the way for this and future research. Without their collective constructive criticism my development of critical inquiry skills would have been stunted. My development was also spurred by my colleagues in science education, in particular Sharon Flanagan who shared miles and miles of stimulating conversations about science learning and teaching at the undergraduate level. I-10 will always bring memories of those class nights.
I am indebted to the LSU Alumni Fellowship administrators for providing financial support of my doctoral education. It would have been impossible for this mother of young children to pursue this optional doctorate in good conscience without the excellent child development services this funding allowed us to have. In addition, the fellowship allowed me to present my findings at several national meetings, and formally enter the academic community at large. You have done a great service to women in academia.

Even with determination, wonderful mentors and funding, I would not have succeeded in this otherwise selfish undertaking without my family’s patience and flexibility. Foremost deserving of my gratitude is my husband Pete for supporting my “optional” endeavor, single parenting on class nights, and for offering his ear when I wanted to share the joys and tensions of scholarly growth. I thank our young sons Emile and Gabriel for the smiles and hugs they brought home from day school that showed me it was OK for Mom to do her work. I thank my parents, Ray and Cynthia Baudoin for grandparenting-in-a-pinch and their urging to finish the Ph.D. so I can get a J.O.B. I thank my sister Gina for her Baton Rouge home away from home, and my brother Adrian for his friendship and encouragement from near and far, as well as for the great story about running at night.

This dissertation is dedicated to Emile, Gabriel and Pete Griffard, and to my past and future students.
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ABSTRACT

The main research question of this study was: What gaps in biochemical understanding are revealed by a range of university introductory biology students as they work through a critically acclaimed multimedia program on photosynthesis, and what are the corresponding implications for elaboration of the Ausubel-Novak-Gowin Learning Theory (ANG, now Human Constructivism)? Twelve students, mixed for ability, gender and ethnicity, were recruited from two sections of "Bio 101." Before and after instruction in photosynthesis, in-depth clinical interviews were conducted. In these interviews participants completed a range of cognitive tasks such as sorting, concept mapping, explaining and predicting. Some of these involved interacting with a computer simulation of photosynthesis. This study primarily employed qualitative case study and verbal analysis methods.

Verbal analysis of the clinical interviews revealed numerous gaps that were categorized into typologies. The two major categories were propositional gaps and processing gaps. Propositional gaps were evident in development of participants' concepts, links and constructs. Significant among these were conceptual distance gaps and continuity of matter gaps. These and other gaps such as convention gaps and relative significance gaps seem to be due to naivete in the discipline. Processing gaps included gaps in graphic decoding skills and relevant cognitive habits such as self-monitoring and consulting prior knowledge. Although the gaps were easier to detect and isolate with the above-average participants, all participants showed evidence of at least some of these gaps. Since some gaps are not unexpected at all but the highest literacy levels, not all the gaps identified are to be considered deficiencies.
The gaps identified support the attention given by ANG theorists to the role of prior knowledge and metacognition as well as the value of graphic organizers in knowledge construction. In addition, this study revealed numerous gaps in graphic decoding, indicating that both direct experience and explicit instruction are needed if students are to “learn how to learn with graphics,” especially those graphics central to understanding a computer simulation’s representations of structures, inputs, processes and outputs. It is hypothesized that gaps similar to those revealed in this study may be at the root of some alternative conceptions documented in the literature.
INTRODUCTION

Theoretical Framework and Warrant

A currently accepted view of learning is that a learner constructs her or his own knowledge after experiencing phenomena or receiving information, evaluating its significance, and incorporating information into an existing knowledge structure (Bodner, 1986; Mintzes, Wandersee, & Novak, 1997; Tobin, Tippins, & Gallard, 1994).

This simplified description of the constructivist view of learning has many implications. If meaningful learning occurs by nonarbitrary and hierarchical linkage of concepts into a propositional or semantic network, then instruction and assessment should be designed accordingly. It then follows that an essential component of instruction is the monitoring of learners' knowledge-building in order to adapt future lessons to their emerging understanding. This often takes the form of formal assessment, but can also be informal and interactive. Monitoring can be time-consuming for instructors to do, and there is still debate on how much or what kind of monitoring is necessary (Doran, Lawrenz, & Helgeson, 1994; Tobin et al., 1994).

Research which contributes evidence that learners are building knowledge in a less than meaningful way, or in a way that is inconsistent with the scientifically accepted view, can help science educators in anticipating and addressing these inadequacies. The Alternative Conceptions Movement (ACM) of the 1980's generated convincing research findings that such scientifically inadequate ideas are common, widespread, age-independent and resistant to change (Wandersee, Mintzes,
& Novak, 1994). These findings surely contributed to the current constructivist view of the learner as an active agent in the learning process rather than as a blank slate that receives knowledge with high fidelity.

The majority of the alternative conceptions research studies in that period focused on school age children, and was more often about physics (especially motion) than about biology, much less biochemical phenomena. Comparatively less is known of college students’ understanding of complex, abstract, biochemical phenomena that require integrating knowledge across a magnitude of scale and disciplinary boundaries (Songer & Mintzes, 1994). The purpose of this study was to determine what kind of information is missing from college biology students’ conceptual frameworks, which may shed light on the basis of some of these alternative conceptions.

Biologists consider photosynthesis to be the most important biochemical reaction on earth (Campbell, 1996; Williams, 1996) because it is the process that fixes carbon from an inorganic to an organic form usable by living things. Photosynthesis is considered the source of virtually all the geosphere’s organic carbon, whether the organic molecule is the cellulose in wood, proteins in the human body, or the hydrocarbons in an oil bed or plastic. In this organic (reduced) form, carbon molecules possess much greater free energy, energy which is ultimately derived from sunlight. This central role of photosynthesis on earth is one of the important concepts underlying the following learning objective listed in The American Association for the Advancement of Science’s (AAAS’) *Benchmarks for Scientific Literacy* (5E, grades 9-12; p. 121):
The chemical elements that make up molecules of living things pass through food webs and are recombined; energy is stored and lost at each web-link; continual input of energy from sunlight keeps the process going.

Meaningful understanding of photosynthesis requires integration of knowledge about light, thermodynamics, organic chemistry, cellular compartmentalization and topology, and stoichiometry—which requires abstract thinking about structures and processes with few visual referents. These difficulties in learning photosynthesis meaningfully are exacerbated by the need to integrate concepts previously taught independently (e.g., cell structure, biochemical cycles, food webs) as well as new concepts not typically addressed in high school biology (e.g., membrane topology, energetics, and the carbon cycle) (Gayford, 1986; Hannay, 1985).

Photosynthesis has the reputation of being difficult to learn. Students may be failing to make cognitive connections between the subordinate concepts of photosynthesis and other biological concepts (e.g., biogeochemical cycles, global warming, evolution, diversity) that lend significance and motivation to learning about photosynthesis. It is also possible that poor visual literacy with respect to spatial orientation and scale hinders exploitation of potentially powerful instructional graphics. A study of these cognitive and visuospatial gaps seems necessary if scientists are to improve their success in teaching about photosynthesis and related topics commonly taught in introductory college biology courses.

Research Questions

The main research question addressed in this study is: What gaps in biochemical understanding are revealed by a range of university introductory biology
students as they work through a critically acclaimed multimedia program on
photosynthesis, and what are the corresponding implications for elaboration of the
Ausubel-Novak-Gowin Learning Theory (Human Constructivism)?

The subquestions of the main question are:

1. What gaps in biochemical understanding can think-aloud protocols,
videotaped program-path analyses, and pre- and postinstruction clinical interviews
uncover as these college students work through an acclaimed multimedia program on
photosynthesis?

2. Do the gaps identified correspond with instruction?

3. Can a typology of the emergent biochemical gaps be constructed?

4. If such a typology can be constructed, how can it be integrated with
ANG learning theory?

Overview

The purpose of the study was to reveal and analyze gaps that exist in college
biology students' conceptual frameworks for the biology and biochemistry of
photosynthesis. Gaps that became apparent from student verbalization during
specially designed cognitive tasks and during a computer simulation of photosynthesis
were analyzed and a typology of them proposed.

This qualitative case study involved multiple cases (twelve college biology
student participants) and embedded units of analysis (e.g., the student, her/his
academic history, and the instructional context). Primary data were taken from
videotaped recordings of cognitive paths taken by the participants during three phases
of clinical interviews. Information in the form of field notes and course documents

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provided additional qualitative data. The field notes resulted from observations of the lectures during the semester. The course textbook, interviews with professors, and participants' lecture notes, examinations and academic records provided additional information about the learning context.

Analysis of such rich data requires highly organized data management. The qualitative data analysis software, NUD.IST™ (Q.S.R. Corporation, 1994), facilitated such transcript and other data management and supported theory building during analysis (Richards, 1994). NUD.IST is an acronym for Non-numerical Unstructured Data Indexing Searching and Theorizing.

The themes that emerged across cases were used to build on current theories of human learning, in particular Ausubel-Novak-Gowin's meaningful learning theory as well as the recent enhancements of it described by Mintzes, Wandersee, and Novak (1997) in their Human Constructivist Learning Theory.

Research Mission Statement

In addition to directing and carrying out a research program, almost all university science professors at major universities are required to teach undergraduate or graduate courses. In spite of this, it has not been customary for these teaching scientists to advance their own formal understanding of pedagogy and cognition. The reasons for this are, admittedly, complex. However it is likely that one result of this disjunction is the low frequency of scholarly research reports in which current thinking in pedagogy and cognition was seriously considered when studying how college students learn science.
It is often stated that most universities' reward structures favor a scholar's research contributions over her/his teaching efforts, therefore there has been little motivation for academicians to apply scholarly modes of inquiry to their teaching tasks. Furthermore, the current methods and paradigms governing research in the natural sciences may not be appropriate for studying human learning at this time. Thus the research base on the learning of science concepts taught at the undergraduate level is thin, although the current science education reform movement is addressing this lack with new funding and professional development opportunities (National Science Foundation (NSF), 1996).

The goal of the research described here is to contribute to the body of knowledge about the learning of complex biological phenomena to supplement research on college science teaching, a traditional unit of analysis. It is hoped that the findings will further the elaboration of a learning theory originally proposed by science educators and will assist teaching scientists in bridging these gaps in understanding via improved instruction.

Because faculty development initiatives on many campuses are currently focused on bringing instructional technology into college classrooms, the findings of this research will also contribute to the knowledge base about how students understand and interact with computer graphics, simulations, and microworlds. Much has been done to promote the use of instructional technology in classrooms, in spite of the paucity of research to support it, and without fully understanding the issues of visual cognition and virtual realities.
Definitions of Terms

alternative conception—a persistent explanatory perspective constructed by the learner that is not compatible with current scientific thought.

biological literacy—the goal state of understanding basic biological principles, the processes of scientific inquiry, the historical development of biological concepts, and the impact of human life on the biosphere.

concept—a perceived pattern or regularity in objects or events that is designated by a label or symbol.

conceptual framework—a view of one’s memory (with respect to a topic) as a network of concepts linked by meaning. The terms cognitive structure, semantic network, schema and knowledge structure are often used somewhat synonymously.

construct—a mental consolidation (chunking) of a set of concepts and propositions that can itself be labeled as a concept would be. For example, photosynthesis is a construct in which are embedded many subordinate concepts and propositions.

gaps—missing propositional or procedural knowledge in one’s conceptual framework in which attributes of or meaningful links between concepts are missing or pedagogically adaptive skills or habits are not evident.

graphic representation—the use of visual objects such as diagrams, graphs, cycles, heuristic tools, or animations to represent an invisible phenomenon, process, or knowledge structure, usually for the purpose of conveying information.

learning—changes in the meaning of one’s experience.
meaningful learning—learning that involves deliberate and explicit linkage of new concepts and propositions with existing knowledge, thereby resulting in substantive (non-arbitrary) conceptual change.

photosynthesis—the autotrophic ("self-feeding") process that occurs in plants (including algae) and some bacteria. This process produces organic sugars from atmospheric carbon dioxide using energy from sunlight.

proposition—a statement of relationship between two or more concepts made explicit by meaningful linking word(s) (e.g., chloroplasts are surrounded by two membranes)

retrieval—the cognitive processes that occur during recall of learned information.

simulation—an activity, often computer-based, which places the learner in a representation of a situation and offers interaction with and control of various components of the related complex system in order to better understand it.
LITERATURE REVIEW

Historical Framework

It may come as a surprise to newcomers to the academic arena of education that research on learning is but one field of inquiry within the discipline. Issues of educational administration, curriculum, multicultural and special needs, and instructional technology development receive as much academic attention as learning does.

It may also come as a surprise that research on learning is itself quite broad. In an attempt to understand the mutually influential traditions and broad trends and issues in educational psychology, three research traditions have been identified that work to understand human learning: the empiricist/behaviorist perspective, the cognitive/rationalist perspective and the situative/pragmatist-sociohistoric perspective (Greeno, Collins, & Resnick, 1996; Searleman & Herrmann, 1994). Each perspective continues to be influenced by its own views about the nature of knowing (associative, constructed, or distributed), the nature of learning and transfer, and the nature of motivation and engagement. These views also influence the designing of learning environments, the formulating of curricula, and the constructing of assessments.

Greeno et al. (1996) acknowledged that these traditions interact historically in a pattern of thesis-antithesis-synthesis. The behaviorists proposed a thesis focusing only on external, readily quantifiable aspects of learning. Cognitivists later proposed an antithesis focusing on the inward, rich mental constructions and processes but neglected the social, and affective conditions. Most recently, the situative view has
provided a synthesis of the others, along with consideration of the benefits of interaction in a rich environment between people and information.

Although pointing to differences between these traditions understates their mutual influence and overlap, the distinction is useful for understanding theoretical commitments and historical development of current ideas in educational psychology. Not only are Skinner and Thorndike historically identified with the empiricist/behaviorist perspective, but also the proponents of connectionism and parallel-distributed processing such as Rumelhart and McClelland. Application of this research has been the interest of those in communications research, specifically reading and speech development.

Contributors to the cognitive/rationalist perspective included Jean Piaget, Herbert Simon, and David Ausubel. Researchers interested in schema theory and propositional network views of memory, and conceptual understanding (including alternative conceptions) identify with the cognitive perspective. Also included are those interested in problem-solving, metacognition and students' epistemological beliefs, and how these influence learning. Thus the Ausubel-Novak-Gowin meaningful learning theory is logically identified with this perspective. In response to the great amount of educational psychology research conducted within this tradition in the past decades, some have cautioned against equating educational psychology with cognition (Bereiter & Scardamalia, 1992; Brer, 1997). The research discussed herein is most significantly influenced by research done within the cognitive/rationalist tradition.
This decade has seen a growing interest in intelligence as a distributed resource, that is, among members of a group, their tools, their artifacts, and practices. Researchers in the situative/pragmatist-sociohistoric perspective claim influence by Dewey and Vygotsky. Whether distributed intelligence occurs during collaborative activities within classrooms, such as reciprocal teaching (Brown & Palincsar, 1989) or between individuals and information sources via computer networks or the Internet (Salomon, Perkins, & Globeron, 1991), proponents focus on the value of designing instruction to be interactive.

It is notable that neurobiological bases of learning do not figure prominently within even one of these categories of educational psychology. Although research in neurocognition is brisk, it is premature to apply the findings broadly to issues in education (Bruer, 1997), although they are beginning to influence and be interpreted by educational psychologists eager to test their models in biological terms (e.g., Anderson, 1997).

The Cognitive/Rationalist Perspective in Science Education: Constructivism

The young subdiscipline of educational psychology called cognitive science was born of an eclectic group of scholars (Bruer, 1993; Gardner, 1985) and gave rise to a view of humans as symbol processors. The artificial intelligence movement arose to test the emerging models of information processing, but waned as it became evident that computers were remarkably deficient in common sense abilities that apparently require a great deal of background knowledge and experience (Bruer, 1993).

Cognitive scientists have long been interested in the mental processes involved in problem solving (Newell & Simon, 1972), which then led to research in science
education that compared how experts and novices differ in this regard (Chi & Bassok, 1989; Kozma & Russell, 1997; Stewart & Hafner, 1994; Zajchowski & Martin, 1993). These findings, as well as emerging evidence that few abilities transfer across domains (Bruer, 1993; Resnick, 1989), underscored the importance of specific domain knowledge to problem solving (Chi & Ceci, 1987), elevating once again the value of knowledge along with general thinking skills in education.

The view of the learner as a *tabula rasa* on whom any information could be written with high fidelity has faded. The sum of research has indicated that any previous experiences (in and out of classrooms) residing in one's explicit and implicit memory systems may contribute to understanding. Not only can these experiences be attended during information retrieval, but this prior knowledge also can filter and modify new information being learned (Bruer, 1993; Carey, 1986; Chi, Slotta, & De Leeuw, 1994). In the last decade in science education, constructivism has become the prevailing view of learning and a referent for instruction (Bodner, 1986; Carr et al., 1994; Mintzes et al., 1997; Tobin et al., 1994).

Once the clinical interview and think-aloud methodologies of Piaget and Simon were put to use by science education researchers, a vast set of erroneous ideas held by learners were identified (Novak & Gowin, 1984; White & Tisher, 1986). They cut across age, ability and socioeconomic levels, and are tenacious, widespread, and difficult to change (Wandersee et al., 1994). As a result of the Alternative Conceptions Movement (ACM), attention turned to how to design instruction for conceptual change (Posner, Strike, Hewson, & Gertzog, 1982; Strike & Posner, 1992).
Meaningful Learning Theory: A Human Constructivist View

The writings of educational psychologist David Ausubel in the 1960’s remained somewhat poorly understood within the behaviorist context dominant in psychology at the time. Ausubel’s assimilation learning theory (Ausubel, 1968) came to the attention of science education researcher Joseph Novak, who saw value and application of Ausubel’s theory for how new knowledge links to an existing hierarchical network of propositions related to one another by meaning (Ausubel, Novak, & Hanesian, 1978; Novak, 1979). For a science educator looking for ways to convey a structure of scientific knowledge to students, the Ausubelian model was inherently appealing.

However this emerging paradigm of “reception learning” competed for the attention that Jean Piaget’s developmental theories were getting in science education at the time. A focus of science education then was on conveying how scientific inquiry generates knowledge more than on what that knowledge is. One small aspect of Piaget’s work, the “stage theory” that learners progress through stages of sensorimotor, concrete and formal operations, received a disproportionate amount of attention by science educators relative to his theories as a whole. A debate over the relative value of content (Ausubelian conceptual learning) and process (Piagetian inquiry learning) ensued (DeBoer, 1991; White & Tisher, 1986), although even their respective proponents agreed that it is not necessary to see the theories as opposed (Lawson, 1978; Novak, 1988).

The concept is of central importance in Ausubel’s learning theory and its later enhancements. It is a mental representation of a perceived regularity in objects or
events (Novak & Gowin, 1984). The word used to identify a concept is a label (e.g., \textit{plant}, \textit{food}, \textit{photophosphorylation}), whereas two concepts along with a meaningful link between them is a proposition (e.g., "light is captured by chlorophyll"; "plants make their own \textit{food}"). When a large group of hierarchically arranged propositions and subsumed concepts can be "chunked" into one concept, this concept can be called a construct (e.g., \textit{photosynthesis}).

Human constructivist learning theory states that learning is \textit{rote} if the new information is learned arbitrarily, or not consciously linked with existing knowledge. In this case memorization of a concept may be relatively easy, but retrieval and application of the concept is hindered by poor "indexing," or links to the relevant information in memory. In contrast, learning is \textit{meaningful} when learners choose to relate new knowledge to relevant concepts and propositions they already know (Novak & Gowin, 1984). Novak used the example of photosynthesis in the introductory chapter of his book to distinguish rote from meaningful learning, and in so doing called for better study of how learners associate the subsumed concepts in their conceptual frameworks:

If we teach students that photosynthesis is the process by which plants convert light energy into food, it should be quite acceptable if they define photosynthesis as 'a food-making process in plants that utilizes light energy.' If the concept of photosynthesis is to be learned meaningfully, however, the student must have some available concept of plant, food, light, energy, and the making or converting. If we do not want a definition of photosynthesis to be learned by rote, we must ascertain to what degree the associated subsuming concepts are present and developed or differentiated. (Novak, 1977, p. 26)

Because of the importance of prior knowledge in his model, Ausubel is well-known for having said that the most important single factor influencing learning is

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what the learner already knows. He urged educators to “Ascertain this, and teach him [sic] accordingly” (Ausubel, 1968). The importance of hierarchy and meaningful links between concepts in memory drove the development of heuristic devices such as concept maps and Gowin’s Vee diagrams. These aid in explicitly presenting the structure of the knowledge to be learned (when used by the instructor as an advance organizer), raising metacognitive awareness of learners (when constructed by students), and in graphically representing cognitive structure deduced from clinical interviews (Novak & Gowin, 1984). Recognition of the value of concept mapping for instructional and research purposes is evident in the large number of research publications in which it was employed (Novak & Wandersee, 1990).

Concept mapping is effective because it aids learning by requiring learners to analyze the underlying structure of the ideas they are studying, which allows for integration of new knowledge into existing knowledge structures (Jonassen & Reeves, 1996; Novak & Gowin, 1984; Novak & Wandersee, 1990), especially in biology (Horton et al., 1993). Semantic networking software that allows students to concept map as part of instruction has been shown to be an effective cognitive tool, which is a tangible or intangible technology that enhances the cognitive powers of human beings during thinking, problem solving, and learning. During instruction, student maps/networks correspond increasingly with those of the instructor. The degree of convergence has been quantitated for research purposes using software such as Pathfinder (Grabinger, 1996; Jonassen & Reeves, 1996).

Many recent findings in cognitive psychology about how learners construct knowledge resonate with Ausubel’s early theories and to some degree with Kelly’s
personal construct theory (Kelly, 1955). In addition, the abundance of findings in the Alternative Conceptions Movement further support Ausubel-Novak-Gowin meaningful learning theory (Wandersee et al., 1994). Findings on information retrieval and educational advantage of metacognitive tools (e.g., concept maps) have led to regular enhancements of the original theory now also known as Human Constructivist Theory (Mintzes et al., 1997). This view of constructivism is mostly concerned with instructional issues. It has some implications for social construction of knowledge in the sciences, and little reference to the radical constructivist view that questions the value of studying an objective reality while holding that all knowledge is idiosyncratic mental representation (von Glasersfeld, 1991; Matthews, 1997). The view of memory assumed within the Human Constructivist View is consistent with propositional network views of memory and schema theory, as well as connectionist or spreading activation views of retrieval.

Alternative Conceptions

Research on alternative conceptions in science was vigorous during the 1980’s, with over 2400 articles having been published on the subject by 1993 when Wandersee et al. (1994) synthesized the overall findings of the ACM. Science educators have come to use the term alternative conception, rather than misconception and other defensibly acceptable terms, because the latter emphasize the learner’s knowledge is incorrect with respect to scientifically correct ideas. On the other hand, the former “confers intellectual respect on the learner who holds those ideas--because it implies that alternative conceptions are contextually valid and rational and can lead
to even more fruitful conceptions (e.g., scientific conceptions).” (Wandersee et al., 1994, p. 178).

Wandersee et al. (1994) synthesized the following claims from the findings of the movement: (a) Learners often have diverse array of ideas that are often at variance with scientific views; (b) These alternative conceptions appear across age, gender, ability levels and cultural backgrounds, and they are resistant to extinction; (c) Teachers often subscribe to the same alternative conceptions as their students; (d) Alternative conceptions sometimes are similar to historical explanations by philosophers and scientists (Duschl, 1994; Wandersee, 1985).

Alternative conceptions may be rooted in the fact that scientific explanations often run counter to internally rational everyday explanations humans spontaneously generate (Wolpert, 1992). Indeed everyday knowledge and scientific knowledge are quite distinct, although everyday knowledge has profound influence on meaningful learning in science (Reif & Larkin, 1991).

While much of the ACM literature has favored such physical topics as Newtonian motion and the particulate nature of matter, some studies illuminated alternative conceptions about biological phenomena, including concepts of life, animal and plant, the human body, genetics, evolution and reproduction. One study logically suggested that, unlike motion and force, biological phenomena that are unlikely to be directly experienced by young children are less likely to engender naive theories (Lawson, 1988). While this may be the case for biochemical aspects of photosynthesis, learners’ everyday experiences with plants and their environmental
needs do seem to lead to alternative conceptions about plant nutrition (Smith & Anderson, 1984; Wandersee, 1985).

**Are Gaps Alternative Conceptions?**

This study aimed to identify gaps in college student explanations of photosynthesis, with a focus on its biochemical aspects. In this researcher's experience in teaching introductory biology at the college level, it has been recognized that students can and do commit numerous propositions to memory as they learn. However, explicit instruction seems to be needed to direct their integration of the propositions into a coherent whole, and to direct their attention to features of instructional graphics that can help them do this.

Complex topics in biology require a "systematic view" in which "one must understand the 'organized cooperative interactions' that occur within the system" (Chi, de Leeuw, Chiu, & LaVancher, 1994). Photosynthesis is one such complex topic requiring a systematic view. Students with such a systematic view of photosynthesis, as evidenced by classroom interactions with college biology students, tended to respond to multiple-choice exam questions requiring simpler propositional knowledge by referring to their larger view and "zooming in" on the relevant part to answer the question. This is in contrast with other students who seemed to search their less-well-indexed memories for the appropriate propositions needed to answer the exam questions. This field observation has been influential in this researcher's view of knowledge structure and retrieval as well, which corresponds very well with the Human Constructivist view of meaningfully-learned knowledge as hierarchical,
internally linked, and multimodal (composed of propositions and images) (Mintzes et al., 1997).

In teaching and in preliminary research conducted on student understanding of photosynthesis, some students have responded to questions with “I never thought of that,” indicating that some propositions that could contribute to their more meaningful understanding of photosynthesis had simply not been considered before then. In this researcher’s experience, every student who has been asked the question “What does the plant do with the ‘food’ glyceraldehyde-3-phosphate that it makes (i.e., its fate)?” has eventually responded that they had never considered it. This has led to consideration of the nature of an alternative conception at this level. Are all incorrect ideas due to “robust naive theories” or do some errors occur because of the lack of a key proposition in the student’s conceptual framework? Are some documented alternative conceptions actually due to improper decoding of graphic representations of abstract structures and processes used as probes? Perhaps some of what investigators detect with traditional instruments for diagnosing alternative conceptions are unconsidered propositions, faulty assumptions or “gaps” in the participants’ knowledge structure or decoding skills.

Therefore one premise of this study is that not all alternative conceptions are alike. A simple, unrelated example is offered to illustrate the point. The common conception in elementary school students that the ocean floor is flat can be labeled an alternative conception, however this seems to have different attributes and causes than alternative conceptions about force and motion, for example. The alternative conception about the ocean floor seems to be due to a faulty assumption made when
one is asked to generate a previously unconsidered proposition about it. Clearly in
this case the label “floor” is responsible for the naive view that it is flat. This begs the
question: how many of the documented alternative conceptions are due to on-the-spot
generation of a theretofore unconsidered proposition? Studying the precise nature of
alternative conceptions may show that some are due to gaps that persist due to lack of
experience with the phenomena or the ideas about them. Therefore the notion that
gaps may be responsible for some alternative conceptions underpinned this study.

Gaps Anticipated at the Start of the Study

The quest for gaps in understanding may be relevant to the discussion about the relative importance of content knowledge in memory development. In defending the role of content knowledge, Chi (1987) suggested that well-known, age-related differences on problem-solving tasks are due to incompleteness (i.e., gaps) in a child’s schema for a concept, which in turn may be due to lack of knowledge about which dimensions of the representation or concept to encode. A sense for the salience of an attribute is a characteristic of expertise (Chi & Ceci, 1987). College biology students may have difficulty understanding the propositions of photosynthesis because they have had no experience that directs their attention to the biochemical significance of these attributes. For example, the concept of proton pumping is not likely to be encoded well if its role in a broader biological sense is not understood. This failure to encode the proposition because it did not seem significant at the time may lead to “propositional” gaps. One subset of propositional gaps anticipated could result from the failure to attend to semantic differences between two related concepts (e.g., energy and high-energy electrons), which in the end were labeled “discrimination gaps.”
In addition, various aspects of photosynthesis are represented graphically during instruction. The traditional graphics used in most introductory college biology textbooks include Cartesian graphics of absorbance and action spectra, electron micrographs and drawings of chloroplast structure, diagrams of biochemical and global cycles, illustrations of classical experiments that led to understanding of photosynthesis, and graphs showing the energy changes of electron transport. Without explicit instruction on the features and limitations of these representations, students are unlikely to encode the very "salient attributes" that the graphics are intended to convey. This could lead to failure to attend to a helpful feature of the graphic or could lead to faulty assumptions about what the graphic represents. Thus "graphic decoding" errors represented another kind of gap anticipated in this research.

The types of alternative conceptions about photosynthesis reported in the literature tend to be related to larger, more abstract roles of photosynthesis in global gas exchange and in "food" production. Although they are labeled "alternative conceptions," they probably represent failures to bridge conceptually distant concepts, such as the relationship between fixation of free carbon dioxide in the Calvin cycle and global carbon dioxide levels responsible for global warming. Thus conceptual distance gaps were a third type of gap anticipated at the start of this study. These "conceptual distance" gaps may be due more directly to students' visuospatial skills that permit them to visualize abstract relationships such as magnitudes of scale, changes over time, nestedness, and stoichiometry. Some of these gaps were witnessed in a pilot study conducted prior to this study (Griffard & Wandersee, 1999b).
Visual Aspects of Cognition

Graphic Representation and Visual Literacy

This study relied heavily on an award-winning computer simulation of photosynthesis, therefore an understanding of how graphic representation of a phenomenon influences learning was necessary. Research on visual aspects of cognition is diverse, from visual literacy to the neurobiological basis of visual processing. The latter field is in its infancy, but there is already evidence that some regions of the brain are responsible for “filling in” when the brain compensates for gaps in visual information (MIT Tech Talk, 1997). Since this spontaneous filling-in may be influenced by prior knowledge and experience, such findings may be relevant to future study of conceptual gaps and naive theories that may spontaneously result to bridge them.

Visual literacy is a young discipline as well. Researchers in the field of visual literacy consider their work to be about the use of visuals for the purposes of communication, thinking, learning, and constructing meaning, among others. Use of images in education is diverse: film, icons, illustration, graphic representation, computer graphics and animation. Graphic representations of phenomena include symbols (pictographic or abstract), maps, graphs (including graphic organizers), diagrams, illustrations, photographs, and three-dimensional models (Braden, 1996).

Encoding Advantages of Graphics: Dual-Coding Theory

Paivio’s Dual-Coding Theory is usually cited as influential in current thinking about cognitive effects of learning with images, namely in using them to encode information contained in the graphic. In brief the theory posits that “cognition is
served by two modality-specific systems that are experientially derived and
differentially specialized for representing and processing information concerning non-verbal objects, events and language” (Braden, 1996, p. 492). In other words, when dimensions of a concept are encountered both visually with an image and verbally with text or oral language, memory (and therefore learning) improves because the retrieval conduit to the encoded information is expanded two-fold. At the same time the conceptual-peg hypothesis has been cited to further support the importance of images in learning. A simplified summary of it is that the conceptual pegs for all memory are non-verbal, and that imagery is the effective variable in recall of verbal and non-verbal (visual) information. Whether information in memory is encoded as images or simply as propositions (even about images) is still a matter of debate between “the image group” and “the anti-image group” (Braden, 1996).

Research on how learners use, or decode, graphics has led to the conclusion that people without experience viewing graphics (in a discipline) have trouble extracting information in them that is abstract, complex, or represented in culture-bound conventions—especially when the objects and concepts shown are unfamiliar. Consequently there is consensus that visual literacy skills (how to view and use graphics) may need to be explicitly taught, although how and to what degree are still under debate (Braden, 1996). This is relevant information to science educators and publishers who rely heavily on pictures to convey information. The ubiquitous use of domain-specific representations such as cycles, spectral graphs, and electron micrographs in instructional materials about biochemistry makes it likely that novice biology students will have trouble decoding them.

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Principles of Graphic Design

Graphic theorist Edward Tufte is known for his work on graphic representation of information, including quantitative data and the representation of the knowledge inferred from those data. He recommends graphic techniques such as use of small multiples, layering and separation, and use of color to help others envision information (Tufte, 1990). In his book about representing quantitative information (Tufte, 1983), he warns against “lying with graphics.” and lauds graphic designers who use data-dense graphics and maximize the data-ink ratio. These recommendations are based on his historical research in graphic theory and have broad application beyond science, and even beyond education. His recommendations support the need for graphic literacy and are relevant to how we teach with graphics.

Fidelity

One concern to those in the field of visual literacy is the resemblance of the symbols used to their referents (Braden, 1996), regardless of whether the graphic is static or dynamic. This is relevant to science education since commercially produced graphics for textbooks or computer-based learning programs are often criticized by teaching scientists for their misrepresentation of the scientific phenomenon. Tufte argues for “graphic integrity,” especially in faithfully representing trends via graphics. However in the representation of a complex phenomenon, fidelity is necessarily compromised in order to reduce cognitive overload (Reigeluth & Schwartz, 1989). Images in textbooks may convey ideas with higher fidelity, but lay science books that aim to reach a broader audience (Hoagland & Dodson, 1995) favor understanding over...
fidelity by using, for example, anthropomorphized cartoon molecules and familiar ideas in graphic analogies.

Fidelity is also an issue in the photosynthesis simulation that was used in this research. Some phenomena are unavoidably distorted or inaccurately represented. For example, scale with regard to time (e.g., speed of the reactions), spatial orientation (e.g., of the compartments within the cell relative to whole plant), and quantity (e.g., the number of NADPH molecules actually in the chloroplast is far greater than the number shown) are inevitably distorted in order to highlight the relevant abstract or microscopic concepts. Attention was paid in this study to whether these distortions affected how the graphics were decoded.

Research on the Use of Images in Science Education

The use of images has been important historically in conveying the ideas of science (Robin, 1993), and has become an increasingly important component of textbooks, growing in number and complexity in successive editions of the same textbook (Wissing, 1996, unpublished data). Nonetheless research on visual cognition and graphics use in science education has been sparse.

Mayer and colleagues have used Paivio’s Dual-Coding Theory as a referent and extended it with findings about learner use of multimedia. They found that learning and transfer were greater when an animation and its verbal narration in a science lesson (on how a bicycle pump works) were given simultaneously rather than successively. This “contiguity effect” was strong for high-spatial learners, leading them to surmise that low-spatial learners are prevented from benefiting because they need to devote more cognitive resources to first step, the encoding of the visual
information. This is in contrast with high-spatial learners who encode the representation readily, therefore can devote more cognitive resources to resolving and corresponding their visual and verbal representations in working memory (Mayer, 1997; Mayer & Sims, 1994). In another study, Harp and Mayer found that viewers of illustrations of high cognitive interest that accompanied text about how lightning forms retained more information than they did from illustrations of high emotional interest (Harp & Mayer, 1997). This challenges the notion that human-interest aspects of such topics significantly improve their instructional value.

Kozma and Russell (1997) found that when they presented chemistry experts and novices with a range of representations (video segments, graphs, animations and equations) of the same chemical phenomena, experts made better transformations between representations (e.g., graph to equation) and made more meaningful groupings of representations based on concepts presented rather than on superficial, media-related similarities. They suggest that these findings inform the development of multimedia instructional materials. The results also indicate the importance of explicitly drawing attention to correspondence among various representations during instruction.

In the life sciences, research on use of graphics has been done on the topics of meiosis, cell structure, the respiratory system and global gas exchange. Kindfield (1991) compared reasoning by experts and novices during clinical interviews as they solved non-traditional genetics problems that required understanding of meiosis. Some tasks asked participants to explicitly identify and discuss various representations of chromosome structure typically used during instruction. She found
that experts correctly translated and transformed the representations. Novices made errors in depicting chromosomes in conventional, familiar line diagrams, which is probably related to alternative conceptions about meiosis and crossing-over, and failure to understand genetic inheritance meaningfully.

Complex flow diagrams were used in a study with high school biology students (Holliday, Brunner, & Donais, 1977). These complex flow diagrams used arrows between gas sources and sinks to show relationships among photosynthesis, respiration and combustion in global gas exchange cycles. Two forms, a picture-word diagram and a block-word diagram, were compared for their ability to help students extract information from them to answer questions. The picture-word diagrams did more to help low ability students than the block-word diagrams, and they improved achievement for lower ability students more than high.

Wandersee (1994) found that college students could better locate a cell nucleus in a micrograph when their instruction included small multiple examples of electron micrographs of eukaryotic and prokaryotic cells rather than a single prototypical example such as frequently encountered in textbooks. This is consistent with the Ausubelian view of a concept as a perceived regularity among numerous examples of it. He also confirmed the psychological principle that it is easier to detect the presence of something (nucleus) than its absence.

Research in visual literacy has found that visuals that are graphic organizers (e.g., concept maps) improved skills such as reading comprehension, understanding science topics and remembering social studies passages. Improvements have been more evident with postelementary students, and particularly when the graphic
organizer was used as an advance organizer (before instruction) as Ausubel intended (Braden, 1996). Teaching students to produce cognitive maps significantly improves understanding of the structure of the domain (Jonassen & Reeves, 1996; Novak & Gowin, 1984).

Use of Graphics in Computer-Assisted Learning

Animation

Rieber has done much of the research on animation in learning. He has found that the learning benefits of animation may be subtle, that learners need to be cued to features of it, and that the role of animation in simulations cannot be studied separately from the simulation (Rieber, 1990; Rieber, Boyce, & Assad, 1990). In one study the animation did not affect learning as much as it decreased the time needed to retrieve the information (Rieber, Boyce, & Assad, 1990). Findings have indicated that animations are motivating to school-age children, potentially frustrating to adults when used in open-ended activities, and vary in their educational benefits to both children and adults (Rieber et al., 1990). However recent meta-analysis indicate larger effect sizes for college students and adult learners, presumably because software is now better matched to these learners (Berger, Lu, Belzer, & Voss, 1994). These results are important and relevant to this research.

One award-winning application of animation to biology learning is that designed by the Biology Study Center at the University of Michigan. They supplemented their already successful high level tutoring software with animations of some of the dynamic biological processes discussed in introductory biology: meiosis, mitosis, protein synthesis and the lac operon. They found that students rated the
animations highly, and that time spent using the study center software was a strong
predictor of exam success (Berger et al., 1994). There was no report of how learners
specifically interacted with the graphic features of the animation.

A small pilot study conducted by this researcher looked at how students
interpreted the information in a photosynthesis animation. That animation was created
by a biology professor for use during instruction, and made available on the Internet.
A finding relevant to this study was that many of the icons used in the animation, such
as the ones for light, the enzyme rubisco, and ATP synthase, were misinterpreted by
college biology majors in a sophomore level cell biology class (Griffard & Wandersee,
1996).

Screen Design, Graphic Interfaces and Feedback

The literature on ideal user-interaction features of instructional software is
generally prescriptive rather than descriptive. The more recent of these prescriptions
recommends that software allow the user to choose paths, offer maps of position in the
linked screens, indicate when time is needed for the computer to access information,
and give feedback that user’s responses have been registered and progress is being
made (Braden, 1996). All of these are features of Logal™'s photosynthesis simulation
that was used in this study. In addition, learning improves when metacognitive cues
are embedded in the computer-based instruction (Lin, Newby, Glenn. & Foster, 1992)
and when learners are allowed control over the feedback they receive (Pridemore &
Instructional Technology in Science Education.

Many forms of instructional technology have been promoted and adopted in science classrooms as part of the current reform movement. The effectiveness of these instructional interventions is not of central interest to this research, however the general trends indicate that with appropriate design and implementation, instructional technology can be very effective.

The microcomputer-based laboratory (MBL) is one form of instructional technology that couples a data-gathering probe (such as a thermometer or motion detector) to a microcomputer. The success of MBL's in teaching scientific concepts and graphical interpretation (Berger et al., 1994; Krajcik, Simmons, & Lunetta, 1988; Mokros & Tinker, 1987) is significant because it tells science educators interested in cognition a great deal about the cognitive benefits of experiencing and graphically interpreting phenomena simultaneously in real time. Contextual-based problem-solving (e.g., the Jasper Woodbury project at Vanderbilt University (Berger et al., 1994; Bruer, 1993)) is a software application built upon the principles of cognitive science which, consequently, is adding to the research base about situated learning and problem-solving. Other types of computer-assisted science instruction include telecommunications (e.g., WaterNet, a national water pollution study conducted by school children), intelligent tutors, hypermedia, microworlds and simulations.

Some of the most well-known research studies on computer-assisted science learning have looked at how students operate in and learn from microworlds designed to teach scientific principles. A microworld has been defined as a computer laboratory environment that simulates real world phenomena that vary in complexity.
depending on the number of variables and how the variables interact (Berger, Lu, Belzer, & Voss, 1994). For example, programs such as Logo, Dynaturtle, ThinkerTools, and Space Shuttle Commander are designed to help the learner discover principles of motion (Berger et al., 1994; Bruer, 1993; Rieber, 1992). These programs create microworlds that allow learners to see what simpler worlds would be like, to manipulate simulated objects and variables in that world, and to design experiments to discover which laws apply in that microworld (Bruer, 1993).

**Computer Simulations**

There are several reasons for using computer simulations in a learning context: to provide a safe environment in which students test hypotheses, to provide reinforcement and self-testing out of class, and to permit "interactive" instruction in the absence of full-time attention from the instructor. In life sciences, simulations can substitute for traditional "wet" laboratory activities (which is desirable to some degree for minimizing need for specialized equipment and supplies). Simulations permit students to focus their attention on principles rather than techniques, to conduct more sophisticated experiments that require higher technical skill than they have, and to avoid the sacrifice of living animals (McAteer et al., 1996). Some simulations are less like mock wet labs than others. Some, like the LogaTM photosynthesis simulation, make the invisible biochemical and organismal changes during photosynthesis less abstract and allow the learner to manipulate variables to witness the changes that result (Matray & Proulx, 1995).

On the surface a simulation such as the LogaTM product used in this research seemed to fit the previous description of a microworld. However, a microworld as
defined by Hannafin et al. (1996) and Rieber (1992) has two essential characteristics that are not found in the photosynthesis simulation. First, a true microworld embodies the simplest model of a domain that is deemed accurate by experts in the field. Typically the microworld conveys a few interrelated principles via experimental manipulation, and are not made explicit in a lesson. This is only partly true of the chosen photosynthesis simulation, since there are numerous relationships that need to be made explicit with text, graphics or voice. Furthermore, although its graphics do not represent scientific understanding of photosynthesis with highest fidelity, neither are they the simplest models, because the biochemical components of photosynthesis probably could not be learned in a less embellished model. The second essential characteristic of microworlds is that the learner can direct how the microworld is structured as (s)he becomes more experienced with it. In the photosynthesis simulation, the learner can manipulate many variables, but not all of them, since to design this extreme flexibility into a computer simulation of this complex system is not economically or pedagogically justified.

If the photosynthesis software is not a true microworld, it might better be described as a symbolic simulation, which is a “population of events or interacting processes on which the learner may conduct any of several different operations” (Gredler, 1996). This is contrasted with experiential simulations in which the learner has a human role to play in a complex, evolving situation that often involves decision-making (e.g., managing hazardous materials spills, emergency patient care, medical diagnosis or bank operations). In symbolic simulations, if the learner has any role in
the simulation it is usually that of a researcher of the scientific phenomenon being simulated.

Symbolic simulations are further categorized as *data universe simulations, system simulations, process simulations, and laboratory research simulations* (Gredler, 1996). The photosynthesis simulation software used in this research is a *process simulation*, since its focus is a naturally occurring scientific phenomenon and it uses interactive graphics that can illustrate unobservable processes. Such software is designed to be used by students to manipulate variables and attempt tasks in order to discover relationships among the variables or to confront their alternative conceptions. This is in contrast with other symbolic simulations in which the scale of the system is much larger (e.g., genetic inheritance simulation), the system involves interactions between natural and constructed components (e.g., water pollution simulation), or the simulation substitutes for a "wet-lab" that is too dangerous or time-consuming (e.g., simulations of chemistry reactions).

Gredler (1996) cites two problems slowing research on how computer simulation technology affects learning. The first is that comprehensive design paradigms derived from learning principles have not been available. This is partly to blame for the mislabeling of a variety of activities as simulations. Second is the lack of well-designed research studies. Instead the literature has tended to be anecdotal and testimonial (Gredler, 1996). Early attempts to evaluate the instructional benefit of computer simulation by meta-analysis indicated no significant positive effect (Dekkers & Donatti, 1981). However these studies were poorly designed and measured outcomes in traditional and simulation-based instruction equally although

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the learning goals of each were different. Thus the discipline that studies the educational uses of computer simulation is in need of agreement on a common research paradigm (Butler, Markulis, & Strang, 1988; Gredler, 1996).

An instructional theory for the design of computer simulations was derived from extensive review of simulations of scientific phenomena (Reigeluth & Schwartz, 1989). It states that a simulation's effectiveness is determined by three aspects of its design: scenario, model, and instructional overlay, the last of which is by far the weakest in simulations created to date. Simulation designers need to consider fidelity to the scenario and model, but are cautioned that highest fidelity may not result in most effective instruction, since overload, transfer, affect and cost mitigate potential benefits of highest fidelity simulations. This is relevant to this research since an evaluation of its instructional effectiveness might be critical for its failure to accurately represent the phenomenon of photosynthesis.

Research on the use of symbolic simulations in science education is even smaller. Most of the extant studies focus on the learning benefits measured after simulations were used in instruction, rather than studying the thought processes involved during work with computer simulations. Very few studies have employed simulations as cognitive probes during think-aloud sessions. Unlike this study, these have focused on problem-solving rather than conceptual frameworks.

Lavoie and Good (1988) used a simulation of water pollution to study the role of prediction skills in problem-solving. In doing so, they identified some behaviors of successful and unsuccessful problem-solvers as they manipulated variables such as oxygen and waste concentration in the simulation. They subsequently recommended
that prediction be considered a component of the learning cycle method of instruction. Simmons and Lunetta (Simmons & Lunetta, 1993) used genetics simulation software in an exploratory study of expert/novice genetics problem-solving, and found that although most behaviors of experts and novices using the simulation were consistent with traditional problem solving, they called into question the expert/novice dichotomy because of some of the alternative conceptions exhibited by the experts.

Photosynthesis

**What is Usually Taught about Photosynthesis in College Biology.**

On a biochemical level, photosynthesis occurs in two stages. The first is a light-dependent set of reactions in which pigment molecules (e.g., chlorophylls, carotenoids, xanthophylls) capture light energy in their bonds by being excited by light of particular wavelengths. This molecular excitation is then transduced (converted) into mechanical energy as a pair of excited electrons, coming ultimately from the splitting of a water molecule, are passed serially among a “chain” of electron acceptor molecules. The result of this electron transport is a gradual loss of energy that is, in turn, exploited to transport a proton from the outside of the thylakoids (membrane “sacs” in the chloroplast) to its inside space. This light-driven accumulation of protons sets up an electrochemical gradient, which in another reaction on the membrane drives the synthesis of adenosine triphosphate (ATP) as the protons move through the membrane channel to the thylakoid exterior once again. The electrons originally passed down the electron transport chain are eventually picked up by a high energy organic intermediate, nicotinamide adenine dinucleotide phosphate (NADP).
The overall products of the light-dependent reactions, therefore, are ATP, reduced NADP and oxygen, which is a waste product from the splitting of water to generate the transported electrons. Except for fueling the competing photorespiration side-reaction, the oxygen product is mostly irrelevant to the remainder of photosynthesis, and most of it diffuses out of the cell and the organism, thus playing a role in global oxygen cycles (Campbell, 1996). Some of the oxygen diffuses to the mitochondria where it is consumed in aerobic respiration within the same cell in which it was synthesized.

The other products of the light-independent reactions, ATP and reduced NADPH, are the sources of energy and "reducing power" needed for the second set of reactions. In the light-independent reactions, carbon dioxide is converted in many steps to a three-carbon sugar in the Calvin Cycle. Carbon fixation requires an energy source as well as high-energy electrons. Breaking the final phosphate from ATP releases the needed energy, and yields ADP which recycles to the light-dependent reactions. Likewise, the high-energy electrons of reduced NADP are transferred to the intermediate sugar product, and then the oxidized NADP returns to the light-dependent reactions (Campbell, 1996).

The resulting three-carbon sugar produced in the Calvin cycle, glyceraldehyde-3-phosphate (G3P), is the photosynthesis product that is considered the plant's "food." As such it can have any of a number of biochemical fates. Most students recognize that it can be readily converted to the six-carbon glucose or twelve-carbon sucrose (table sugar), or stored in large polymers of glucose called starch. But these are just temporary fates of G3P, since sucrose is simply a transport form and starch is a
storage form of G3P. Eventually, the sucrose arrives at its destination elsewhere in the plant (e.g., roots), and the stored starch will be broken down to glucose then G3P and used by the cell (Campbell, 1996).

What is G3P’s fate then? Ultimately the G3P is either used as an energy source or as a building material. About half of the G3P produced is later consumed as an energy source during cellular respiration in the plant cell’s cytoplasm and mitochondria. This process oxidizes, or “burns” the G3P to release energy in the bonds, and thus it releases carbon dioxide as the “waste” product of this process. This G3P oxidation energy is used to make ATP, the primary source of energy for most cellular functions.

The other major fate of G3P is that of a building material. Plants take in no organic molecules from the soil or air, thus all organic molecules found in plant cells must be synthesized de novo from G3P. This includes all cellulose cell walls, chlorophyll molecules, enzymes for the Calvin cycle, DNA, phospholipids and proteins of the cell membranes, vitamins, oils and amino acids (Campbell, 1996). It is this fate of G3P that has been difficult to convey to students, and is likely to be one kind of gap students have about photosynthesis. Even a teaching module developed to address such alternative conceptions attributed only an “energy” role to the plant’s food, and not a role as a building material (Bishop, Roth, & Anderson, 1986). Furthermore, the more global role of photosynthesis in carbon, oxygen, and water cycles is not made explicit in many classrooms.

Understanding photosynthesis involves learning a large number of concepts and therefore labels (vocabulary). Although it is arguable that it is possible to learn
about photosynthesis as in the above paragraphs without resorting to the large number of new terms (40 in Campbell’s chapter on photosynthesis), meaningful discussion of the process is enhanced when scientific labels can be used appropriately.

Figure 1. Schematic diagram of photosynthesis (adapted from Campbell, 1996, p. 200).
What is Known about Learning of Photosynthesis

During the Alternative Conceptions Movement a variety of research approaches has sought to illuminate students' ideas about photosynthesis. Alternative conceptions have been revealed by studying documents such as textbooks (Barass, 1984; Storey, 1989), and by administering a variety of paper and pencil instruments to large samples of students. One such instrument is the Photosynthesis Concept Test (PCT) that is made up of open-ended questions about instances and phenomena and asks students to predict and explain them (Wandersee, 1985; Institute for Research on Teaching, 1985). The target concepts of the PCT are listed here:

1. Plants make their own food internally; this food is the plant’s only source of food.

2. Food made by plants is matter that they can use as a source of energy.

3. Food supplies the energy that plants need for life processes.

4. Water and carbon dioxide are changed into another form of matter as a result of a chemical reaction.

5. Water and carbon dioxide travel to leaves where they are involved in the making of food; food travels from where it is made to all parts of the plant.

6. During photosynthesis, energy from the sun is changed into energy in the form of food (glucose, sugar, starch).

7. The food that plants make is their only source of energy.

8. Animals depend on plants for food and oxygen. Only green plants can make the energy containing food that all animals need.

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Wandersee designed and used the PCT in a nation-wide, cross-age survey using multiple-choice and open-ended questions to reveal a common alternative conception from elementary to university level: plants obtain their nutrition from the soil (Wandersee, 1985). Eisen and Stavy (1988) administered their own instrument (with 14 open-ended questions about oxygen release, respiration, autotrophic feeding, and sunlight energy) to high school and college students. Both studies produced multiple-choice or open-ended written responses that depended on common language for interpretation of terms like “food,” “respiration,” “energy,” and qualifiers like “most important,” thus variation in how the subjects construed the meanings of the questions may be a source of error (Abimbola, 1988; Jungwirth, 1988; Wandersee, 1988).

Students of all ages possess strikingly similar alternative conceptions about photosynthesis (Anderson, Sheldon, & Dubay, 1990). Wandersee et al. wrote that “the notion that green plants synthesize their own food intracellularly seems to pose an almost insurmountable problem for many students. When asked about plant nutrition, a large proportion of individuals, including those who have taken several previous biology courses, insist that plants obtain food from the soil.” (Wandersee, 1994; p. 184). Although most students understand that plants need water, air and light, they fail to understand the roles these materials play in the process (Lumpe & Staver, 1995). Among the common alternative conceptions are that (a) photosynthesis keeps the plant green; (b) food for plants include water, soil, air, minerals, and sunlight; (c) the term “food” is misunderstood; (d) photosynthesis is simply a gas-exchange process; (e) light is used to keep plants warm; and (f) photosynthesis is the
respiration of plants (Lumpe & Staver, 1995). Some of these faulty conceptions
become less evident with increased schooling (Treagust & Haslam, 1986; Wandersee,
1985).

Primary reports of alternative conceptions about photosynthesis were followed
by studies that applied or correlated this knowledge with other learning activities. The
learning of photosynthesis (as measured by concept map evaluation and traditional
exam) was correlated with study strategies in another research report (Hazel &
Prosser, 1994). One practical case study observed how a teacher attempted to alter her
students’ alternative conceptions about photosynthesis (Smith & Anderson, 1984), but
this study relied solely on classroom and teacher planning observations, and not
student interviews. Knowledge of student alternative conceptions in photosynthesis
was also used as a basis for developing remedial instruction (Amir & Tamir, 1994). In
that study the researchers used graphs of photosynthetic rates and limiting factors.
thus the results may have been confounded by the ability of the subjects to interpret
graphical data. A more recent study, using qualitative as well as quantitative
techniques, found that students working in collaborative peer groups developed more
scientifically correct conceptions (i.e., the PCT target conceptions above) of
photosynthesis than did students working alone (Lumpe & Staver, 1995).

Researchers using non-interactive, paper-and-pencil approaches to
understanding alternative conceptions have recognized the limitations of using
traditional instruments since the reason behind a student’s selection is not evident.
Furthermore, even written responses to open-ended questions are necessarily
language-bound, and do not allow interaction with the students to better understand
what they meant by their responses. The power of a diagnostic instrument seems to depend on its ability to externalize the student's reason for his/her choice. The two-tier approach promoted by Tamir (Tamir, 1989) and Treagust (Haslam & Treagust, 1987; Peterson & Treagust, 1989; Treagust & Haslam, 1986) is, on the surface, an improvement over the traditional multiple-choice instrument. In these the first tier of each item (a traditional forced choice question) is followed by the student's justification either in a multiple-choice or open-ended form. However, this researcher's small-scale study that took a qualitative look at this quantitative approach documented numerous instances in which student responses would have been wrongly diagnosed as alternative conceptions (Griffard, manuscript in preparation). For these reasons, a qualitative, interactive approach seemed most appropriate for this study.

Very few of the aforementioned studies have addressed how students understand energy transformation at a cellular level, namely in photosynthesis and cellular respiration. One that did identified several difficulties in understanding energy transformation, namely the complementary, reciprocal relationship between photosynthesis and respiration, the use of everyday language to define respiration and food, and fragmented knowledge resulting from rote learning (Songer & Mintzes, 1994). That study used structured clinical interviews, concept maps and an open-ended instrument with specially designed tasks to collect data for their study on college students' understanding of respiration. From these the researchers identified an array of alternative conceptions, and concluded that novice students (i.e., college freshmen) often do not offer explanations at the cellular level, but rather at the organismal or community level, but that instruction improves thinking at the cellular
level. Instruction was able to address some conceptual difficulties, but it exacerbated others. Lastly they concluded that if alternative conceptions are not addressed in introductory-level courses, they are likely to persist throughout undergraduate years.

Naturalistic Inquiry

In the past twenty years most disciplines that study humans, including science education, have experienced the emergence and acceptance of a new paradigm for conducting research: the naturalist paradigm. Proponents of qualitative research argue that traditional quantitative approaches to inquiry have limited usefulness in the study of humans (Lincoln & Guba, 1985; Smith, 1982).

Qualitative and quantitative paradigms differ in many ways. The qualitative paradigm considers the nature of reality to be multiple, holistic, and constructed, whereas the quantitative paradigm views reality as single, tangible, and fragmentable. The qualitative paradigm considers the relationship between knower and known to be interactive and inseparable, whereas the quantitative researcher prevents this interaction. In qualitative research, only time- and context-bound working hypotheses are possible, whereas in quantitative research broad generalizations are the goal. Qualitative research views causation as a mutual, simultaneous shaping of entities such that cause and effect are indistinguishable, whereas quantitative research holds the view that there are real causes that can be uncovered. Finally, qualitative research accepts that the investigators' values and tacit knowledge are inseparable from the inquiry, whereas this is unacceptable in traditional quantitative research (Lincoln & Guba, 1985).
Qualitative research has several other characteristics. As opposed to studying subjects in an experimental setting with instruments that make data quantifiable, qualitative research is typically conducted in natural settings, and data are collected by a human instrument via participant observation, interviews and artifact analysis. Data analysis is inductive, and theory is grounded in the data. The research design emerges instead of being decided *a priori*, and the outcomes are negotiated with the research participants. Sampling is purposive rather than random, and trustworthiness of the data is valued over traditional validity criteria (Lincoln & Guba, 1985).

Although some early proponents of naturalistic inquiry argued that the paradigms are so distinct that they are incompatible, others have disagreed (Howe, 1988). The debate has resulted in broad acceptance of research conducted in either paradigm so long as it conforms to standards in the discipline (Good, 1993; Howe & Eisenhart, 1990). Another consequence is the emerging view that mixing the methodologies within a study is advantageous (Chi, 1997; Hauslein, Good, & Cummins, 1992; Songer & Mintzes, 1994). The current centrist view seems to be that the methodology should be chosen in accordance with the research question at hand, which often includes employing a mixture of qualitative and quantitative methods in the research design, data collection, and analysis (Patton, 1990).

The research discussed here employed qualitative interview, observation, and document analysis methods which were much better suited to the search for gaps in propositional networks than quantitative methods would have been. That is not to say that quantitation is never indicated during analysis of coded protocols (Chi, 1997). On the contrary, frequency counts and numerical comparisons were useful for
understanding the data presented, even though the data did not readily lend themselves to statistical analysis.

**Overview of Qualitative Data Collection Methods**

Patton (1990) among others list interviews, observations, and document and artifact analysis as common sources of qualitative data. He describes a continuum of interview approaches, from the informal conversational interview, to the interview guide approach, to the standardized open-ended interview. As the structure increases in this list, the flexibility decreases, but collection of systematic data that are somewhat directly comparable between participants is possible. Because of the narrow focus of the study and the desire to compare the participants’ understanding of this narrow topic, the format used in this research was nearly that of a standardized, open-ended interview (Patton, 1990), in which the questions are carefully worded. However, there was some flexibility built in so that the researcher could have the participant elaborate on some of her/his explanations.

Clinical interviews are a kind of qualitative interview used frequently in science education research, having originated with Piaget trying to understand children’s conceptual development. In clinical interviews, participants are presented with objects or events to respond to, and they are asked precise questions about them (Novak & Gowin, 1984). These objects can be cards, graphics, living things, or even a computer simulation of a scientific process as it was used here.

Because of the value of concept maps for representing knowledge, researchers have used them in several ways with respect to the clinical interview. Some have transformed the interview data into concept maps outside of the session (Champagne,
Klopfer, Desena, & Squires, 1981), some have trained participants how to map prior to the study (Pearsall, Skipper, & Mintzes, 1997), and some co-construct a map with the participant during the interview session itself (Wandersee & Abrams, 1993). The last of these was the most desirable for this research because of its metacognitive value for the participant and for the feedback on accuracy (trustworthiness) that the participant could offer.

Some qualitative research relies more heavily on participant observation and recording of field notes than this study did. The stages of fieldwork are entry into the field, collection of field notes on observations, and the closing stage. Entry requires negotiation with the stakeholders, and often permission from administrative bodies if the research is in classrooms. Since the observer is often the observed, Patton (1990) suggests becoming part of the initiation process of those in the study setting rather than appearing after the socialization process is mostly complete. For this research, observations were made of the classrooms from the first class day into the semester, until all data were collected. Another reason to attend from the first class of the semester was to note all references made by the instructor to any of the processes involved in photosynthesis that were taught later in the semester.

Most qualitative field data are collected by participant observers, which makes the socialization process and the second stage very significant. Since the lecture courses that were observed in this research were quite large (150-200 students), socialization was not an issue. Consequently, closure at the end of the study was not significant.
Data Analysis

This stage of data collection and interpretation typically comes after the observations and interviews. It is a study of the collected notes and interviews, as well as content analysis of relevant writings or other artifacts of the setting (Patton, 1990). In this research, artifacts of learning in the college biology classroom were available for analysis, including textbook passages, lecture notes and graphics used by the professor, and class notes taken by the students. Additional data subject to content analysis were written exams or assignments. Such written artifacts can be subjected to techniques such as concept propositional analysis (CPA) (Mintzes et al., 1997; Novak & Gowin, 1984), which is a way to systematically analyze the propositions inherent within a body of expository text. Analysis of the data at this stage is very “messy,” with large volumes of documentation. Analysis was facilitated by designing coding and indexing schemes using the qualitative data analysis software such as NUD.IST™.

Measures to Insure Credibility and Trustworthiness.

Patton (1990) recommends triangulation of data, investigators, and analytic methods in the effort to gain confidence in one’s research. Trustworthiness is enhanced also when the data are analyzed from different theoretical viewpoints or from mixing quantitative with qualitative approaches. Analysis of the data from more than one viewpoint is discussed in the Conclusions. Using multiple interviewers was not appropriate for this study because of the need for common lines of questioning and common goals of the questioning across cases. Participants were debriefed about the content and the purpose of the study at the end of the study. They will receive an abstract of this study and have an opportunity to react to the findings. They were not
asked to directly comment on the findings and their quotes because over a year had elapsed since the interviews, making it unlikely that they would have remembered the thought processes at those moments.

Methods for Studying Human Cognitive Structure

Researchers in education have come to regard learning outcomes as the correspondence between the structure of the discipline (content area) and a student’s cognitive structure or knowledge structure (Champagne et al., 1981; Hoz, Bowman, & Chacham, 1997). Cognitive structure has been described as the organized and interrelated set of propositional knowledge that one has and stores in long-term memory (Ausubel et al., 1978). It has been pointed out that this view of cognitive structure, among others, views memory as a rather stable entity, and does not address issues of concept use (Hoz et al., 1997). Thus any hypothetical constructs proposed by researchers are necessarily based on external representations of this knowledge, and need to be validated. This is the goal of both psychometric (hard, experimental) and edumetric (soft, clinical) approaches in research on cognitive structure.

Edumetric and Psychometric Probes

Probes for cognitive structure currently used in science education research are more commonly of the clinical, edumetric sort. Probes used in clinical interviewing include citing definitions, grouping concepts and describing criteria for membership, and constructing of semantic nets or concept maps. One reason for the shift from the psychometric approach is that its instruments do not portray cognitive structure as it is currently thought to exist (i.e., schemas and propositional networks). Another reason is that its methods do not require the participant to elaborate on her or his responses,
making the results heavily dependent on inferential leaps on the part of the investigator, which is a challenge to trustworthiness of the data (Hoz et al., 1997).

Those interested in research on educational technology recommend a shift in focus from research on the media to research on the learning that results from it (Grabinger, 1996). The methodology strategies Grabinger recommended for examining the cognitive processes of learning include think-alouds, written-question generation, ranking and classification techniques (such as sorting tasks), concept maps, and video-stimulated interviews.

Once the verbal data are gathered, its analysis should be systematic. Some have found it useful to evaluate the levels at which processing was occurring when the statements were made. This can be done using a coding rubric similar to that used by Chan and colleagues (Chan, Burtis, & Bereiter, 1997). They used a five-level knowledge processing activity scale when they examined how individuals and groups process scientific information that either builds on or contradicts their understanding of the phenomenon. The scale describes activities indicative of five levels of knowledge building: subassimilation, direct assimilation, surface-constructive, implicit knowledge building, and explicit knowledge building. Alternatively, in studies in which behaviors in problem-solving were evaluated, checklists of behaviors were devised and used when reviewing videotapes of the interviews (Lavoie & Good, 1988; Shotsberger, 1993).

The above edumetric approaches to understanding cognitive structure and processing can still have a quantitative aspect. The degree of relatedness among the concepts in concept maps and card sorting tasks is subject to quantitation. This has
been done a variety of ways, including F-sort (Hauslein et al., 1992), flow-mapping (Anderson & Demetrius, 1993), ConSAT (Champagne et al., 1981; Hoz et al., 1997) and using such computer programs as Pathfinder (Bates, Warkentin, & Rea, 1993; Kokoski & Housner, 1994; Koubek, 1991).

Some of these studies used a mixture of qualitative (think-aloud protocol analysis) and quantitative approaches complementarily to better understand their participants' cognitive structures (Hauslein, Good, & Cummins, 1992; Pearsall, Skipper, & Mintzes, 1997). Some studies that mix qualitative and quantitative methodologies do so at different stages of the analysis: qualitative data which are coded and categorized, then subjected to quantitative analysis (e.g., Chi, 1994, 1997).

Because this research is a search for patterns of gaps that exist in college biology students' explanations of photosynthesis, the primary data came from the clinical interview and the resulting verbalization protocols. Interviews alone however were not sufficient to understand the sources of these gaps; observations of classrooms and document analysis of student class notes and textbook served as secondary sources of context data.

**Verbal Analysis**

Having research participants think aloud while performing some cognitive task such as problem solving or concept sorting has been a common way to collect data about cognitive structure. The traditional method has been protocol analysis (Ericsson & Simon, 1993), which was originally developed by researchers of artificial intelligence and cognitive science in order to identify the decontextualized logical processes involved in problem-solving rather than conceptual structure. Protocol
analysis assumes the verbalizations reflect the content of short-term memory, which is the information from long-term memory being heeded at any one time. Participants are carefully instructed to speak out loud any thoughts that come to mind as they read and solve a problem, without directing explanations to the researcher. The resulting think-aloud protocols are studied and information about cognitive processes are inferred from them.

Verbal analysis (Chi, 1997) represents a deviation from protocol analysis in that the former is interested in the domain-specific cognitive structure and retrieval that leads to the resulting think-aloud protocol, whereas the latter focuses on the logical strategies that are involved in information processing in general, and across domains. In verbal analysis, gestures and artifacts that resulted during the think-aloud task are analyzed as well as utterances. In addition, protocol analysis compares the problem-solving protocol of the participant with an ideal template and measuring the degree of match. Verbal analysis does not assume the existence of such a template, and analysis of the protocol is idiographic, or based on its own terms. This makes the analysis more problematic, or "messy," but less theory-laden.

Because the purpose of this research is to understand cognitive structure more than information processing strategies, verbal analysis was preferred over protocol analysis. In brief, verbal analysis consists of seven steps:

1. Reducing or sampling the protocols;

2. Developing a coding scheme based on syntax (sentences) or activity features (pauses) (This sets a "grain size" for the remainder of the analysis);
3. Operationalizing evidence in the protocols that constitutes a mapping to some chosen formalism;

4. Depicting the mapped formalism graphically (e.g., with concept mapping, CMap software or NUD.IST™);

5. Seeking patterns in the mapped formalism;

6. Interpreting the patterns; and

7. Repeating the whole process, perhaps coding at a different grain size (size of linked network of propositions and their microinferences).

The data analyzed in this way are usually verbal protocols, but can include videotape transcripts or field notes from observations. How these steps were adapted for the study is elaborated in the Methods section that follows.

The Goal of Biology Education: Biological Literacy

The goal of current reform efforts is science literacy for all citizens (American Association for the Advancement of Science, 1993; Biological Sciences Curriculum Study, 1995; National Research Council, 1996; National Science Foundation, 1996). Scientific literacy has been defined as the ability to:

1. recognize the unifying themes of a discipline. In biology these are evolution, reproduction and inheritance, growth and development; homeostasis; matter, energy and organization; and interaction and interdependence;

2. make sense of scientific findings reported in the popular media;

3. distinguish science from pseudoscience and understand the limits of scientific knowledge; and
4. gather more information as needed to inform oneself, and make personal, societal and civic decisions based on that information.

Paul Hurd is credited with this definition of scientific literacy. He recommends that because of the information explosion in the science, emphasis in science education should be on “learning how to learn” (Biological Sciences Curriculum Study, 1993).

The Biological Sciences Curriculum Study (BSCS), established in 1960, is one of the few of the post-Sputnik curriculum agencies to have survived. It has seen its mission as the development of instructional materials and curricula in response to recommended reforms based on emerging biological and pedagogical knowledge. BSCS published Developing Biological Literacy (Biological Sciences Curriculum Study, 1993) in which it made recommendations for high school, two-year and four-year college priorities for curricular content, instructional strategies and assessment that will lead to biological literacy. It proposes the following biological literacy model in which several levels of literacy are recognized:

1. Nominal literacy means that a student is literate “in name only,” meaning that they can identify words as belonging to the biological sciences domain but cannot use them and are likely to have serious alternative conceptions about them.

2. Functional literacy means that the student can define terminology, label prototypical diagrams, and generate memorized explanations for biological phenomena.

3. Structural literacy is the minimal level we should require, according to BSCS. Students at this level are able to generate explanations for processes or
structures in their own words and may begin to wonder about how some phenomena are related.

4. Multidimensional literacy is usually attained by biology graduates, especially those who have been motivated by a real world problem that requires integration (for example, in research or teaching). Persons at this level are able to make connections spontaneously between diverse phenomena within biology, such as understanding the role of photosynthesis in a novel ecosystem, or the role of molecular genetics in classical inheritance. Multidimensionally literate persons also understand how biological phenomena relate to physics, chemistry, and geology. Those at this level recognize deficiencies in their own understanding and seek to fill them.

Because this study looked at how biological knowledge grows, the BSCS literacy model was relevant as a framework in which to understand that growth. The BSCS literacy levels were preferred over test grades or grade point average in the evaluation of the participants’ pre- and postinstruction understanding of photosynthesis. It would also have been desirable to use the BSCS criteria to recruit “above average” and “average or below” students for this study, however interviewing all applicants to determine literacy level was not practical prior to participant selection. Therefore academic record (grade point average) was used as primary screening criteria. The Phase 1 interview data allowed a rough assessment of preinstruction photosynthesis literacy level, and Phase 2 interview data allowed the same for postinstruction photosynthesis literacy level.
In Developing Biological Literacy (1993), BSCS analyzes topics across the domain of biology and recommends whether the topic is essential, optional, or nonessential for students at the secondary and postsecondary levels. BSCS has designated photosynthesis as one of the "essential" topics to be taught at the high school and college level. By comparison, the perennially popular topics such as digestive, circulatory and gas exchange systems were designated "optional" within the same unifying principle of energy, matter and organization.

Nature of Scientific Knowledge and Science Education

Scientists generally conduct their work as though the object of their inquiry, nature, is an objective, predictable, albeit complex, reality. This is the epistemological bias of this researcher as well. But this scientific realism stance is but one epistemological position a researcher can adopt (House, 1991). Postmodern philosophers have questioned the existence of an objective reality and the need to invoke one (Schwandt, 1994; von Glasersfeld, 1991). It has been no surprise that sharp criticism of these views has come from scientists (Klotz, July 22, 1996), who do not readily accept that their academic domains are merely social constructions. But how does this affect how we teach science or how we conduct research on science learning? Is the science we teach a "correct" portrayal of reality, or is it constructed?

It has been said that the goal of science education should be to move the student to progressively better (more scientific) explanations of phenomena (Wittrock, 1994). This view requires confidence that science can generate knowledge that is increasingly "correct." It also requires a constructivist view that learning is incremental and that a student's learning of a science concept falls somewhere on a
continuum (Good, 1991) from immature prescientific conception to the prevailing view of the phenomenon among those scientists on the cutting edge in that discipline (i.e., from worse to better). It is generally agreed among scientists that nature itself is the arbiter of where the endpoint of that continuum lies. Although many disciplines can make a claim for such a continuum in their disciplines, they have no such ultimate arbiter of its endpoint. Thus science education directly or indirectly judges student understanding against a standard set by scientists in that field.

The same forces that mold and modify a student's explanation of a scientific phenomenon over time may well be at work in the sociology of science. Indeed it has been noted that students' conceptions often undergo changes similar to those that have occurred historically (Mintzes et al., 1997; Wandersee, 1985; Wandersee, 1992). Subtleties in the prevailing view and new findings are continually discussed in scientists' literature. Scientific knowledge is not as static as it is often portrayed in science classes: the endpoint moves. Revolutions occur regularly and paradigms shift (Kuhn, 1970), but they are not quite so dramatic in K-12 science content, as the textbooks only gradually change in response to widespread acceptance of the new paradigms among scientists. Some who defend the value of teaching the knowledge even if it may change recognize that as knowledge grows diverse findings coalesce into a simplified model, making the knowledge more accessible to learners (Harding & Vining, 1997). This is not to say that teaching the "big ideas" of the discipline is justified since doing so cannot replace or "short-circuit" the learning process.

The above comments about epistemological commitments and the continuing content versus process debate are relevant to this research. The epistemological
commitment of this researcher is to scientific realism, but with the recognition that the reality behind the data is more complex than is typically evident from reductionist approaches alone. This researcher nonetheless values the relatively stable body of knowledge about photosynthesis, in spite of the fact that it, too, continues to grow (Sarbu, Kane, & Kinkle, 1996; Williams, 1996). She believes that complex biochemical aspects of photosynthesis taught at the college level cannot be understood by students via laboratory inquiry alone. To be meaningful, the knowledge students construct about photosynthesis needs to be integrated from numerous related propositions (or knowledge "pieces"), and, in this researcher’s opinion, this is best accomplished explicitly via excellent instruction (that includes experiential learning) at the college level.

These commitments influenced the design of this study, which is at once nomothetic and idiographic. While the methodology is typical of idiographic research in which student knowledge is studied qualitatively and valued on its own terms, this researcher recognizes and accepts that their knowledge is necessarily in transition toward a more and more scientifically “correct” form. This is a nomothetic position since understanding will be judged in reference to an outside standard for the current explanations about photosynthesis. This research also places value on higher level propositional knowledge that can (and hopefully does) lead to a more integrated, systematic view.
METHODS

Research Design

Since the purpose of this study was to understand the nature and source of a human and societal issue, education, this study is considered an example of applied research. A desired result of applied research is the contribution to theories that can be used to formulate interventions (Patton, 1990). This research may lead to development of theoretical and instructional improvements that will acknowledge gaps and help students bridge them.

The primary unit of analysis for this study was the participant’s conceptual framework for photosynthesis. This unit of analysis is embedded in and influenced by subordinate units of analysis: instruction, learning habits/skills, prior knowledge, and affect/motivation. Instruction itself has several components that are subject to study: the professor, textbook, lecture notes/visuals, assignments, and exams. All decisions about the research design, from sampling to analysis, were made with the consideration of the primary unit of analysis (Yin, 1994).

The focus of the study was the identification of gaps, but another dimension of analysis is how these gaps compared across biological literacy levels and across two sections of a single course. Therefore this was a comparative case study involving multiple cases. The goal of this research was to understand complex conceptual frameworks in depth, which called for a qualitative approach with a small number of participants. The sampling therefore was purposive rather than random. The selection criteria were based first on ability level (as an indicator of biological literacy level), and then on the secondary units of analysis listed previously: instruction, learning.
habits/skills, prior knowledge and affect/motivation. A flow chart of this study is shown in Appendix B.

Recruitment/Purposive Sampling

Primary Participant Pool: Biology 101

Because of the importance of success in the introductory course in one’s major (Halyard, 1993), the primary source of participants were students enrolled in an introductory biology for science majors, “Biology 101,” at a major university in the Deep South.

Professor/Section Selection

In the semester the study was conducted there were four sections of Biology 101 offered, of which two were chosen as primary participant pools. The instructors for those two sections were Dr. “Corey” and Dr. “Reese.” Dr. Corey is a mammalian ecologist and the course coordinator with ten or more years teaching experience and a very good teaching record. He is experienced with instructional media and is sensitive to pedagogical issues. Dr. Reese is a zoologist/molecular biochemist and full professor with among the best teaching evaluations Dr. Corey has seen.

Dr. Corey’s and Dr. Reese’s sections were chosen as participant pools since both professors have good teaching reputations and both responded favorably to this researcher’s request to conduct research on this topic with their students. Furthermore, both sections were taught on the same days, which facilitated the researcher’s attendance at all class meetings. Another of the course instructors was eliminated since he serves as the Graduate School representative on the researcher’s doctoral committee.
Lecture Observations

Although the clinical interviews provided the vast majority of the data needed to construct a typology of gaps, knowledge of the participants’ instruction informed choices about methods (e.g., which terms to include in mapping tasks) and aided interpretation of the participants’ responses. Therefore the researcher attended all of Dr. Corey’s and Dr. Reese’s lectures that semester up to and including those on photosynthesis. Dr. Reese lectured on topics at a rate about twice that of Dr. Corey. Following the same list of topics to be covered, Dr. Reese addressed photosynthesis in one lecture in the fourth week of the semester, whereas Dr. Corey did so in two lectures beginning in the seventh week. Lectures on photosynthesis were audiotaped. In all lectures extensive notes were taken.

Interactions with Professors

At the start of the semester both professors were invited separately to have lunch with the researcher so that they could be familiarized with the how the study would involve them. Dr. Corey accepted this invitation, while Dr. Reese declined. Only details about the logistics for participant recruitment and lecture attendance were discussed, not objectives or anticipated findings. Both were aware that the study would be about student understanding of photosynthesis, and that a simulation would be used, but neither appeared to change their planned lectures as a result. Their exam questions were similar to those from past semesters. The number and rigor of the questions on photosynthesis were much higher on Dr. Corey’s exam than Dr. Reese’s. Dr. Corey’s exam questions expected more integration of previous topics (e.g., transport, organic macromolecules) than Dr. Reese’s exam, which consisted of simple
recall questions. Although Dr. Reese lectures on the same topics in the same order, he said that he believes the content is too difficult for them and most students do not do well on it. All of his exams contained extra questions that allowed students to earn bonus points. Dr. Corey’s attitude is that of enthusiastic confidence and approachability that let one participant, Cheryl, know that he is available during office hours to help them reach the high standard. All participants from his section enjoyed his class and felt they were learning. By comparing their class notes with their friends’ or the information in the simulation, four participants of six from Dr. Reese’s section (Rhyan, Rhea, Rashad and Randy) made comments in the interviews that indicated they felt their course did not prepare them as well as it could have.

The researcher met once with both professors together to ask for their feedback about the photosynthesis simulation. Dr. Corey was already familiar with it, whereas Dr. Reese did not have much comment about it. After being asked to critique it, Dr. Corey and the researcher wondered what might cause ATP synthesis to be blocked, and whether a plant virus was known to do this. Dr. Reese had no contribution to that inquiry. When asked how students think about and learn this, Dr. Corey said they don’t realize plants undergo respiration as animals do. Dr. Reese said he never really thought about it.

Both professors agreed to have their students complete a short questionnaire (Appendix F) immediately following their exam that included photosynthesis. These questions were designed to determine how well students transferred information learned earlier in the semester to photosynthesis. Since the majority of students had
no investment in conscientiously completing the questionnaire, only those completed by the participants in this study were analyzed.

**Participant Recruitment**

The researcher requested and received permission from Dr. Corey and Dr. Reese to recruit participants in their first class sessions of the Spring 1998 semester. A five-minute recruitment announcement was made and application/consent forms were distributed and collected from the students. It was explained that the participants selected would agree to meet three times for clinical interviews lasting from one to two hours, and that at the completion of the study they would be compensated fifty dollars for their time. On the application form (Appendix D) applicants indicated consent to participate in this study involving them as human subjects, as well as consent for the researcher to view their academic records. Most students in both sections completed and submitted the applications.

**Participant Selection**

Six subjects were selected from each of these two sections of Biology 101. They were traditional students following curricula that required this course. Selection from the applicants was based on achievement only to the extent that subjects were selected across a range of academic ability. Selection was by purposive intensity sampling: applicants with grade point averages of 3.0 or higher were categorized as “above average,” and those with grade point averages less than 3.0 were considered “average or below.” The applicants’ personalities and their perceived ability to think aloud during cognitive tasks were considered. In each of the two sections of the course, three students were selected at each of two achievement levels. Two (2)
sections times two (2) achievement levels times three (3) at each level equals twelve (12) participants. Half of the participants were female. Of the entire group, two males were Hispanic (Carlos and Raul). One female (Chanda) and one male (Rashad) were African-American.

Note that pseudonyms were not arbitrarily chosen. Names beginning with C were enrolled in Dr. Corey’s section and names beginning with R were enrolled in Dr. Reese’s section. In addition, those names whose second letter is H indicate that their grade point averages show higher ability (>3.0), and those names whose second letter is A indicate that their grade point averages show average ability or below (<3.0). Some names (Chanda, Carlos, Raul, Rashad) indicate ethnicity as well.

Description of Participants

Chanda is an African-American female student planning to major in one of the basic sciences. She was an honor student at her high school, which she now thinks was “easy.” Her parents are both accountants who are also taking courses part-time toward accounting degrees at the university in their hometown. Chanda has always wanted to be a physician, and she understands that there is a lot involved in getting accepted into medical school. Chanda was in her second semester of college at the time of the study, and was disappointed in her performance during the first semester (grade point average 3.13). She withdrew from Biology 101 her first semester due to dislike of the instructor. In her second semester she made all A’s, including in Dr. Corey’s Bio 101 course and in Chemistry. Her grade point average after four semesters was 3.75. During the interviews she spontaneously exhibited numerous metacognitive behaviors such as summarizing, making orienting statements, and self-
correcting. Her personality was that of a focused, calm, and ambitious woman. During clinical interviews she communicated clearly and stayed on task. She rarely made self-deprecating comments even in jest, although her self-doubt took other forms, such as assuming an extra level of complexity (since she understood the one at issue) or withholding a correct prediction for fear of being incorrect.

Charles is a Caucasian male student on full scholarship and is active in the Honors Program at the university. He is an only child of a chemist employed by the federal government and a part-time librarian whose undergraduate degree was in biology. He claims his interest in chemistry had little to do with his upbringing. Charles was in his second year in a chemical engineering curriculum at the time of the study, but changed his major to chemistry that semester. He describes his best learning experiences as those he had in his favorite high school science teacher’s classes, and he hopes to offer this experience to others by becoming a high school science teacher. He is planning to enter a postbaccalaureate teacher certification program upon graduation. His transcript shows his grade point average at the time of the study was 3.8. Charles has diverse interests beyond academics. He is warm, driven by intellectual stimulation, and not inclined to speak without thinking first. Often in the first interview he exerted control of the tasks by subtly making comments that pointed out inadequacies of the simulation. This continued until he encountered the mechanism window and was impressed by the pedagogical value of it. It appeared that he held more respect for people and software that personally challenged him. His respect for the researcher seemed to increase when he was challenged to the point of learning something new or gaining a new perspective he did not have before.
Cheryl is a Caucasian female student on full scholarship at the university. She was an honor student in high school and is the youngest daughter of aging parents. She is majoring in kinesiology because she is interested in human movement, but hopes to go to graduate school in physiology and earn a Ph.D. She is an eager student who after her first biology exam began going to Dr. Corey’s office hours regularly to get clarification of class topics. Although she is not hesitant about asking questions and getting information about careers, she has had limited life experience that would address her naivete about academia and research. She seemed unaware that kinesiology outside of her university is a field dominated by athletics and physical education. She was in her second semester at the time of the study, and had a grade point average of 3.8 at the time. Cheryl is a bright and confident, but anxious, talkative, and self-doubting woman. During clinical interviews she spoke very quickly and externalized every thought process. This made her self-doubts and her monitoring habits readily evident, and thus provided valuable data. She felt more comfortable in the second interview and was less concerned with “looking dumb.” Throughout both interviews she referred to and generated numerous sketches or graphic representations of her understanding, indicating that she is a highly visual learner.

Caroline is a Caucasian female whose mother is Asian Indian and father is French. She was raised by her grandmother in a Hispanic area of the United States. She attended a large public high school with an excellent reputation where she was able to take many elective science courses, such as marine biology. She did so because she liked the teacher and learned well in those classes. She was majoring in computer science at the time of the study but had decided to follow in her mother’s
footsteps and become a research nurse. She works with her mother in a cardiology research project in a nearby metropolitan area on the weekends. Caroline was in her fourth semester and had a 2.4 grade point average at the time of the study. She earned a B in Bio 101 and has since raised her average to 2.6. Although her science background is strong and she provided numerous data indicating she has more ability than is evident in her grades, she seems to lack confidence. Perhaps her high school experience being average among very bright students has prevented her from seeing herself as a promising science student.

Cathy is a Caucasian female who transferred to the university from out of state. Her parents are originally from the university’s metropolitan area. Cathy’s high school experience was similar to Caroline’s: large public school with a lot of science electives. She is on the cheerleading squad for the university and has the boundless energy that goes with it. Cathy has wanted to be a high school biology teacher, apparently more for the team sponsoring opportunities than teaching. She keeps coming back to an education curriculum in spite of her parents’ and others’ admonitions about teaching as a career. She has changed her program of study repeatedly since beginning college. She was a secondary science education major with a grade point average of 2.6 at the time of the study. She earned a B in Bio 101, and has since changed her major to communications disorders. During clinical interviews she was chatty, witty, energetic, and impulsive (which led to many mistakes). She wanted to understand the content and devised her own study tools (posters of the process of photosynthesis) that she brought to share at the interviews. That she chose to do this in a graphic form indicates she is a visual learner. She made many
humorous self-deprecating comments about her responses, and often looked for feedback with eye contact and by directly asking.

Carlos is a Hispanic male student whose father is from Central America and mother is Italian-American. Although his father spoke no English when arriving in this country, Carlos does not feel that his Hispanic heritage made his upbringing different than his Caucasian friends’ experiences. He described his high school biology preparation as “excellent” and took advanced electives. Since high school Carlos has followed in his father’s footsteps in grocery store management. He is studying to be a nurse, with his parents’ support, but he really wants to work for the FBI someday as a detective. He predicts he will opt for the former to satisfy his parents and be able to have the family life he hopes for. Carlos was in his fourth semester with a grade point average of 2.7 at the time of the study, although he believes he has the ability to have a better academic record. Before he started working during semesters he had a 3.6 grade point average. In the semester before the study he dropped Bio 101 because of the instructor. He earned a C in Dr. Corey’s Bio 101 course. During the interviews Carlos showed evidence of a strong echoic memory--applying information he heard mentioned only once or in passing by the simulation or by the researcher. He learns in the class itself and does not do much traditional studying outside of class. Carlos seems to be mature, conscientious, reliable, and hard working. In the clinical interviews he was similar to Chanda: focused about completing the tasks. He did not tend to stray, nor did he seek feedback for his responses.
Rhonda is a Caucasian female who had just transferred to the main campus of
the university after one semester at a regional commuter campus where she earned all
B’s. She had been an honor student at her high school, a parochial school in the same
small town. This was Rhonda’s first semester on the main campus where she
continued to follow a psychology curriculum. Her career plan was to go to graduate
school in psychology and become a clinical psychologist/counselor. Although she
withdrew from Bio 101 with Dr. Reese within days of her Phase 2 interview, she was
allowed to remain in the project since she had attended and studied for classes up to
and including photosynthesis. Her transcript shows that she enrolled in and earned a
D in general biology for non-science majors the following semester. Her grade point
average was still around 3.0 in her most recent transcript. Rhonda was a poised but
timid and confused participant in the clinical interviews. Her biology background
seems to be very weak and she did not try to amend her deficiencies with in situ
schema construction using available clues. She responded that she didn’t know or
wasn’t sure to most tasks in the interviews. In all cases the data from her interviews
are outliers. She was the only student to have nominal photosynthesis literacy at both
phases of the study. Data from her verbalization protocols contributed little to the
findings of this study.

Rhea is a Caucasian female student who also had been an honor student in her
hometown parochial school. At the time of the study she had not decided which
curriculum to follow, but was considering either business or medicine. Her grade point
average was 3.7. She felt she had the ability to be a physician, but was not sure she
wanted the demanding schedule of medical school, residency or even private practice.
She was in her third semester at the university, and seemed to be preoccupied with sorority rush and related Greek functions. In the semester before she had taken a biology course for non-science majors, in which she earned an A easily. She then earned a B in Dr. Reese's Bio 101 course. Since then she has been following a premedical curriculum and has declared a zoology major, but has made B's in most of her courses. Her grade point average is currently 3.3. Although Rhea completed her tasks conscientiously and provided valuable data, during the interviews she was not as inclined as other high-achieving students to welcome questions that brought her deeper into the content (e.g., the carbon cycle, and the role of photosynthesis in producing all organic molecules on earth). Her intellect was not as ambitious as other above-average students in the study.

Rhyan is a Caucasian male student who was in his fourth year in a chemical engineering curriculum at the university. He was a graduate of the city's most prestigious magnet school, although he thought of himself as average when enrolled there. Like his father and uncles he chose this university and decided to study engineering. Since working in the chemical industry every other semester in the co-operative program, he has decided that engineering does not have enough contact with people in whose lives he could make a difference. He has decided to finish his engineering degree to "have something to fall back on" to support the family he hopes to have, but wants to pursue a career in medicine. He considers himself a good but not exceptional engineering student who works hard and tries to understand the complex concepts taught in his engineering classes. Rhyan's experience in a demanding curriculum makes him believe the premedical curriculum is easy by
comparison. He plans to take his prerequisites for medical school and take the MCAT (medical college admissions test). Rhyan earned the highest grade on the exams in Dr. Reese’s Bio 101 class. He was unimpressed by the level of rigor of the exams, which were very similar to those of past semesters. He earned an A in this course as well as in the subsequent Zoology course. During the clinical interviews Rhyan was a pleasant, confident, interactive, conscientious participant. He completed tasks, thought aloud, asked good questions, and did not fatigue in spite of in-depth probing of some of his ideas.

Raul, a Hispanic male student, had the most interesting academic background of all the participants. Raul’s parents both immigrated from Cuba, and his father is an engineer. Although Spanish was his first language, Raul, like Carlos, does not believe his upbringing was any different than his Caucasian friends’. He was in his senior year as a physics major at the time of the study, and was taking Bio 101 because it was required. He is a graduate of the state’s residential magnet high school. Interaction with culturally-identified Hispanics for the first time at that high school was a “culture shock” for him. Once he began his studies there he felt misled because he was made to believe students of the high school, on the campus of a public university, would have a great deal of interaction with the university faculty. After graduation he attended a large university out of state on a full scholarship, but, disenchanted with the physics faculty, he changed his major from physics to theater to finance before losing his scholarship for academic reasons. He claims he fell into an abyss because he was taking courses without their prerequisites and taking heavy loads while working. He eventually dropped out of that university and transferred to
this university in his home town. Raul said he has always been analytical. He reads Aristotle, Kuhn and other philosophers of science for his enjoyment, and he has maintained a website for several years in which he logs his views and offers debate about these writings. In his application for this study he reported his grade point average to be 2.3, which includes his academic record at his other university. Raul considers himself an intellectual and foresees an academic career. His hobbies are theater and fencing. He enrolled in philosophy of science courses, and began to consider graduate education in the field, but felt the field was “slipshod” and lacking of rigor. He challenged this researcher when she used the word “paradigm” and demanded a definition, then suggested that although this is the common use, Kuhn did not intend it this way. Raul does not seem to bother with studying for his non-physics courses. He learns what there is to be learned by going to class and seems to scorn the traditional note-taking and study strategies of typical students. He earned a C in Bio 101. In interviews he completed all tasks confidently and conscientiously, was witty and engaged, and was eager to continue the interviews if they might lead to topics of his interest that he could debate.

Rashad is an African-American male student majoring in chemistry and minoring in African-American studies. His choice of science arose from his positive experience in precollege science and pharmacy programs at a nationally-recognized historically black college in his hometown. He wants to apply his chemistry knowledge to pharmaceutical research, which he anticipates may involve some study of botany. He and his twin sister both graduated from an urban public magnet school which has a 100% Black student population. Their parents, divorced, are both public
school principals. Rashad was selected because he noted on his application that this was his third attempt in this course. Twice before he earned D’s, but finally earned a B in Dr. Reese’s course. At the time of the study he was in his second year at the university after a rocky start that earned him a 2.2 average and a stay on academic probation. His explanation for that poor performance was immaturity, and too much time spent playing in the dorm. Rashad exhibits determination and focus that has been frequently witnessed by this researcher in other graduates of his high school where the motivational messages are abundant and pervasive. During the clinical interviews Rashad was happy to share what he knows, making his explanations more impressive by sprinkling them with content-specific words not previously mentioned in the interview (e.g., oxidative phosphorylation). He was respectful, conscientious and engaged, but occasionally looked fatigued from the experience or by his perceptions of others’ expectations of him. His grade point average continues to be around 2.2.

Randy was a Caucasian male student from a small farming community’s public high school where he was the salutatorian of his class. His father manages the golf course at a local country club and his mother is a clerk with a public agency. He was in his second semester at the university in a premedical curriculum at the time of the study. He loved all of his science courses in high school, especially those that involved dissection, and he hopes to be a surgeon. After the shock of his first semester grades (grade point average 2.3), Randy followed his parents’ advice to withdraw from his fraternity and spend much more time studying. He attends and studies for all of his classes but is not quite sure if he is studying effectively. Randy
was a friendly, interactive and uncomplicated participant who seemed to be grateful for the opportunity to learn while participating in this research. He was engaged in all the tasks, was upbeat in spite of his unstated appraisal that his knowledge was insufficient for answering the task questions confidently, and was in awe of those who could. He earned a C in Dr. Reese’s Bio 101 class.

Table 1. Summary of participants as self-reported in personal interview.

<table>
<thead>
<tr>
<th>Student</th>
<th>GPA</th>
<th>Class</th>
<th>Major</th>
<th>Career Plan</th>
<th>Sex</th>
<th>Race</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chanda</td>
<td>3.1</td>
<td>freshman</td>
<td>undeclared</td>
<td>medical doctor</td>
<td>F</td>
<td>AfAm</td>
<td>A</td>
</tr>
<tr>
<td>Charles</td>
<td>3.8</td>
<td>sophomore</td>
<td>chemistry</td>
<td>high school sci. teacher</td>
<td>M</td>
<td>Cauc</td>
<td>A</td>
</tr>
<tr>
<td>Cheryl</td>
<td>3.8</td>
<td>freshman</td>
<td>kinesiology</td>
<td>Ph.D. in physiology</td>
<td>F</td>
<td>Cauc</td>
<td>A</td>
</tr>
<tr>
<td>Caroline</td>
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<td>research nurse</td>
<td>F</td>
<td>Cauc</td>
<td>B</td>
</tr>
<tr>
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<td>secondary ed.</td>
<td>high school biol. teacher</td>
<td>F</td>
<td>Cauc</td>
<td>B</td>
</tr>
<tr>
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<td>sophomore</td>
<td>nursing</td>
<td>nursing or detective</td>
<td>M</td>
<td>Hisp</td>
<td>C</td>
</tr>
<tr>
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<td>freshman</td>
<td>psychology</td>
<td>clinical psychologist</td>
<td>F</td>
<td>Cauc</td>
<td>n/a</td>
</tr>
<tr>
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<td>freshman</td>
<td>undeclared</td>
<td>business or medicine</td>
<td>F</td>
<td>Cauc</td>
<td>B</td>
</tr>
<tr>
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<td>chemical eng.</td>
<td>medical doctor</td>
<td>M</td>
<td>Cauc</td>
<td>A</td>
</tr>
<tr>
<td>Raul</td>
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<td>physics</td>
<td>Ph.D. in physics</td>
<td>M</td>
<td>Hisp</td>
<td>C</td>
</tr>
<tr>
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<td>B</td>
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<tr>
<td>Randy</td>
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<td>biochemistry</td>
<td>medical doctor</td>
<td>M</td>
<td>Cauc</td>
<td>C</td>
</tr>
</tbody>
</table>

Photosynthesis Simulation Software

Software Selection

Because the study described here employed simulation software in a relatively new capacity as a cognitive probe, it was important that interpretation of the findings not hinge on the quality of the software. Thus it was preferable to use an acclaimed simulation program already on the market. The simulation software probe was selected by seeking Internet sites and advertisements in educational journals about educational software for biology, by interacting with biology professors who use technology in their classes, and by surveying exhibitors’ booths at national science teachers’ conventions. The only product encountered that met the criteria of being a
simulation of photosynthesis was that of Logal Corporation’s Explorer Series, one component of which is Photosynthesis™. Their promotional CD-ROM contains sample activities from the full product that has all the manipulable features of the simulation as well as several activities. The full product contains much more for use in classrooms, such as journal templates, electronic evaluation by the teacher, and potential for text customization. Upon review of the full product, it was concluded that these auxiliary features were unnecessary for this project. A pilot study conducted in April 1997 indicated that the demonstration version offered all the features needed for use as a cognitive probe in the research described here.

Logal Corporation has offered simulation software for secondary and postsecondary science education since the early 1990’s. Although LogaT™’s physics and biology Explorer series have garnered many awards from parents’ and educators’ organizations, the photosynthesis simulation part of Biology Explorer was the 1993 winner of Educom’s Higher Education Software and Curriculum Awards Program. It was considered to have the “best design” and to be the “best natural science software (Biology).” It also won a “Gold Award” from Parents’ Choice. No other life science software exhibitor at the 1997 meeting of the National Science Teachers’ Association offered any photosynthesis software at all, much less an award-winning simulation of the process.

Software Description

Like many of Logal™’s products, Photosynthesis™ simulates the natural phenomenon by allowing the user to vary inputs and other factors and observe the result graphically and pictorially. In Photosynthesis™, environmental variables such
shown both with a running Cartesian graphic of oxygen production and with “empty/full” gauges for sugar and oxygen production.

The package also allows the user to switch from the whole leaf model window to a mechanism window which elaborates on where these factors have their effects on the biochemical mechanism. In this window, most steps can be blocked to see what happens as a result. The abbreviations and icons for molecules have pop-up windows that provide clues to their identities, usually in the form of a chemical equation of the reaction that the molecule participates in. These may be difficult for learners to interpret without guidance, which seems to be a prerequisite for effective use of computer simulations (Berger & Good, 1998).

Use of the Software as a Probe in Clinical Interviews

Several features of the demonstration version of the simulation were exploited in the study as explained below. Mr. Greenfinger was the subject of the introductory tutorial used in Phase 1 interviews, whereas the other features, A Delicate Balance and The Electrons were used in Phase 2 interviews.

Meet Mr. Greenfinger

In the introductory activity (used in Phase 1 clinical interviews) the user is introduced to Mr. Greenfinger who is hoping to improve his tomato yield. The user is lured into the animation by being told that a photosynthetic rate of 60 (arbitrary units of oxygen production) is needed for tomatoes to yield fruit. In successive screens, the user is explicitly shown how to adjust various factors such as light intensity and ambient temperature as Mr. Greenfinger addresses his poor yield by cutting down a shade-producing tree and growing some tomatoes in a hothouse. The icons for water
intake, ambient relative humidity, and carbon dioxide intake are scattered about the window but the user is not explicitly directed to them.

One of Mr. Greenfinger’s dilemmas is that a virus has attacked his crop. The user then runs the simulation to find that the sugar and oxygen production are dropping rapidly, in spite of sufficient water and carbon dioxide input. The user is then directed to switch to the “mechanism” window to illustrate the various subcellular processes occurring. When s/he does so it is evident that a “block” has occurred at the step of the process that synthesizes ATP (adenosine triphosphate), a product of the light-capturing reactions that is necessary for the carbon fixation (sugar synthesizing) reactions.

**A Delicate Balance**

This activity has the user adjust stomate openings during photosynthesis to understand the delicate balance between maximizing carbon dioxide intake (thus sugar production) while minimizing water loss through these pores in the leaf. One feature of *A Delicate Balance* was of special value for uncovering gaps. The first step was to reduce the light intensity to zero (as at night) in order to show how stomates respond by closing. Each participant was asked to explain why, in the absence of light, oxygen came into the plant and carbon dioxide left. Their explanation allowed probing of the alternative conception or gap that animals, not plants, undergo cellular respiration which consumes oxygen and produces carbon dioxide. A related misconception is that plants undergo respiration only at night in the absence of photosynthesis.
The Electrons

This challenging task is the only part of the simulation that relies heavily on the mechanism window in which the electron flow, proton flow, NADP, ATP and Calvin cycle are schematically represented. Graphic decoding gaps (as listed in the shortcomings below) were anticipated here, as well as gaps in integrating the biochemical aspects of the process. Because some of the gaps anticipated were related to two-dimensional representation of molecular actions and arrangements in three-dimensional space, there were frequent interactions with the participant about what the graphics represent.

For Phase 1 (preinstruction interview) of this study, the participants worked through “Meet Mr. Greenfinger” introductory windows described above and attempted to get the photosynthesis rate up to the target. The rationale for placing this activity in the first clinical interview was two-fold. First, the activity could serve as an advance organizer for the instruction they would soon receive on photosynthesis in their biology course. Second, this activity could serve to orient the participant to the features of the simulation, thus decreasing the interview length in Phase 2 (postinstruction interview) which would be the major source of data. Not only would the participants and their performance in the course benefit from this activity, but the data collected in Phase 2 would be richer and hopefully based on better understanding. This was desirable since gaps may be more evident in a rich network of concepts, whereas poor learning may have so few meaningfully linked propositions that “holes” are not evident. An analogy is that holes are apparent in woven fabric, but not in a bundle of loose threads.
Some activities of the simulation software were not selected because they do not probe common alternative conceptions or were designed with other purposes less relevant to this project (e.g., graphing skills). Some required too much time or repetition for their potential value to this project (e.g., altering carbon dioxide levels in the atmosphere).

**Limitations of this Software**

Some limitations of the software are related to the fidelity/accessibility balance needed when designing simulations (Reigeluth & Schwartz, 1989). Photosynthesis is a complex process that occurs in three dimensions over time, and can be understood at many levels, from electromagnetic, to chemical, to cellular, to organismal, to geological. As such, its representation in two-dimensional graphics is unavoidably constrained. The following are some shortcomings attributed to this constraint identified prior to data collection:

1. The spatial relationship between the leaf and the mechanism windows is not explicit. It is not clear whether one is an overlay of the other or a telescoped diagram of a segment of the other.

2. The screen is crowded, particularly in the mechanism window.

3. The significance of arrows, colors, and icons that represent flow are not self-explanatory and need to be made explicit.

4. The Calvin cycle is drawn to look like it is sequestered in a compartment, which it is not.

5. Photorespiration is too prominent in the Calvin cycle in the mechanism window. This may bait students to think that oxygen is consumed as a part of
photosynthesis rather than in the competing side-reaction that photorespiration is. This may engender confusion about plants’ need for oxygen.

6. The simulation does not state more global roles of photosynthesis in global oxygen and carbon cycles, and in \textit{de novo} synthesis of all organic molecules in the plants’ cells.

7. No details of the Calvin cycle and its intermediates are provided. Reference to textbook would required for understanding the details of the Calvin cycle.

8. No details of light capture/pigments are provided, only labels such as “ps1” and “ps2.” Reference to textbook would be required for understanding light capture.

Figure 2. Leaf and Mechanism Windows of LogalTM’s Simulation (adapted from software)
At least one shortcoming has to do with an incorrect proposition built into the text of the simulation. In “Meet Mr. Greenfinger,” the user is being introduced to the mechanism window. When Mr. Greenfinger’s tomatoes are not producing and the mechanism window shows that ATP synthesis is blocked, the simulation shows that removing the block by “adding ATP to the soil” improves the condition of the plants. This is unlikely to work in a living plant for many reasons. First, plants do not take up organic molecules from the soil. Second, it is unlikely that ATP would be able to cross cell membranes to enter the plant. Third, ATP is biochemically labile, making it unlikely that it could remain intact in the soil for sufficient time to be taken up by the roots. Biochemists consider ATP to be a cellular commodity; that is, it is thought to be consumed in the cell that produced it.

Data Collection

Interviews

Clinical Interviews with Participants

Due to the kinds of questions asked in this study and the assurances provided by the researcher that risks to the participants were not anticipated, this study was granted an exemption from oversight by the university’s Institutional Review Board (Appendix E). Assurances included anonymity for all participants. All interviews were transcribed by the researcher or a paid transcriptionist. Transcriptions and all subsequent analysis and public presentation of the data (in journals or presentations) use non-identifying pseudonyms. At the completion of the project, participants gave their written consent for the researcher to use audio or video segments in academic
presentations which may include their voice or likeness. In such cases pseudonyms will still be in use.

To prevent fatigue, tasks were designed to be explicit, terse, and tailored to the cognitive level of the participant. Interviews directly between the researcher and student were therefore no longer than one hour total, and sessions in which participants interact with the computer simulation were no longer than one hour in addition. Two hours is typical of a college laboratory class, and the activities in this study were slightly more cognitively demanding than a two hour lab class. From their body language it was evident that some students (Rhea, Rashad, Caroline) found the second interview to be fatiguing toward the end, as expected from a cognitively challenging set of tasks. Others seemed to enjoy and welcome the interactive stimulation (Cheryl, Charles, Randy, Cathy, Rhyana). The remainder seemed neither fatigued nor eager, but alert and helpful in this project nonetheless (Carlos, Raul, Rhonda, Chanda).

Scheduling. Clinical interviews were scheduled with participants in the university’s College of Education Computer Lab. Three interviews with each participant took place. The Phase 1 interview was scheduled during the semester prior to photosynthesis instruction. Phase 2 interviews were scheduled during the week prior to or immediately following the exam that included photosynthesis. Phase 3 interviews were scheduled to take place within the month following the photosynthesis exam.

Recording of interviews. Sessions were videotaped and audiotaped for the purpose of data collection. Photographs were taken as a record of the results of the
participants’ concept sorting and mapping activities (e.g., on the white board), and occasionally of the participants in the process of completing some activities.

Questioning during the interviews. Participants were asked planned questions throughout the structured, open-ended interviews. Some questions were asked *ad hoc* in response to the emerging data; the researcher’s pedagogical content knowledge was a resource in determining these *ad hoc* questions. In all cases the wait-time standard of five seconds was followed. In spite of the researcher’s care to not indicate whether the participant’s response was correct, many participants (including all the females) sought clues to determine whether the researcher evaluated their responses positively. They inferred evaluative clues from the context of the next question or from facial expressions they strained to interpret. While care was taken not to provide this feedback through body language, participants made comments (e.g., “oh, you don’t think that’s right, do you.”), usually based on their level of confidence. Even if the researcher postponed interaction to keep them talking, they sometimes talked themselves down a cognitive path reinforced by the non-interaction, amplifying their confidence regardless of the correctness of their response. This information is provided to contextualize the data collection.

Most interviews eventually led to an *ad hoc* line of questioning that required deep processing. The goal of these questions was to better understand the gaps (especially the conceptual distance gaps). Therefore information (in the form of suggestive questions or hints) was eventually provided that allowed the participant to eventually bridge their gaps. Not to do so would also have raised the frustration level of the participants whose “need to know” was heightened by the line of questioning.
Therefore as the gaps were probed more deeply, teaching in this way was permitted, which was another benefit for the participants. Many quotes provided in the Results section are examples of these lines of questioning that revealed the nature and cause of some gaps. In these cases, whether the participant’s gap persisted in spite of questioning is distinguished from cases where the participant was able to be led to bridging her/his gap.

**Phase 1: Preinstruction clinical interview.** The first interview with each participant included item-sorting tasks, card-sorting followed by co-concept mapping, introduction to the simulation, and a personal interview.

**Warm-up/sorting task.** In the Phase 1 interview each participant was asked to perform a sorting task of living and nonliving materials. The ten items in the set were: rock, seashell, loose green leaves, jar of dried basil, single dried Shiitake mushroom, young living red bean plant, dried wood, fresh sweet potato, jar of baker’s yeast, and fresh cabbage. First the participants were asked to sort them into living (or once living) and nonliving, then provide criteria for their groupings. Then the participants were asked which of the items came from a photosynthetic organism. This activity served as a warm-up task and gave some indication of the sophistication of the non-biochemical aspects of their photosynthesis knowledge.

**Card-sorting task: co-construction of concept maps.** Each participant performed a concept-sorting task in which s/he was asked to sort the concepts of photosynthesis into two groups: those they recognized and those they did not recognize. For each that they recognized they provided a brief oral definition, then categorized the cards hierarchically to eventually produce a co-constructed concept.
map. The following thirty-two terms were the major concepts in bold typeface in the photosynthesis chapter of *Biology* (Campbell, 1996) that were printed on adhesive notes for sorting: photosynthesis, autotrophs, heterotrophs, chlorophyll, mesophyll, stoma(ta), light reactions, Calvin cycle, NADP, photophosphorylation, carbon fixation, wavelength, electromagnetic spectrum, visible light, photons, carotenoids, photosystems, reaction center, primary electron acceptor, photosystem I, photosystem II, rubisco, chemiosmosis, noncyclic photo-phosphorylation, oxygen, cyclic photophosphorylation, water, protons, thylakoid membrane, ATPase (ATP synthase), ATP, glyceraldehyde-3-phosphate.

Some concept labels in boldface in the textbook were omitted to reduce the cognitive load of the participants. They were eliminated due to redundancy in the task or because they are not as central to the understanding of photosynthesis. The fourteen omitted terms were cyclic electron flow, noncyclic electron flow, spectrophotometer, absorption spectrum, chlorophyll *a*, action spectrum, C₃ plants, photorespiration, C₄ plants, bundle-sheath cells, mesophyll cells, PEP carboxylase, crassulacean acid metabolism (CAM), and CAM plants.

Introduction to the photosynthesis simulation. Each participant proceeded at her/his own pace through the “Mr. Greenfinger” screens of the photosynthesis simulation. This activity introduced them to the variables (and their icons) that affect the rate of photosynthesis. First each participant followed the introductory tutorial that demonstrated how to manipulate variables of light intensity, wavelength, temperature and water intake. They were also asked to explain what they saw happening in the simulation’s windows after each manipulation. This provided a great deal of data.
about how a novice user decodes the graphics in that simulation. After other features of the simulation not demonstrated in the introduction were made explicit to them, they were instructed to manipulate the variables in order to get the maximal photosynthesis rate s/he could. Finally, each participant was asked to summarize the reactants and products of photosynthesis, and transfer information presented in the simulation to a prototypical living plant. Following the clinical interview tasks each participant was interviewed about her or his personal and academic history and career plans.

Table 2. Summary of tasks in Phase 1 interview

<table>
<thead>
<tr>
<th>Phase 1 tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>item sorting tasks</td>
</tr>
<tr>
<td>living/nonliving sort</td>
</tr>
<tr>
<td>photosynthetic/nonphotosynthetic sort</td>
</tr>
<tr>
<td>term sorting tasks</td>
</tr>
<tr>
<td>recognize/don't recognize</td>
</tr>
<tr>
<td>define those recognized</td>
</tr>
<tr>
<td>co-concept mapping of recognized terms</td>
</tr>
<tr>
<td>simulation</td>
</tr>
<tr>
<td>self-paced introduction</td>
</tr>
<tr>
<td>explain-aloud graphics</td>
</tr>
<tr>
<td>get maximum photosynthetic rate</td>
</tr>
<tr>
<td>summarize inputs/outputs</td>
</tr>
<tr>
<td>transfer to living plant</td>
</tr>
<tr>
<td>personal interview</td>
</tr>
</tbody>
</table>

Phase 2: postinstruction clinical interview. The second clinical interviews were scheduled after their instruction and around the time of their exam on photosynthesis. In that interview each participant carried out several sorting tasks, a concept mapping task, simulation tasks, transfer tasks and responded to probing questions.
Warm-up/sorting task. As a warm-up activity they first sorted ten items (yogurt, egg, Spanish Moss, fresh celery, box of Miracle-Gro™ plant food, recently picked dandelion flower, dried red bean, lichen, peanut, acorn) several times. First they sorted the ten items into living (or once living) and non-living and explained why. Next they identified which of the ten items had at least one living cell in them at that moment, and explained why they thought so. Then they identified which of the items having a living cell were undergoing cellular respiration, and which were undergoing photosynthesis at that moment. As the sorting tasks progressed they generated data that served less of a warm-up purpose and more of a data collection purpose.

Card-sorting task: co-construction of concept maps. Next each participant sorted adhesive notes onto which were written words representing various concepts of photosynthesis. These were not all the same terms used in Phase 1. This list included only twenty-one main ideas discussed in both Dr. Corey’s and Dr. Reese’s lectures on photosynthesis. These concepts were sunlight, water, oxygen, light-dependent reactions, ATP, NADPH, sugars, CO₂, Calvin (-Benson) cycle, thylakoid, chlorophyll, photosystems, stroma, electrons, protons, rubisco, electron transport, chemiosmosis, carbon fixation, ATPase (ATP synthase). First they were to sort the concepts by what they thought they were, under the headings molecule, process, subcellular component made of many molecules, and other. Following that, they were asked to further subdivide those they categorized as molecules into organic, inorganic, and if organic into proteins, nucleic acid, lipid, carbohydrate. Following these sorting tasks, a photograph was taken to record the result.
The next task was to place the above concepts into concept map form, complete with hierarchy and words that linked the concepts and made their relationships explicit. Some participants had been exposed to concept mapping in other courses (e.g., Cheryl's chemistry course). The researcher served as a co-mapper and initiated the task by putting the concept photosynthesis as the superordinate, or top, concept, then light-dependent reactions and Calvin-Benson cycle under it with linking words. Then the researcher told the participant, "Let's construct a map that shows how you understand these concepts to be related. First put those concepts related to the light reactions under it, and related to the Calvin cycle under it, and those that are related to both in the middle, and those unrelated to either on either side." After sorting the terms the participant dictated to the researcher where concepts should logically be placed and which linking words would best describe their relationships. When they mentioned a concept not in the set, it was added by writing it on a blank adhesive note.

Photosynthesis simulation tasks. Next each participant completed several tasks using the computer simulation of photosynthesis. First they were asked "Did you think at all about this simulation in the last few weeks?" Then some participants were asked to summarize what they saw happening in the initial leaf and mechanism windows. Any errors in graphic decoding were corrected at that time. Then the participants completed the "electrons" section while thinking aloud. They were asked to read all the text aloud. "The electrons" section first asked the user to predict and test what would happen to oxygen production, NADPH production and ATP production if electron flow were blocked, then to explain, based on the results, which
is directly related to oxygen flow and how they are linked. The next activity in “the electrons” was to predict what would happen to NADPH production if light intensity, water intake and carbon dioxide intake were independently lowered to zero. Their responses provided clues to their understanding of how the various components of the process are interrelated.

The second task using the simulation asked the participant to use the blocker tool and block the ATPase. When a second channel appeared as a result, the participants were asked to interpret what they thought the structure was and propose how such a thing could interrupt ATPase activity without directly blocking it. This allowed for probing of their understanding of the nature and role of the proton gradient in ATP production. It provided especially valuable data about how the students in each professor’s section differed in how they decoded the icon representing the ATPase block.

The third task in the simulation used a window in the “A Delicate Balance” section. The participants were asked to notice and explain why in the absence of light carbon dioxide appeared to flow out of the leaf and oxygen flowed in. This allowed for probing of their understanding of how cellular respiration and photosynthesis are related in plants, and contributed to understanding of the respiration gaps.

Next the participants were asked to transfer their understanding to a three-dimensional felt fabric model of a chloroplast. First they were asked “Do you recognize what this might be?” They were then asked where in the model, for example, oxygen is produced, or protons accumulate. Their actions and responses served to clarify how the participants decoded the simulation’s graphics, especially
with regard to nestedness, scale, and orientation. This task generally served a summative function for the participant, but occasionally generated important data about orientation and nestedness gaps.

The next few activities allowed the participants to refer to the simulation’s images. They were asked to imagine they could put a dot of ink on the carbon atom coming into the Calvin Cycle and watch where it goes. It was phrased this way to remove the need to understand isotopic tracking that the simulation used to convey the continuity of carbon and oxygen atoms. In the Phase 1 interviews the participants were introduced to radiolabeling. In Phase 2 it was desirable to avoid directly eliciting their memory of that labeling in favor of externalizing their conceptual framework about the continuity of matter. After the question was posed, each student was prompted to keep predicting various fates of this marked carbon atom as it was transformed by the processes of the global carbon cycle. Some were asked to predict alternative scenarios. They repeated the task with oxygen, by predicting the fate of a marked oxygen atom being released from the splitting of water. Likewise, the student was prompted to continue predicting various fates of this marked oxygen atom as it moved through the oxygen cycle. For some students this was a significant cognitive activity that “got deep,” and tied photosynthesis with the global carbon cycle and even petrochemical processing. The depth of the questioning was tailored to the participants’ backgrounds. Those with poor understanding or who were obviously fatigued were not questioned to the same depth that others were.

In the final set of tasks the participants were asked to transfer their understanding to several specific cases. First they were asked whether they thought
the living tomato plant present was undergoing photosynthesis at that moment and why. They were asked where the required inputs were coming from and what the plant was producing as a result. They were asked what was happening to the sugar and oxygen the plant just produced. Next they were handed a box of Miracle-Gro™ plant food and asked what they thought it provides the plant and whether it substitutes for any part of photosynthesis. Finally they were handed a specimen of living Spanish Moss and were asked what they thought it was and how, if it is a vascular green plant, it gets what it needs for photosynthesis. At the end of the second clinical interview they were asked about their lab experiences with photosynthesis, and were offered an opportunity to make changes in their concept maps.

The length of this interview had advantages and drawbacks. One advantage was that more probes could be used to look at many aspects of their conceptual frameworks. Another is that the prolonged engagement in a single session revealed gaps that would not have been apparent with one probe or a short session. A drawback was that as each interview progressed the questions became tailored to probe further the individual's previous responses in the same session. This gave the interview paths a fractal quality that it made it difficult to isolate and compare the data from later tasks, e.g., the transfer to living plant task, across cases. The choice was made to forego standardization in favor of deep probing that was tailored for the individual participant. The same questions were asked, but the knowledge the participants drew from to respond was highly dependent on what had happened earlier in the interview. This diversity also made it more difficult as time went on to distinguish which responses were spontaneously elicited from their own knowledge.
and which were derived from the interview’s line of questioning. This is another reason the analysis focused on the secondary data (verbalizations, explanations) more than the primary data (direct responses to tasks) as explained in the Results section.

Table 3. Summary of tasks in Phase 2 interview

<table>
<thead>
<tr>
<th>Phase 2 tasks</th>
</tr>
</thead>
<tbody>
<tr>
<td>item sorting tasks</td>
</tr>
<tr>
<td>living/nonliving sort</td>
</tr>
<tr>
<td>those that have a living cell right now</td>
</tr>
<tr>
<td>those undergoing photosynthesis right now</td>
</tr>
<tr>
<td>those undergoing respiration right now</td>
</tr>
<tr>
<td>term sorting tasks</td>
</tr>
<tr>
<td>molecule/process/subcellular component/other</td>
</tr>
<tr>
<td>further categorize organic molecules</td>
</tr>
<tr>
<td>co-concept mapping</td>
</tr>
<tr>
<td>sort into light/dark reactions</td>
</tr>
<tr>
<td>make map</td>
</tr>
<tr>
<td>simulation</td>
</tr>
<tr>
<td>electrons (mechanism window)</td>
</tr>
<tr>
<td>block ATPase</td>
</tr>
<tr>
<td>delicate balance</td>
</tr>
<tr>
<td>transfer to chloroplast model</td>
</tr>
<tr>
<td>carbon label/oxygen label</td>
</tr>
<tr>
<td>transfer to living plants</td>
</tr>
<tr>
<td>photosynthetic input/output</td>
</tr>
<tr>
<td>role of Miracle-Gro™</td>
</tr>
<tr>
<td>Spanish Moss</td>
</tr>
</tbody>
</table>

Phase 3: delayed postinstruction. This shorter session was planned so that unforeseen lapses or problems could be addressed. Since this was unnecessary the session was instead used for collection of data that will be analyzed separately. Participants responded to exam questions about photosynthesis from the other professor’s exam as well as items from a two-tier diagnostic for alternative conceptions about photosynthesis. Photocopies of class notes and exams were collected and participants were paid at this time.
Data Analysis

Analysis of Clinical Interview Protocols

Chi's verbal analysis method (1997) was modified to analyze the protocols from the clinical interviews, namely the participants' utterances and gestures as s/he performed each of the tasks. Although Chi recommends data reduction by sampling, none of the suggested methods for doing so would preserve the protocols' integrity, especially given how the long interviews progressed distinctively. Therefore no reduction or sampling was done. Events in the protocols that provided evidence of gaps or provided clues to why the gap exists were isolated from the text by cutting and pasting using the indexing functions in NUD.IST™. A method based loosely on unitizing and categorizing (Lincoln & Guba, 1985) was useful for coding the data. During the transcription, kinds and sources of gaps emerged and were recorded in NUD.IST™ as tentative "nodes" to which telling instances in the protocols were indexed. The emerging typology was depicted graphically using NUD.IST™'s tree diagram of the categories and sub-categories the researcher was finding in the data. Since the goal of this research was the identification of gaps in student conceptual frameworks, the chosen depiction is a "gap map" which resembles a concept map. Patterns in the formalism were studied further to refine the categories, then to generate reports for each node which provided the framework and data in the Results section. Some findings were summarized as frequency counts as appropriate for understanding the data. The patterns interpreted from the final typology were then discussed and interpreted in the Conclusions.
Analysis of Co-constructed Concept Maps

Concept maps attempted by participants in Phase 1 are shown (Appendix H) but were not studied further since there was insufficient information contained within them to provide a background literacy score. Term-sorting data and definitions instead provided data for that. Concept maps from Phase 2 were scored using a rubric discussed in the Results section.
RESULTS AND DISCUSSION

There are two levels of data presented in this section. Primary "intentional" data documented the participants' solutions to the tasks (e.g., sorting tasks, concept maps, predictions in the simulation). Secondary "incidental" data documented the participants' verbalizations and gestures that were indicative of the cognitive processing involved in generating those solutions. The goal of the clinical interview tasks was to elicit these secondary verbalizations during the process of completing the tasks, therefore they were valued over the specific task responses that made up the primary data. These secondary data provided the greatest amount of support for the typology that emerged. This is generally the case in protocol analysis in which analysis of the cognitive path taken takes precedence over the subject's answer to the problem at hand. Unlike protocol analysis of context-free problem solving, however, this study sought to understand how knowledge and processing interact specifically in the context of photosynthesis.

Secondary data were also preferred because cases in which these data somehow influence interpretation of the primary responses to the tasks were so numerous and idiosyncratic that primary data were in general less significant to the project than secondary data. Therefore few of the primary data were systematically analyzed independently of the secondary data. Furthermore, since all participants were pressed to make choices even when they were not at all confident, much of the primary data (especially the item sorting tasks) do not represent firm statements they made. Participants were reluctant to register a commitment to choices when they did not know the correct answers. Therefore it would be unfair to them to represent their
choices as confident, carefully thought-out responses to the task at hand. Most were simply reactions to propositions being considered for the first time.

Primary Data

The primary data are presented in Appendices G and H. Primary data from tasks included as “warm-up” activities, summation opportunities, and segues into the next task were subjected to less intensive analysis. Any direct scoring of the tasks is provided simply to summarize the primary data. Exceptions include the term sorting task in Phase 1 and the co-mapping task in Phase 2. These were selected as indicators of overall literacy at the pre- and postinstruction stages, respectively. They were selected because they both took place in the interview before the simulation and both entailed much verbalization and general thinking about the concepts of photosynthesis. Since these tasks were early in the interview, responses to them could be compared across cases. Rubrics were developed for evaluating these tasks to assign a score and a comparable literacy level to each participant at Phase 1 and Phase 2. The primary data in the Phase 2 term-sorting task and co-concept mapping task were also useful for identifying set membership gaps and simple missing link gaps, respectively.

Phase 1

To review, Phase 1 tasks were item sorting (living vs. nonliving and photosynthetic vs. nonphotosynthetic), term-sorting and co-concept mapping, introduction to the simulation, achieving the maximum photosynthetic rate, summarizing the inputs and outputs of photosynthesis, and explaining how a living plant is using these inputs and outputs. From these tasks there are primary data

95
provided (Appendix G) for item sorting tasks, term sorting tasks, and co-concept mapping tasks. The introduction to the simulation generated no primary data. All participants were able to achieve the maximum photosynthetic rate, but did so at differing rates that did not seem to depend on a factor of interest to this study. All participants provided satisfactory summaries of photosynthesis and were able to apply these to the living bean plant, thus no primary data are shown for these tasks. Protocol data for all Phase 1 tasks contributed secondary data.

**Determination of Preinstruction Literacy Level**

Ideally, similar tests would have been used to determine literacy levels before and after instruction, and concept maps would have been preferred. Since no participant in Phase I had enough integrated knowledge about photosynthesis to suggest many relationships among the chosen seed concepts for a concept map, the data from the term-sorting task were used to assign a preinstruction photosynthesis literacy level. A background knowledge score was calculated and literacy level assigned for each participant by reviewing the transcripts of their term-sorting tasks that occurred prior to exposure to the photosynthesis simulation in the Phase 1 interview.

As stated in the Methods, the 33 terms drawn from the textbook chapter were chosen to be the terms to be sorted in the term-sorting task and the seed concepts for the co-concept mapping task. Some terms were recognized by all participants, and some were recognized by none (Table 4).

The following scheme was used for scoring participants’ preinstruction literacy level using the term-sorting task responses. For each term, one point was
assigned if the participant said s/he recognized the term. Another point was assigned if a valid proposition was offered for that term (beyond a generic guess or “is involved in photosynthesis”). A third point was assigned if the term was meaningfully linked with photosynthesis or other terms in the set. Some terms that logically group together were counted as one, since understanding one term (or not) would usually mean understanding the others (or not). The terms counted as one were autotrophs and heterotrophs (paired opposites); photosystems, photosystem I and photosystem II; and photophosphorylation, cyclic photophosphorylation, and noncyclic photophosphorylation.

Their raw scores divided by the total possible (28 x 3 = 84) yielded the rounded literacy scores (in %) seen in Table 5. Boundary scores that approximate literacy levels were determined by comparing the scores participants received to the following predetermined criteria for what would constitute nominal, functional, structural or multidimensional literacy with regard to photosynthesis. Nominally literate participants could say photosynthesis relates to plants, light. Functionally literate participants could say it’s the plants’ way to make food “from” light, and that photosynthesis is needed for the plant to grow, and that chlorophyll is involved. Such a participant may produce or refer to the general equation and may be able to provide definitions of the light and dark reactions. Structurally literate participants could specify the exact role of carbon dioxide, water and light in the light and dark reactions, and identify ATP and NADPH as products of light reactions consumed in the Calvin cycle that produces sugar. A multidimensionally literate participant would have been able to recognize the role of photosynthesis in global carbon, oxygen and water cycles.
S/he would have been able to visualize gas exchange within plant cells as well as with environment. S/he would also have been able to visualize the fate of the sugar product as not only the substrate for respiration but also as starting material for synthesis of all the plant's organic molecules. The participant whose score was less than 20 (Rhonda) was designated nominally literate, and all other participants whose scores were between 20 and 50 were designated functionally literate.

Table 4. Frequency that concepts were recognized in Phase 1 (out of 12).

<table>
<thead>
<tr>
<th>Concept</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>12</td>
</tr>
<tr>
<td>Visible light</td>
<td>12</td>
</tr>
<tr>
<td>Protons</td>
<td>12</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td>12</td>
</tr>
<tr>
<td>Oxygen</td>
<td>12</td>
</tr>
<tr>
<td>Glucose</td>
<td>12</td>
</tr>
<tr>
<td>Chlorophyll</td>
<td>12</td>
</tr>
<tr>
<td>ATP</td>
<td>12</td>
</tr>
<tr>
<td>Wavelength</td>
<td>11</td>
</tr>
<tr>
<td>Stomata</td>
<td>11</td>
</tr>
<tr>
<td>Photons</td>
<td>11</td>
</tr>
<tr>
<td>NADP</td>
<td>10</td>
</tr>
<tr>
<td>Light reactions</td>
<td>10</td>
</tr>
<tr>
<td>Electromagnetic spectrum</td>
<td>10</td>
</tr>
<tr>
<td>Primary electron acceptor</td>
<td>9</td>
</tr>
<tr>
<td>Heterotroph</td>
<td>9</td>
</tr>
<tr>
<td>Autotroph</td>
<td>9</td>
</tr>
<tr>
<td>Carbon fixation</td>
<td>8</td>
</tr>
<tr>
<td>Calvin cycle</td>
<td>8</td>
</tr>
<tr>
<td>Thylakoid</td>
<td>7</td>
</tr>
<tr>
<td>ATP synthase</td>
<td>7</td>
</tr>
<tr>
<td>Reaction center</td>
<td>6</td>
</tr>
<tr>
<td>Photosystem I</td>
<td>5</td>
</tr>
<tr>
<td>Photosystem II</td>
<td>5</td>
</tr>
<tr>
<td>Mesophyll</td>
<td>5</td>
</tr>
<tr>
<td>Carotenoids</td>
<td>4</td>
</tr>
<tr>
<td>Photosystems</td>
<td>3</td>
</tr>
<tr>
<td>Cyclic photophosphorylation</td>
<td>3</td>
</tr>
<tr>
<td>Chemiosmosis</td>
<td>3</td>
</tr>
<tr>
<td>Photophosphorylation</td>
<td>2</td>
</tr>
<tr>
<td>Noncyclic photophosphorylation</td>
<td>2</td>
</tr>
<tr>
<td>Glyceraldehyde-3-phosphate</td>
<td>1</td>
</tr>
<tr>
<td>Rubisco</td>
<td>0</td>
</tr>
</tbody>
</table>

Phase 2

The following primary data from the Phase 2 tasks are provided in Appendix H: item sorting results, term sorting results, co-constructed concept maps, and responses from “The Electrons” simulation task. Primary data from the felt fabric model task were not included because the task generally served a summative function; the way participants used the model generated secondary data. Similarly, the
“Delicate Balance” simulation task served more as a visual probe for generating secondary data. In the ink label task, participants generated a variety of possible paths through which carbon and oxygen atoms could be found in their respective biogeochemical cycles. These and all later tasks which used probes for anticipated gaps (tomato plant, Miracle-Gro™ fertilizer, and Spanish Moss) were tailored ad hoc for the participant based on what had occurred by that point in the interview. These open-ended tasks took place at the end of the interview, and were posed in ways specific to the participant at that moment, and therefore do not compare well across cases. These tasks instead provided a great deal of secondary data.

Table 5. Preinstruction (Phase 1) photosynthesis literacy levels.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Score</th>
<th>Literacy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chanda</td>
<td>38</td>
<td>functional</td>
</tr>
<tr>
<td>Charles</td>
<td>29</td>
<td>functional</td>
</tr>
<tr>
<td>Cheryl</td>
<td>28</td>
<td>functional</td>
</tr>
<tr>
<td>Carlos</td>
<td>33</td>
<td>functional</td>
</tr>
<tr>
<td>Caroline</td>
<td>29</td>
<td>functional</td>
</tr>
<tr>
<td>Cathy</td>
<td>31</td>
<td>functional</td>
</tr>
<tr>
<td>Rhea</td>
<td>30</td>
<td>functional</td>
</tr>
<tr>
<td>Rhonda</td>
<td>14</td>
<td>nominal</td>
</tr>
<tr>
<td>Rhyman</td>
<td>43</td>
<td>functional</td>
</tr>
<tr>
<td>Randy</td>
<td>31</td>
<td>functional</td>
</tr>
<tr>
<td>Rashad</td>
<td>26</td>
<td>functional</td>
</tr>
<tr>
<td>Raul</td>
<td>29</td>
<td>functional</td>
</tr>
</tbody>
</table>

Determination of Postinstruction Literacy Level

A postinstruction literacy score and level were assigned to each participant based on their Phase 2 co-constructed concept map. Participants were asked to link twenty-one seed concepts with meaningful linking words in a logical hierarchy. The researcher started by suggesting that the big idea is photosynthesis, and that the two
major parts of photosynthesis are the light-dependent reactions and the Calvin cycle
(italicized terms are 3 of the 21 seed concepts in the set). These provided the base
from which the participant first sorted the remaining 18 terms, then suggested linking
words to make the relationships explicit. The researcher assisted them in this
construction by writing in their suggested links, but without suggesting relationships.
When the participant made detailed explanations, the researcher distilled their words
and offered a more concise set of linking words which they approved or amended.
Participants were allowed to add extra concepts to their maps as they saw fit. The
maps shown in Appendix H are those produced in the co-concept mapping task before
being revised at the end of the interview by the participants who chose to do so.

A scoring rubric was developed specifically for the maps in this study since
other concept map scoring rubrics would not have captured the information in them
nor assigned a number to them commensurate with the knowledge represented therein
(Novak, 1984). The maps being evaluated were redundant since all used the same
twenty-one seed concepts with the same superordinate concept and first level
subordinate concepts provided by the researcher. Since the same cross-links and no
examples were anticipated it was better not to use the published rubrics in which
features such as these are disproportionately valued.

In the scoring rubric, the base score came from awarding two points for each
proposition provided by the participant. When participants put more than one concept
on one end of a proposition (e.g., the light reactions produce ATP, NADPH), it was
scored as two separate propositions. Similarly, if participants formed a proposition in
which other concepts were included in the link (e.g., protons provide energy to make
ATP), this was scored as two separate propositions. Incorrect propositions were awarded no points. One point was subtracted for each proposition in which a link was made but no explanatory linking words were provided or the links were too vague or unrelated to the target proposition. One point was added for each cross-link included in the map. Links were considered cross-links only if they linked concepts from the light reactions to the dark reactions. Literacy levels were assigned according to the map score. Any participant whose score above the "ideal" minimum of 40 was designated structurally literate (Charles, Cheryl, Chanda, Caroline, Cathy, Carlos, Randy, Raul), while participants whose scores were between 15 and 40 were designated functionally literate (Rhyan, Rashad, Rhea). The participant whose score were less than 15 was designated nominally literate (Rhonda).

There are limitations to assigning literacy levels based solely on the concept map. Since the seed concepts were all directly related to photosynthesis, the map captures proximate relationships more than conceptually distant ones. For example, neither respiration nor carbon cycle was included in the seed concepts, and therefore the co-constructed concept map did not probe the participants’ understanding of how photosynthesis fits into the larger biological context. Thus multidimensional literacy would not have been detected by the concept map alone, nor is it justified to conclude from these data alone that conceptual distance gaps (discussed later) exist. However the maps did capture the knowledge that is traditionally emphasized and valued in introductory biology classes. Therefore scoring of them does provide a measure of photosynthesis-specific knowledge that resulted from instruction.
Since the Phase 1 term-sorting task and the Phase 2 map relied only on closely related seed concepts (those traditionally emphasized in textbooks and lectures), the pre- and postinstruction scores are limited in their value for identifying gaps in integration. However, the maps did identify simple missing links confined to the photosynthesis construct. In the future, use of such a method to expose a broader range of gaps would be improved by including a wider range of seed concepts.

It would have been desirable to compare the knowledge exhibited by the participants before and after formal instruction in photosynthesis. Since the two scores for each participant were not arrived at in the same way, they should not be directly compared. However criteria for each of the four literacy levels were operationalized for this study, and scores were useful for assigning literacy levels to participants within Phase 1 and within Phase 2. It is the opinion of this researcher that the literacy levels of each participant can be compared from Phase 1 to Phase 2. As discussed above, the maps alone could not assess knowledge characteristic of multidimensional literacy (because of the scope of the seed concepts used). However, auxiliary secondary data indicated that no participant had attained this highest literacy level. This observation allowed the assignment of the nominal, functional and structural literacy levels shown in Table 7. All of the participants from Dr. Corey’s section progressed from functional to structural literacy, while improvement among those participants from Dr. Reese’s section was varied. Rhonda did not improve beyond nominal literacy, while Rhea, Rhyann and Rashad did not improve beyond functional literacy. Raul and Randy improved from functional to structural literacy.
It is acknowledged that the validity and reliability of these rubrics has not been established. It is also acknowledged that the trustworthiness of the comparison is challenged by the fact that different measures were used to designate pre- and postinstruction literacy levels. Nonetheless it is apparent that Dr. Corey’s students’ understanding of photosynthesis improved more consistently than Dr. Reese’s students’ did.

Table 6. Summary of scores on Phase 2 co-concept mapping.

<table>
<thead>
<tr>
<th></th>
<th>Chanda</th>
<th>Charles</th>
<th>Cheryl</th>
<th>Carlos</th>
<th>Caroline</th>
<th>Cathy</th>
<th>Rhea</th>
<th>Rhonda</th>
<th>Rhyan</th>
<th>Randy</th>
<th>Rashad</th>
<th>Raul</th>
</tr>
</thead>
<tbody>
<tr>
<td>base score--# prop’ns x2</td>
<td>2</td>
<td>38</td>
<td>52</td>
<td>52</td>
<td>82</td>
<td>66</td>
<td>64</td>
<td>78</td>
<td>26</td>
<td>8</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td># incorrect prop’ns x2</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-6</td>
<td>0</td>
<td>-4</td>
<td>0</td>
<td>-8</td>
<td>0</td>
<td>-8</td>
<td>0</td>
</tr>
<tr>
<td># vague or missing links x1</td>
<td>-1</td>
<td>-2</td>
<td>0</td>
<td>-27</td>
<td>-7</td>
<td>-2</td>
<td>-13</td>
<td>-6</td>
<td>0</td>
<td>-6</td>
<td>-2</td>
<td>-1</td>
</tr>
<tr>
<td># cross links x1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>40</td>
<td>51</td>
<td>53</td>
<td>60</td>
<td>60</td>
<td>58</td>
<td>65</td>
<td>16</td>
<td>8</td>
<td>26</td>
<td>41</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 7. Postinstruction (Phase 2) photosynthesis literacy levels

<table>
<thead>
<tr>
<th>Participant</th>
<th>Score</th>
<th>Literacy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chanda</td>
<td>51</td>
<td>structural</td>
</tr>
<tr>
<td>Charles</td>
<td>53</td>
<td>structural</td>
</tr>
<tr>
<td>Cheryl</td>
<td>60</td>
<td>structural</td>
</tr>
<tr>
<td>Carlos</td>
<td>58</td>
<td>structural</td>
</tr>
<tr>
<td>Caroline</td>
<td>60</td>
<td>structural</td>
</tr>
<tr>
<td>Cathy</td>
<td>65</td>
<td>structural</td>
</tr>
<tr>
<td>Rhea</td>
<td>16</td>
<td>functional</td>
</tr>
<tr>
<td>Rhonda</td>
<td>8</td>
<td>nominal</td>
</tr>
<tr>
<td>Rhyan</td>
<td>26</td>
<td>functional</td>
</tr>
<tr>
<td>Randy</td>
<td>44</td>
<td>structural</td>
</tr>
<tr>
<td>Rashad</td>
<td>23</td>
<td>functional</td>
</tr>
<tr>
<td>Raul</td>
<td>41</td>
<td>structural</td>
</tr>
</tbody>
</table>
Secondary Data

Secondary data in the form of verbalizations during tasks are presented in the context of the typology of gaps that emerged in this study. Relevant portions of the typology are presented with each section to facilitate discussion of the data that support the typology as proposed (Figure 3). Where quotes are offered to support the typology, the symbol "..." is used to denote a pause of at least three seconds. A longer series of dots estimates the length of the pause such that each dot denotes one second. Empty brackets "[ ]" indicate where a portion of the protocol was omitted, usually for clarity or continuity. When brackets contain words (e.g., he [Dr. Corey]), they identify antecedents or provide other such context missing from the excerpt but present in the intact transcript. Occasionally comments are included (e.g., [this is correct]) to guide readers without much background in photosynthesis.

The identified gaps (Figure 3) fall into two broad categories: propositional gaps and processing gaps. As expected, participants showed evidence of gaps in their conceptual frameworks as they retrieved and evaluated propositions from long-term memory. This category of gaps is designated propositional gaps. Simultaneously the participants were processing and encoding available information in the form of graphics and text. In doing so they exhibited numerous gaps in the thinking and graphic literacy skills they used along the way. This category was designated processing gaps. A macroscale map of the superordinate categories is shown in Figure 3.
Clues about the participants' conceptual frameworks came from their verbalizations throughout all the tasks. The categories of propositional gaps that emerged corresponded with the three levels of organization of knowledge: concepts, links and constructs. To review, a concept is defined as a perceived pattern or regularity in objects or events, and labels (or "terms") are the words used to identify these concepts. In photosynthesis the major concepts considered were the seed concepts used in the sorting and mapping tasks in the interviews. Meaning lies in the links that relate these concepts to each other in propositions. These propositions are statements of relationship between concepts, which are presumed to be the nodes of a conceptual framework. Assimilation of related networks of subordinate concepts into a larger superordinate concept is labeled a construct. A conceptual framework is defined as the interconnected set of declarative statements (propositions) that are presumed to be a form in which long-term memory stores information.

The three major categories of propositional gaps that emerged corresponded with these three levels of organization. *Conceptual gaps* were recognized when...
participants gave evidence that a significant attribute was missing from her/his concept. *Linking gaps* were recognized when links were missing between concepts. *Gaps in biochemical constructs* were evident when understanding of a complex biochemical construct related to photosynthesis (e.g., *thermodynamics* or *continuity of matter*) was underdeveloped.

The last category of propositional gaps, *naivete gaps*, is the only one based on the cause of the gaps rather than the nature of the gaps. While it is true that all learning can be considered a progression from naivete toward expertise, instantiations of these gaps were so grouped because they tended to be about propositions one learns as a result of extended exposure via cognitive apprenticeship rather than about explicit instruction about them. These instantiations included difficulties related to evaluating relative significance and applying domain-specific conventions.

There are two ways that the propositional gaps presented in this section may seem to overlap. One is that a conceptual gap may be aggravated by a graphic decoding gap, and the persistence of the former may be due to naivete. This apparent overlap is actually an instantiation of how processing iteratively interacts with propositional knowledge. Another way gaps seem to overlap is that some concepts, for example, gradient, are discussed under more than one category of gaps. This observation is discussed further, but appears to be due to such nodes being involved in several levels of organization of the framework. Since one's defining features of a concept are necessarily propositional (e.g., "enzymes are proteins" or "light is a form of energy"), the boundaries between conceptual, linking and construct gap categories are not absolute. Indeed, gaps in constructs may at their core be due to some
combination of conceptual and linking gaps. These observations are mentioned here
to prompt the reader’s attention to them in the data discussed in this section.

Figure 4. Typology of propositional gaps.

**Conceptual Gaps**

Errors or lack of clarity evident in the participants’ understanding of concepts
were considered evidence of conceptual gaps. Two categories of conceptual gaps
were identified: discrimination gaps and set membership gaps.

**Discrimination gaps.** Discrimination gaps were evident when participants did
not carefully discriminate between two related but nonsynonymous concepts.
Evidence included subtle or blatant misuse of a concept label, or not distinguishing
when its meaning changed with context. High discrimination of label use is
characteristic of experts in a field, therefore some of these cases are less worrisome
pedagogically than others.

Many discrimination gaps seemed to occur at the level of retrieval: words that
sound the same often caused misretrieval of the other’s propositions. The most
common discrimination gap (and probably easiest to bridge) was using or interpreting
*stoma* for *stroma*. Both terms are plant structures that function in photosynthesis, but
they function at different levels of organization of a plant. *Stoma* is the name for a pore in the leaf surface, and *stroma* refers to the liquid matrix inside the chloroplast that is the site of the dark reactions. Seven of the 12 participants made this echoic error. Sometimes the error was in misreading *stoma for stroma* in the popup icons in the simulation. This could have been avoided had the instructors, simulation and the researchers used the anglicized version of the term, *stomate*. Rhea even referred once to *stromata*, a hybrid of these two unresolved concepts. Failing to attend to the distinction probably contributed to more serious misunderstanding, such as shown by Caroline in Phase 2 when concept mapping the concepts of the Calvin cycle. Her ambivalent use of the prepositions “through” and “into” provided a clue to the researcher that she had not reconciled the meanings for *stoma* and *stroma*.

Caroline

Carbon dioxide goes into the stroma.

Researcher

OK, carbon dioxide does what?

Caroline

Goes in through the stroma? Through or into.

Researcher

Enters stroma. or enters..?

Caroline

I’m not sure if it’s through the stroma, or just enters the stroma.

Researcher

Are you thinking of the stomata?

Caroline

Maybe.

Researcher

Are you thinking of the thing on the outside of the leaf?

Caroline

Yeah, but I thought he [Dr. Corey] said stroma today [in class].

What aggravated her discrimination of these two concepts is that carbon dioxide can be said to enter both the stroma and the stoma, depending on one’s frame of reference. That she was not committed to a particular frame of reference indicates an interacting orientation gap. Similarly, Randy in Phase 1 said, “the sugar exits through the stroma.” This is true, but it is likely that he envisioned *stoma* since he made a decoding error earlier that led him to conclude that sugars actually exit the leaf through the stomata (discussed with graphic decoding gaps). Another error due to
echoic misretrieval was Rhea’s tentative confusion of *stomata* for *stamen* ("the male parts of plants").

Caroline also had a difficult time discriminating between *chloroplast* and *chlorophyll* when working with the fabric model. This was evident when she asked whether chloroplast is a membrane, and which of the two was a liquid. Other discrimination gaps were more subtle. Cheryl and Charles were two participants who were keenly attentive to label use. When asked in Phase 2’s co-concept mapping task to provide linking words between *photosynthesis* and *oxygen*, Cheryl was reluctant to say that photosynthesis "gives off" oxygen (although it is acceptable) because she knew that *plants* give off oxygen. Similarly when explaining the simulation’s leaf window she was not able to discriminate *sugars* and *nutrients*.

Cheryl: The water is coming in here, the carbon dioxide is entering, the leaf is taking the carbon dioxide, and then you have the production of sugars I guess, or is it the nutrients? I don’t think that sugars are actually the nutrients from the leaf, is it [sic]?

Cheryl was reluctant to accept similar and acceptable propositions because she did not resolve whether another usage was correct. In contrast Charles went ahead and used two terms synonymously even when he was not sure if he should. When identifying the icons in the mechanism window’s thylakoid membrane, he typed CFl for the icon that the simulation called the *ATPase*. When this was pointed out to him, he said, “I wonder if it’s the same thing.” This may have been a case of “test-driving” propositions (discussed in processing habits later).

In the simulation tasks Chanda and Carlos both used the word *pumping* to describe one attribute of the ATPase. Although its name suggests an ATP-hydrolyzing
function, it is actually a passive channel. This error was observed in a pilot study as well (Griffard & Wandersee, 1999b). This discrimination gap may be due to an anchor proposition students commonly rely on to distinguish membrane pumps from membrane channels: pumps require ATP. That this ATPase involves ATP may cause learners to misattribute pumping to the ATPase.

When discussing types of molecules the concept of organic escaped those participants who did not have an organic chemistry background. In the context of biochemistry it means anything carbon-based. Randy thought organic simply meant "living." Although Rashad’s and Cheryl’s chemistry backgrounds were good, they did not want to categorize water, oxygen and carbon dioxide as inorganic because of how fundamental they are to life. This can also be considered a convention gap due to naivete.

What was understood by the word “living” varied among participants too. Few used attributes biologists use to characterize life. Randy even went so far as to think that if it was made by a living thing then it has cells and it is or was once living. This is often true, but he failed to discriminate living from produced by a living thing when he assumed that dairy products are living because “they’re nutrients and proteins.” This was his reason for categorizing yogurt as living, not because of the active bacterial culture in them that was the reason for including the yogurt in the item sorting task. A fully developed understanding of the convention for the meaning of organic and living identifies these as being due to naivete as well.

When explaining the reversed gas exchange at night in the “Delicate Balance” task, it was apparent that Raul was unaware of how the meaning of respiration

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changed with context: “I thought that respiration was the putting out and taking in of gases no matter what they are.” This gap is due to a pattern he recognized that characterized ventilation (“breathing,” not cellular respiration), but failed to discriminate them in context.

Chanda’s explanation of the events depicted in the simulation’s leaf window in Phase 1 included her use of the term membrane to mean both the cell membrane and the epidermis of the leaf.

Researchers Show me where the water is entering, where the reactants are entering and where the products are going.

Chanda Water seems to be entering the [base] of the leaf. Carbon dioxide seems like it’s entering the membrane of the leaf, the inner membrane. The oxygen is, I’m not sure if it’s coming out of the stomata. It looks like it’s exiting that membrane also [emphasis added]. Sugar seems it’s coming out of, I don’t know exactly what that [mesophyll tissue layer] is, but it’s also coming from within the cell of the leaf, the cells of the leaf, the membranes.

While the use of the term membrane to name a biological interface at any level is semantically correct, it is more commonly used to refer to cellular and subcellular interfaces. Chanda may be aware of how membrane can be correctly applied in several frames of reference, however it seems more likely that she has exhibited a discrimination gap in reconciliation of these uses of the label. Her failure to discriminate frames of reference may be evidence of an orientation gap described later.

Other instantiations of discrimination gaps were Rashad’s misuse of the label mechanism, and Cheryl’s initial categorization of ATPase as a process. Cathy
categorized photosystem as a process also. These are cases of failing to discriminate the processes from the players in those processes.

An interesting discrimination gap was the application of the psychoanalytical definition of fixation to photosynthesis. When explaining carbon fixation, both Caroline and Carlos described it as a "need for carbon" rather than as a process that converts it from inorganic to organic form. This led Caroline to label the entire set of dark reactions as carbon fixation, which is not absolutely incorrect. Many biologists prefer to label only the rubisco reaction or the Calvin cycle as carbon fixation.

Carlos, Cheryl and Caroline used the term gradient readily and confidently. However, the more they used the term in different contexts, the more it became clear that they viewed it simply as an accumulation of protons in the thylakoid rather than as a situation in which different concentrations exist across a selective barrier. This is different from their view because theirs does not explicitly require that the concentration on the outside be lower for there to be a gradient. The following two examples show how Cheryl's choice of prepositions gave away this discrimination gap.

Cheryl The H⁺ gradient is inside the thylakoid membrane.

Researcher Give me a sentence. Chemiosmosis is the process...
Cheryl ...in which you move your protons through this gradient.

A troubling conceptual gap witnessed was that about the nature of light and what exactly it provides photosynthesis. Twice in the Phase 1 interview Cheryl stated that light provides heat for photosynthesis. This is not the attribute of light that is relevant to photosynthesis. Indeed, the heat from the sun is not light itself. Rather it
is the effect of its transformation to thermal energy after collision with matter. She seemed to be unable to discriminate radiant and thermal forms of energy. Heat does affect the process, but negatively. It is not the source of energy as Cheryl envisioned it, rather it is the reason that evaporative cooling via transpiration is needed to protect the temperature-sensitive process that photosynthesis is. Another gap was evident about the nature of light when Chanda stated that photons of light provide electrons to the photosystems. This indicates a failure to discriminate energy (light) from matter (electrons). Ironically both participants were able to understand most of photosynthesis meaningfully in spite of this fundamental gap.

Table 8. Summary of discrimination gaps.

<table>
<thead>
<tr>
<th>Discrimination Gaps</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>stoma/stroma/stamen</td>
<td>7</td>
</tr>
<tr>
<td>plants/photosynthesis “gives off” oxygen</td>
<td>1</td>
</tr>
<tr>
<td>sugars/nutrients</td>
<td>1</td>
</tr>
<tr>
<td>CF1/ATPase</td>
<td>1</td>
</tr>
<tr>
<td>pumping/diffusing</td>
<td>2</td>
</tr>
<tr>
<td>organic/living</td>
<td>3</td>
</tr>
<tr>
<td>breathing/respiring</td>
<td>1</td>
</tr>
<tr>
<td>cell membrane/other membranes</td>
<td>1</td>
</tr>
<tr>
<td>mechanism or process/players in those processes</td>
<td>2</td>
</tr>
<tr>
<td>carbon/Freudian fixation</td>
<td>2</td>
</tr>
<tr>
<td>gradient/accumulation</td>
<td>3</td>
</tr>
<tr>
<td>light/heat/electrons</td>
<td>2</td>
</tr>
</tbody>
</table>

Set membership gaps. Set membership gaps were witnessed when participants were unable to identify with which group an item should be categorized. The term-sorting task in the Phase 2 interview revealed most of the set membership gaps. In that task the participants sorted the terms into categories to which they belonged: molecules, processes, subcellular structures, or other. After this sorting, the
participants then sorted the molecules into inorganic or organic, then the latter into categories of organic molecules.

Before this last sorting, participants were asked to name the “four categories of organic macromolecules,” rather than being told these categories. Although it was the same label as that used in their classes, organic macromolecules did not cue their long-term memory. Several students began to name the six most commonly occurring elements in living things (C, H, O, N, P, S). When the researcher suggested one category (e.g., “proteins”), this example cued retrieval of the others (lipids, carbohydrates, nucleic acids). These four, along with “inorganic,” were the five categories for the second sorting. The ideal sorting scheme is shown in Table 9. After naming the four categories as proteins, lipids, carbohydrates and nucleic acids, the participants then further sorted the organic molecules they identified into those categories.

Table 9. Ideal sorting of terms in Phase 2.

<table>
<thead>
<tr>
<th>Process</th>
<th>Subcellular Component</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>light-dependent rxns</td>
<td>thylakoid</td>
<td>electrons</td>
</tr>
<tr>
<td>carbon fixation</td>
<td>photosystems</td>
<td>protons</td>
</tr>
<tr>
<td>chemiosmosis</td>
<td>CF1 complex</td>
<td>sunlight</td>
</tr>
<tr>
<td>Calvin cycle</td>
<td>stroma</td>
<td></td>
</tr>
<tr>
<td>electron transport</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Protein</th>
<th>Lipid</th>
<th>Carbohydrate</th>
<th>Nucleic Acid</th>
<th>Inorganic</th>
</tr>
</thead>
<tbody>
<tr>
<td>rubisco</td>
<td>chlorophyll</td>
<td>sugars</td>
<td>ATP</td>
<td>NADPH</td>
</tr>
</tbody>
</table>

Although both sections of Bio 101 addressed these major groups of organic macromolecules near the beginning of the semester, few participants were able to
spontaneously transfer that knowledge to this task without help. Raul said, "I know
[ATP is] the energy currency of the cell," but he admitted that it never occurred to him
to wonder what it was chemically. Once pointed out it was obvious to some
participants that this task was something they should be able to do. When Rhea
realized this set membership gap in her understanding, she said "god, I feel so dumb."
The set membership gap was observed in most participants, except Charles who was
the only participant who sorted all the molecules as expected, indicating that he had
learned those concepts about the organic macromolecules meaningfully earlier in the
semester.

An interesting phenomenon is the fact that several participants were unable to
sort many of the molecules in the first sorting (molecule, process, subcellular
cOMPONENT, other), but could correctly categorize them in the second sorting (proteins,
lipids, nucleic acids or carbohydrates). For example, Cheryl did not identify rubisco
as a molecule in the first sorting, but recognized in the second sorting that it was an
enzyme and therefore a protein. In addition she originally categorized chlorophyll as
a subcellular component, but when the molecule categories were provided she
reconsidered because she knew it was "definitely organic." She also could not
identify ATPase as a molecule at first, but when told that it was she immediately
recognized it was a protein "because proteins are what helps move the particles [in]
facilitated diffusion!" She, like other participants, recalled proximate memberships
much better than ultimate.

Rashad knew that chlorophyll was a pigment, but was reluctant to categorize it
as a molecule. Nor was he not confident about categorizing oxygen as a molecule
since he saw it as an element. The label oxygen in the photosynthesis context connotes the diatomic molecule \( \text{O}_2 \). This example is described here since this gap caused his misunderstanding of oxygen’s membership in the molecule category, but this set membership gap seemed to be due to a discrimination gap about the use of the label “oxygen” as an element or a molecule depending on the context.

Some set membership gaps were evident in tasks other than the term-sorting task. When the simulation asked which compounds were produced as a result of the light reactions, Chanda knew that ATP was produced, and that it was a molecule, but was not sure whether it qualified as a compound. Molecule and compound are usually used synonymously; distinction in their meanings depends on the scale of the context (micro or macro, respectively). But Chanda’s set membership was ultimately due to a naivete gap about the subtle distinction between the meanings of these two synonyms that is not explicitly stated in science courses. This example highlights how gaps can be related: her set membership gap was due to her inability to discriminate the terms molecule and compound, which is due to her naivete in the discipline.

In Phase 2, Cathy was reluctant to agree that oxygen is produced in the light-dependent reactions since she knew it is a product of the noncyclic pathway, which is but one part of the light reactions. This illustrates a set membership gap in her understanding of how something being a product of the noncyclic pathway also makes it a product of the light reactions. Caroline likewise showed a set membership gap in the Phase 2 concept mapping task when she wanted to group the entire set of terms in the sorting task under light-dependent reactions since they all ultimately depend on
light. This set membership also could be considered due to naivete since what is generally considered “light-dependent” is a convention she did not know.

The specific set membership gaps from the secondary data that are discussed above are summarized in Table 10. Table 11 shows a summary of the frequency of set-membership gaps tallied from primary data of the term-sorting task (Appendix H).

Table 10. Summary of set membership gaps in secondary data.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Member</th>
<th>Correct Set</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cheryl</td>
<td>rubisco</td>
<td>molecule</td>
</tr>
<tr>
<td></td>
<td>ATPase</td>
<td>molecule</td>
</tr>
<tr>
<td>Rashad</td>
<td>chlorophyll</td>
<td>molecule</td>
</tr>
<tr>
<td></td>
<td>oxygen</td>
<td>molecule</td>
</tr>
<tr>
<td>Raul</td>
<td>ATP</td>
<td>molecule</td>
</tr>
<tr>
<td>Chanda</td>
<td>ATP</td>
<td>compound</td>
</tr>
<tr>
<td>Caroline</td>
<td>light-dependent rxns</td>
<td>photosynthesis</td>
</tr>
</tbody>
</table>

Table 11. Frequency of errors in Phase 2 term-sorting task (tallied from primary data in Appendix H).

<table>
<thead>
<tr>
<th>Participant</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chanda</td>
<td>5</td>
</tr>
<tr>
<td>Charles</td>
<td>2</td>
</tr>
<tr>
<td>Cheryl</td>
<td>1</td>
</tr>
<tr>
<td>Carlos</td>
<td>10</td>
</tr>
<tr>
<td>Caroline</td>
<td>3</td>
</tr>
<tr>
<td>Cathy</td>
<td>3</td>
</tr>
<tr>
<td>mean</td>
<td>4.0</td>
</tr>
<tr>
<td>Rhea</td>
<td>6</td>
</tr>
<tr>
<td>Rhonda</td>
<td>15</td>
</tr>
<tr>
<td>Rhyan</td>
<td>6</td>
</tr>
<tr>
<td>Randy</td>
<td>10</td>
</tr>
<tr>
<td>Rashad</td>
<td>6</td>
</tr>
<tr>
<td>Raul</td>
<td>4</td>
</tr>
<tr>
<td>mean</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Linking Gaps

This category of gaps was the first to be anticipated when this study was proposed. The researcher’s teaching experience suggested that at the root of some
students' erroneous conceptions were links that failed to form between concepts. If
one holds a view of knowledge as a linked network, then one would predict that some
links would fail to form between concepts, or nodes in the network. These could be
simple missing links between conceptually close concepts or gaps in the “big picture”
between conceptually distant concepts. Cases of both types were indeed found, and
these are discussed here.

**Simple missing link gaps.** These are failures to encode simple,
straightforward relationships that are typically made explicit by professors and
textbooks. It would appear that these kinds of gaps, if identified, could be easily
bridged with didactic instruction, though of course whether explicit instruction bridges
such a gap in one’s conceptual framework is highly dependent on whether the learner
is primed to incorporate the proposition into her/his framework. The relative value of
didactic instruction is relevant to the case of Charles discussed later.

The co-constructed concept mapping task revealed simple missing link gaps
when participants were unable to link some of the seed concepts to the rest of the map
(Table 12. Appendix H). Simple missing link gaps also were evident in the secondary
data when participants knew that two concepts were related but were unable to
explicitly state a relationship between them. For example, Cathy could say carbon
fixation was “something about...organic molecules, inorganic molecules,” and that
autotrophs had to do with “like eating or something.” Randy recalled from reading his
textbook that the abundance of oxygen was related to evolutionary history and
photosynthesis, but could not make a statement linking these. Inability to generate an
explicit relationship may be a symptom of passive studying in which students have become accustomed to multiple choice assessment that merely requires recognition.

Other simple missing links were for propositions about, for example, when a chicken’s unfertilized egg cell dies (Cathy, Charles), or when cells in a stalk of celery cut from its root die (Chanda, Rhea). These propositions were simply not known by that participant (and probably not by most biologists). Not knowing those links was not a prerequisite for further understanding therefore they were not considered deficiencies. Other gaps acted as gatekeepers for further knowledge construction. For example Rhyan did not know Spanish Moss was a plant, therefore he could not discuss photosynthesis further until his gap was bridged by the researcher. When Cathy’s gap about flowers producing seeds was bridged, this helped her understand where the seeds in the item-sorting tasks in Phase 2 came from, and she could better evaluate whether they contained living cells.

One of the few gaps that could be clearly identified in Rhonda’s poor understanding was the fact that CO₂ is carbon dioxide. She never said “carbon dioxide” in the interviews, and referred to it only as “carbon” (e.g., “a lot of carbon is good” for making the photosynthesis rate go up), though not always correctly. A reason for the difficulty in finding gaps in her framework may be understood with the analogy that it is easier to find a hole in woven fabric than in a pile of loose threads. In general it was easier to detect missing links in participants with good understanding of photosynthesis.

Fewer instantiations of simple missing link gaps were found in the secondary data than were originally expected. If the above fabric analogy holds, it should have
been easier to find gaps in participants with good understanding of photosynthesis. This was generally true for gap categories other than the simple missing link gaps. It may have been difficult to detect simple missing link gaps in the participants with a good understanding of photosynthesis because the gaps were either not there or else the gaps are obscured by the framework they appear to have built to get around the missing information. Participant explanations made up most of the secondary data, and such explanations can be generated while circumventing gaps. Whether this happened would have remained undetectable had Charles not explicitly asked the researcher questions that pointed out his simple missing link gaps. After the researcher bridged two of these gaps, he readily integrated the new links into an apparently rich framework. In the first example, Charles was unfamiliar with the meaning of “fixation.” When provided with a definition, he was able to tie it in with the rest of his conceptual framework immediately.

Charles       What’s carbon fixation?
Researcher    Fixation...Do you have a mental idea of what fixation is in general in organic chemistry?
Charles       No.
Researcher    It’s conversion from inorganic to organic, so whether you’re talking about nitrogen or carbon, conversion to organic...
Charles       So that goes with dark reactions! [correct, spontaneous bridging]

Once he had his gap about proton flow bridged, as seen in the next interchange, Charles was able to integrate his new proposition with numerous other propositions in his framework. The following interchange is also provided in the discussion of processing gaps to illustrate the value of his metacognitive awareness for identifying his own gaps.
Charles: Can I ask you a question? I can ask [even if you won’t answer]. Is that what H goes through [pointing to CF1 ATPase]?
Researcher: Uh huh.
Charles: OK, so when it’s stepped down in energy, it’s releasing energy, and letting hydrogens through, and this lets them go back across the gradient. And the energy when they go back across turns ADP into ATP, and that powers the Calvin cycle which occurs in the stroma and makes the sugars [this is all correct].

Prior to this interchange Charles seemed to have subconsciously constructed his framework with something analogous to architectural arches or strongbacks that provided support for the higher level construction in spite of there being missing links subsumed within it. These space holders may support the growing framework until simple missing links can be bridged. Thus one could speculate that meaningful learners may have more infrastructure to their conceptual frameworks that permit gaps and still allow growth around them until these gaps can be bridged. In this case Charles’ metacognitive awareness of his simple missing link gaps “primed” him to learn the missing propositions didactically. Thus didactic instruction seems to be most effective for bridging gaps when learners recognize them, which leads to a strong “need to know.”

The simple missing link gaps identified above are summarized in Table 12.

The fact that few simple missing links were obvious in the secondary data may be related to the psychological principle that the absence of something (in this case a link) is harder to detect than its presence. It may be necessary to hone interview methods to be able to study cognitive “place holders” and other missing link gaps in future studies.
Conceptual distance gaps. As stated previously, this category of gaps was anticipated at the start of the study because they had been witnessed before in pilot studies and in classroom teaching. Conceptual distance gaps were evident in two ways. One was when participants failed to transfer on their own what they learned earlier in the semester in a less rich context (e.g., membrane transport, pH, respiration and diffusion) to photosynthesis. These conceptual distance gaps seemed simply to be unconsidered propositions: those links between two topics the participants had simply never thought about before then. Most of the gaps discussed in this section are of this type and are discussed next. Another way conceptual distance gaps were evident was in the participants' ability to integrate two complex phenomena within the topic of photosynthesis in a way that would allow the participant to state a relationship between them. These phenomena (ATP synthesis and NADPH synthesis) were both within the domain of photosynthesis, but integrating them required considering them at a larger frame of reference or grain size. This ATP/NADPH Link Gap was evident in the primary responses to "The Electrons" simulation task. A typology of conceptual distance gaps is shown in Figure 5.

Most evidence for the first kind of conceptual distance gap came from the clinical interviews, but additional data came from a short questionnaire (Appendix F) administered to Dr. Corey's and Dr. Reese's students as adjunct questions to their exams. The relevant part of the questionnaire contained four traditional multiple choice questions designed to determine whether respondents had a sugar fate gap, gas diffusion gap, pH gap or transport gap in their conceptual frameworks. Answering the questions on the instrument was optional, although all participants in this study did
complete the instrument (except Rhonda who withdrew from the course before the exam). The participants' responses are tallied in Table 13. Two additional kinds of these conceptual distance gaps (*role of water gap, respiration gaps*) were identified during data analysis.

Table 12. Summary of simple missing link gaps in secondary data.

<table>
<thead>
<tr>
<th>Name</th>
<th>Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chanda</td>
<td>Celery cells die after ___ time after cutting.</td>
</tr>
<tr>
<td>Cheryl</td>
<td>Celery cells die after ___ time after cutting.</td>
</tr>
<tr>
<td>Charles</td>
<td>An unfertilized chicken egg dies after ___.</td>
</tr>
<tr>
<td></td>
<td>Carbon fixation ___ organic molecules.</td>
</tr>
<tr>
<td></td>
<td>H ions ___ CF1 ATPase</td>
</tr>
<tr>
<td>Cathy</td>
<td>Carbon fixation ___ (in)organic.</td>
</tr>
<tr>
<td></td>
<td>Autotrophs ___ eating.</td>
</tr>
<tr>
<td></td>
<td>An unfertilized chicken egg dies after ___.</td>
</tr>
<tr>
<td></td>
<td>Flowers ___ seeds.</td>
</tr>
<tr>
<td>Rhonda</td>
<td>CO₂ ___ carbon dioxide.</td>
</tr>
<tr>
<td>Rhyan</td>
<td>Spanish Moss ___ plant.</td>
</tr>
<tr>
<td>Randy</td>
<td>Abundance of oxygen ___ evolution.</td>
</tr>
<tr>
<td>Raul</td>
<td>ATP ___ product or reactant of the Calvin cycle.</td>
</tr>
</tbody>
</table>

Figure 5. Typology of conceptual distance gaps.
Table 13. Summary of conceptual distance gaps indicated by questionnaire.

<table>
<thead>
<tr>
<th></th>
<th>Chanda</th>
<th>Charles</th>
<th>Cheryl</th>
<th>Carlos</th>
<th>Caroline</th>
<th>Cathy</th>
<th>subtotal</th>
<th>incorrect</th>
<th>Rhea</th>
<th>Rhonda</th>
<th>Rhyan</th>
<th>Randy</th>
<th>Rashad</th>
<th>Raúl</th>
<th>subtotal</th>
<th>incorrect</th>
</tr>
</thead>
<tbody>
<tr>
<td>sugar fate</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>4/6</td>
<td>x</td>
<td>na</td>
<td>x</td>
<td>x</td>
<td>Rhea</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>3/5</td>
</tr>
<tr>
<td>oxygen diffusion</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>4/6</td>
<td>x</td>
<td>na</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>5/5</td>
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<tr>
<td>pH</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>0/6</td>
<td>x</td>
<td>na</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>4/5</td>
</tr>
<tr>
<td>transport</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>3/6</td>
<td>na</td>
<td>na</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>1/4</td>
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<td>total incorrect</td>
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<td>1</td>
<td>2</td>
<td>3</td>
<td>11/24</td>
<td>4</td>
<td>na</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>14/19</td>
<td></td>
</tr>
</tbody>
</table>

Sugar fate gap. This gap is defined as the inability to envision several possible fates of a sugar molecule produced by a plant cell in photosynthesis. At first Raul could not even picture much use for sugar by plants since “they’re kind of sessile,” indicating a limited, anthropomorphic view that the role of sugar is to fuel movement. Some participants (Carlos, Rhyan, Rashad, Randy) were able to say or be led to understand that plants break down the sugars for energy. Others (Chanda, Charles, Cathy, Cheryl, Raul, Rhea) explicitly labeled that process cellular respiration. In spite of leading, others still could not propose that sugars can be broken down in respiration (Caroline, Rhonda). This is distinct from but probably related to plant respiration gaps discussed later.

But cellular respiration is only one possible fate of sugar. Another fate is arguably at least as important, and that is that photosynthetic sugar is the starting material for biosynthesis of every other organic molecule produced in a plant cell. Every student who has been asked the above question to date (including in other studies) has exhibited this biosynthesis gap. Only Carlos, Charles and Rhyan came close to bridging it. Carlos and Charles suggested that the sugar could be used to make cellulose (the carbohydrate that makes up the cell wall). Rhyan spontaneously predicted that the plant cell would make “structural components” from the sugar.

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Rhyan: I guess it utilizes some of the sugar.
Researcher: For what?
Rhyan: For some of the reactions I guess.
Researcher: What does it do with the rest of the sugars?
Rhyan: Probably stores them.
Researcher: What will it do with them later?
Rhyan: Use it up when sugar production is low, probably. Or, um, I'm not too sure. Sugar can be used for structural purposes, or not [wondering].
Researcher: What do you mean, 'structural purposes'?
Rhyan: Structure like for cellular structural purposes as far as rigidity. I know in most of these cases it's cellulose, is the primary cellular structural component of all of these, but I guess there's a possibility that it could be used as a structural component. But I would think more likely that it would be used for energy production and stored for when there are low levels of sugar production.

Carlos, Charles and Rhyan saw that the sugars could build "structures" (static cytoskeletal elements), but not DNA, enzymes, phospholipids and all other cellular components. Therefore all participants still had some type of a biosynthesis gap since they could not recognize that photosynthetic sugar is not simply an energy source, but the starting material for all biosynthesis in plant cells. Note above that Rhyan cited storage as one fate of sugar. Chanda also said that the sugar can be stored. Since storage implies future use, this correct albeit shallow response was not valued to the degree that other fates were. Another shallow response was that sugars could be used to make more sugars, which was a fate offered by Rhonda, Rhea and Cathy.

Most Phase 2 interviews reached a point where the line of questioning could lead the participants to bridge their own biosynthesis gaps. When a participant was asked whether the living plant there in the room would probably be larger in a few days, all said it would. They were then asked whether the cells in the plant would simply get larger or the number of cells would increase. Again, all correctly said that
the cell number would increase. This was followed by the researcher’s suggestion that increasing the cell number implies providing each new cell with numerous molecules of DNA, enzymes, and cell membrane phospholipids, for example. When asked where these organic molecules came from, Chanda at first suggested these molecules would come from other cells. Caroline and Rhea attributed the weight increase to water intake rather than to carbon dioxide fixation, and Chanda later attributed it to accumulation of sugar. From the interchanges later Rashad and Carlos seem to have at least partially bridged their biosynthesis gaps as a result of the line of questions.

Researcher OK, where do you think the carbon for that DNA would come from?
Rashad From sugar.
Researcher From sugar? you think that...[he interrupts]
Rashad Or from the carbon dioxide that I breathe. [correct]

Researcher Where would the carbon for those molecules come from?
Carlos From the plant, well the excess carbon that it didn’t need.
Researcher Carbon dioxide? or carbon like in G3P (sugar)?
Carlos Like in G3P.

Note above that Rashad provided both proximate (sugar) and ultimate (carbon dioxide) sources for the carbon. Cheryl was led down the same line of questioning, but could not readily envision a biochemical process that could convert sugars to other molecules: “I don’t see how sugars could do that though.” In contrast, Raul at first thought sugars could provide carbons for DNA synthesis, but retracted to say instead that sugars all go to respiration. He was reluctant to acknowledge the sugar product had a role to play in biosynthesis for photosynthetic cells.

Researcher Where do you think the carbon for that DNA would have come from?
Raul [ ] From the sugars presumably. For consistency there.
Researcher You think the sugars could be a source for those carbons.
Raul       Yeah yeah yeah but that doesn’t make any sense. The sugars are just combusted. And it’s the energy from that process that’s used [to make the DNA].

Many participants were led to bridging the gap that carbon dioxide provides the carbons for new organic synthesis. Charles readily predicted in Phase 2 that the sugar produced in photosynthesis could be broken in cellular respiration. When his understanding was probed further he stated that this would lead to production of ATP, which is correct. This afforded an opportunity to further probe his understanding by pointing out that, since the light reactions produce ATP, then why would nature bother with cellular respiration? The objective of this line of questions was to suggest that NADPH produced in the light reactions is the source of reducing power needed to fix carbon dioxide into energy-rich sugars needed for biosynthesis. If photosynthesis were only needed for ATP production, there would be no need for respiration at all (which would have dramatically changed evolutionary history).

Researcher  [If sugar is only needed for ATP synthesis, then] why didn’t it [the plant] just do light reactions [which make ATP]?
Charles      They don’t get just as much? It’s more efficient?
Researcher  How could you get more energy? If you’ve made ATP, then turn around and make sugar, then turn around and make ATP out of it, it would seem like from the laws of thermodynamics that you couldn’t create energy. It would seem like you could make ATP this way [light reactions]. Is ATP all that, I mean, is the point of the food just to be broken down to make ATP?
Charles      And may, uh, structures. Uses organic molecules to [make structures].

Charles was eventually led to bridging this biosynthesis gap, but still may not understand the significance of NADPH in organic synthesis.

Rhyan was finally led to understand that even the carbons in chlorophyll came from carbon dioxide fixed in the Calvin cycle.
Researcher: OK, do you think any of those carbons [in G3P sugar] could end up in [looks at board] ...you said chlorophyll was an organic molecule, right? Where do you think the carbons for chlorophyll come from?

Rhyam: OH!!!!!

Another task that revealed a biosynthesis gap was the Miracle-Gro™ task in Phase 2. In this task participants were asked to consider the ingredients in this product and explain how they could help a plant grow better. Their responses revealed a gap in their understanding about plant nutrition very related to the biosynthesis gap. Since plants synthesize all their organic compounds from photosynthetic sugars (that are made only of carbon, hydrogen, oxygen and phosphorus), significant amounts of inorganic minerals are needed from the soil for the synthesis of organic molecules that require them. For example, nitrogen is needed in amino acids and nucleic acids in high amounts. Participants with good chemistry backgrounds recognized the ingredients were inorganic, and mostly metallic. But none were able to propose a role for them other than as “vitamin” analogs.

Very few of the participants’ interviews brought them to the point of considering the origin of the carbon in organic petrochemicals such as plastics. Those that did were led to the proposition that virtually all organic carbon on the face of the earth, even those in petrochemicals, were first converted to an organic form by photosynthesis (with few exceptions). Charles enjoyed this revelation so much that he immediately said he was thinking of becoming certified to teach biology as well as chemistry. Rhea’s reaction was not as enthusiastic: “Now you’re getting too deep.”
Table 14 summarizes the various suggestions participants made for the fate of photosynthetic sugar mentioned above. Note that the possible fates range, left to right, from least to most complex.

Gas diffusion gap. In all Phase 2 clinical interviews the participants were asked to follow the path of a labeled oxygen atom after being released from the light reactions. Most of the participants who were directly asked responded that oxygen went directly out of the leaf into the atmosphere. This is not altogether correct since oxygen will simply diffuse from higher concentration to lower concentration, and that flow changes depending on conditions. Since oxygen is a reactant in cellular respiration, which occurs in all living cells at all times, oxygen produced in photosynthesis diffuses from source to sink (chloroplast to mitochondrion) usually within the same cell. However the rate of oxygen production is greater than consumption when photosynthesis rate is high, at which time there is net atmospheric release of oxygen.

<table>
<thead>
<tr>
<th></th>
<th>make more sugar</th>
<th>stored energy production</th>
<th>cellular respiration</th>
<th>structures all organic biosynthesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chanda</td>
<td>+</td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Charles</td>
<td></td>
<td>+</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Cheryl</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Carlos</td>
<td></td>
<td>+</td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Caroline</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cathy</td>
<td>+</td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Rhea</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhonda</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Rhyan</td>
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<tr>
<td>Randy</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Rashad</td>
<td></td>
<td></td>
<td></td>
<td>*</td>
</tr>
<tr>
<td>Raul</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note. + indicates fates suggested spontaneously. * indicates fates suggested after leading questions by researcher.
On the questionnaire, only Chanda and Carlos responded that oxygen would “diffuse to the area of lower concentration, such as the mitochondria.” Both participants had had their Phase 2 interviews within days before that exam during which the questionnaire was administered, and therefore their gaps were probably bridged by their experiences in the interviews. In that interview Chanda was asked questions that made her aware of the fact that respiration and photosynthesis are occurring simultaneously, and therefore the processes can exchange gases between them.

Researcher [where would the oxygen go after it is produced?]
Chanda It would go through the [cell] membrane, well no, then it would go to the mitochondria.
Researcher Why do you think it would go to the mitochondria?
Chanda Um, or it could just leave the leaf.
Researcher Which one do you think it is? Or do you think it could be both?
Chanda Both, I think it could be both.

Researcher Why do you think it [oxygen] would go to the mitochondria again?
Chanda Because I know that it’s an input of cellular respiration.
Researcher And how do things like oxygen move in and out of cells, or through cells?
Chanda Through the membranes.
Researcher What force moves things like that? What’s the property of molecules, one outcome of which is that they move?
Chanda Gradient?

She also was able to say that carbon dioxide is the form in which the carbon atom leaves cellular respiration, and said that this carbon dioxide can then go back to the chloroplast for the Calvin cycle. Chanda seemed to understand that oxygen would move to the mitochondria. However, her verbalization a short time later indicated that she thought it was out of respiration’s need that oxygen moved there rather than as the
unavoidable consequence of molecular motion of substances that causes them to move
down their concentration gradients.

Researcher  OK, so then it would tend to stay there, or tend to move away
from there?
Chanda     I think it would move away.
Researcher  And it would move toward areas of?
Chanda     Less concentration.
Researcher  And where would those areas be? Where would be the area of
lowest oxygen concentration in a plant cell?
Chanda     I'm not sure.
Researcher  Why did you say mitochondria [earlier]?
Chanda     I just, well I mean, going back to cellular respiration, I just
thought that that's where [oxygen was] going.

Therefore Chanda still had a partial gas diffusion gap in the interview. On the
questionnaire she responded correctly to the question, which was written in a way that
could have completed the bridging of that gap by calling attention to diffusion's role.

In the Phase 2 ink-label task Carlos was able to follow an oxygen atom more
readily than most others in the study. Almost all participants could be led to see that
oxygen released from the thylakoid could diffuse to the mitochondria. However
Carlos spontaneously completed the cycle by explaining how that oxygen atom could
later return to the light reactions in the form of water to be split again in the same cell.

Carlos    Then the water that came out of the mitochondria could possibly
be used in photosystem 2 and be broken down.
Researcher Hmmmm. And the ink would be back in the oxygen [molecule]
again?
Carlos     Yeah, and the ink would be back on the oxygen.

When including a human in that oxygen cycle, he correctly stated the oxygen “could
be used as the final electron acceptor in the electron transport chain” which would put
the oxygen into a molecule of water. This showed he had a meaningful understanding
of how photosynthesis and respiration are related.
Cathy bridged her gap more successfully in Phase 2 (later) compared with Phase 1 when she simply said “I think it [oxygen] just goes into the air.”

Researcher: You [your cells] just made the CO₂ [in cellular respiration], it just diffused out of the mitochondria. What might happen to the CO₂?
Cathy: Oh, the CO₂ is going to go to the ....dark reaction.
Researcher: What might happen now [to the oxygen released in photosynthesis]? It’s in the plant cell
Cathy: It’s gonna release it, oxygen.
Researcher: All the oxygen goes directly out of the plant cell?
Cathy: No, some of it.
Researcher: Some of it stays behind?
Cathy: Some of it, if it stays behind, then it could go back with hydrogen to form water. I don’t know [grinning; suspecting she bridged her gap]
Researcher: Really?! Where? In a plant cell? [sarcastically] Oxygen can combine with hydrogen to form water? In mitochondria? Like in respiration? [leading her]
Cathy: Yes [confident] it can, can’t it? [pleased with herself]

Rhea, Rhyan, Charles, Cheryl also had to be led to bridging these gas diffusion gaps. Some did so more spontaneously than others, depending on how the leading questions were framed.

pH gap. Only Charles’ and Cheryl’s Phase 2 interviews reached a level of questioning that probed how well they integrated their understanding of pH learned earlier in the semester with photosynthesis. pH is a measure of hydrogen ion concentration, with low pH corresponding to high proton concentration and therefore high acidity. Charles indicated he understood this in the following interchange.

Researcher: Let’s say the sun is beating down on this [felt chloroplast] model. What would be the most acidic space? The stroma or the thylakoid space?
Charles: I would say the thylakoid space [correct].
Researcher: What about when the sun’s not shining?
Charles: They would be about equal [correct].

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Dr. Corey had items on his old exams that required bridging the pH and other gaps. These items directed Charles’ and Cheryl’s (and apparently their classmates’) attention to this gap, and they directed their studying to address it. Judging from the absence of such questions on his exam, Dr. Reese did not expect his students to bridge these kinds of conceptual distance gaps. The pH gap was also probed in the questionnaire. The questionnaire responses (Table 13) indicate that none of the participants from Dr. Corey’s section has this gap, whereas all of the participants from Dr. Reese’s section, except Raul, had this gap.

Transport gap. The energy (light) dependent pumping of protons into the thylakoid space is an example of active transport, whereas the diffusion of protons through the ATPase is an example of facilitated diffusion. These two types of membrane transport were discussed earlier in the semester in both sections. No line of questioning intentionally led to investigation of a participant’s understanding of how facilitated diffusion and active transport fit into photosynthesis, however both the questionnaire and Dr. Corey’s exam contained items about this relationship. Only Cheryl showed explicit understanding of these in the interview, which she attributed to “office hours” with Dr. Corey. In spite of this, she (along with Carlos, Cathy and Rashad) missed this item on the questionnaire, possibly due to carelessness.

Respiration gaps. There were many ways participants exhibited gaps in their understanding of how photosynthesis and respiration are related. Some of the following respiration gaps seem to be related to gas exchange gaps, and some are discussed with continuity of matter gaps later. As discussed later, that these gaps are related across categories does not mean the categories overlap or should be collapsed.
In each case the gap is due to distinct ways that some attribute of the concept (e.g., respiration) is not integrated in a participant’s conceptual framework. This justifies distinct categories.

The following data were chosen as evidence for how well participants integrated photosynthesis with cellular respiration, a conceptually similar topic taught immediately before photosynthesis in both sections of the course. Respiration gaps were especially evident in follow-up questioning after the “ink-labeling” task and “transfer to living plant” task. The target understanding is that the source of oxygen for cellular respiration is water split in photosynthesis, and the sink for carbon dioxide generated in cellular respiration is the Calvin cycle of photosynthesis. Oxygen cycle gaps and carbon cycle gaps are instantiated by failures to recognize this exchange of oxygen and carbon between photosynthesis and respiration. These are discussed first. Another category of respiration gaps is the plant respiration gap which is the failure to acknowledge that plants, like all living things, undergo respiration.

As mentioned in the Sugar Fate section above, Raul, Rhyan, Rashad and Caroline could follow the path of carbon through photosynthesis and respiration, but the interchanges later indicate difficulty in identifying the sugar-catabolizing reaction explicitly as cellular respiration.

Researcher: OK, so let’s say you’ve got this G3P molecule. That’s the sugar that it makes in photosynthesis. What might happen to it now? You’re going to follow that carbon atom.
Raul: It’s in the sugar.
Researcher: What might the plant do with that sugar?
Raul: Use it as a supply of energy.
Researcher: OK, in what reaction?
Raul: Combustion reaction, right? Yeah.
Researcher: Respiration, that is combustion.
Researcher: Now let’s say you could still watch that ink and you’ve got it on that sugar. Carbon in sugar. Where might it go next, and where is it physically in the plant right now?
Rhy. Well apparently it’s going to be in the stroma.
Researcher: Then [ ] what might happen to it?
Rhy. Then it’s utilized [his word for consumed] in photorespiration [this is incorrect, probably a word slip]... Where is it?..I’m trying to think of where glycolysis, OK, glycolysis starts in...cytoplasm. OK.
Researcher: Uh huh.
Rhy. Alright, outside of that [thylakoid]. And finishes up in the mitochondria? That’s where more ATP is produced.
Researcher: OK, and then where is our ink?
Rhy. OK, then it leaves there as....smaller carbon compounds.
Researcher: How small?
Rhy. .....2 carbons? possibly?
Researcher: Or one? [making suggestion to bridge his gap]
Rhy. Or one.
Researcher: What do you think the one-carbon compound is? It leaves the entire process of respiration as a one-carbon compound, which is?
Rhy. Carbon dioxide I guess [this is correct].
Researcher: So where is our ink because we just made carbon dioxide.
Rhy. Oh, let’s see [looks at simulation]
Researcher: It’s not in the picture.
Rhy. Yeah. Um,........I wonder if it [the carbon dioxide] can be utilized again [in Calvin cycle]? [enthusiastic about bridging gap after productive pause]

When Rashad in Phase 2 was asked to follow an oxygen atom made in photosynthesis into his body, he understood that it is transported by hemoglobin to his cells, but could not bridge this gap between oxygen entering and the process that uses that oxygen.

Researcher: Then where might it go [once in your cell]? Is there a place in your cells that uses oxygen?
Rashad: Sure [laughs]. I don’t know.
Researcher: Why do you breathe?
Rashad: Actually I don’t know why I do. I know I do [breathe], but I really don’t know why.
Later he was asked about this again. In the following interchange he expressed his frustration at not being able to put the big picture together.

Researcher: Which part of your cell might the oxygen go to next?
Rashad: That's a very good question....
Researcher: Is there a place in your cells that uses oxygen?
Rashad: Not that I can think of offhand.
Researcher: Why do you breathe? ...Why do you need oxygen?
Rashad: ...As simple as it is, it's not something [I know]. It's a real big picture, especially for someone like me.

Caroline correctly stated that when the oxygen leaves the plant it can go into making water, and return to the thylakoid membrane for the light reactions. However when asked which process converted oxygen to water, she could not say without guidance that it was cellular respiration.

Researcher: So oxygen leaves the plant cell, leaves the leaf, and where might it go then?
Caroline: The atmosphere.
Researcher: The atmosphere. Then is it stuck in the atmosphere forever?
Caroline: [inaudible] recycles it.
Researcher: Into where? the plant?
Caroline: Maybe, or water. It goes, makes water, and then goes back into the [thylakoid]
Researcher: Makes water where?
Caroline: In the atmosphere?
Researcher: In the atmosphere? That's possible I suppose. And then is there a process that maybe takes oxygen and converts it to water that happens in cells?
Caroline: I don't know what it is.
Researcher: You don't know what it is? Take a deep breath.
Caroline: Respiration?
Researcher: Cellular respiration.
Caroline: Takes oxygen and makes water?
Researcher: Uh huh.

Rhyan eventually bridged several gaps between photosynthesis and respiration, and enjoyed doing so.
Researcher: If there's more [oxygen] being produced than used, it will leave the plant, right?

Rhyan: OHH!!! Yeah! That's good! Wait, I've got a question then. This goes back to like, self-sustaining organisms, you know. OK, so if we've got carbon coming in, or carbon dioxide coming in, produces sugars in this process, and then sugars are broken down and used

Researcher: [in the] mitochondria

Rhyan: Right, and then it goes off as carbon dioxide, we still have the same amount of carbons in there, right?

Researcher: Can you control where the CO₂ goes?

Rhyan: No, I guess not.

Researcher: It's going to diffuse. Some will diffuse here, but this will be the lowest concentration [at Calvin cycle’s fixation step].

Rhyan: OHH!! OK. So it's just a diffusion process. Let's see. If we can route this [carbon dioxide] back, it would be so much more efficient!

The notion that only animals, not plants, undergo respiration in this study is labeled a plant respiration gap. It also has been identified in several studies as a common alternative conception in high school and college students (Haslam & Treagust, 1987; Songer & Mintzes, 1994). It is notable that in this study the participants' position on the issue depended on the task in which the question was posed.

In the item sorting tasks at the start of Phase 2, participants were asked to tell which items contained at least one living cell, and then tell which among those were undergoing cellular respiration. Nine of the 12 participants thought at least one plant item was undergoing cellular respiration, but none said that the reason plant items were not undergoing respiration was because they were plants. Rhea and Cheryl’s statements implied that if the item is alive then it necessarily is undergoing respiration.

Researcher: Do all living things undergo cellular respiration?
Researcher All plant cells too?
Rhea Only if they’re living.

Cheryl [A cell] has gotta constantly do it so that it can stay alive. I guess if it was dead it wouldn’t have any.

However, another task prompted different responses. In the “A Delicate Balance” simulation task, participants explained why at night the plant in the simulation took in oxygen and gave off carbon dioxide. They often did not tap the same proposition as they did in the item sorting task. Although Cheryl made the above statement earlier in the same interview, she did not apply it in the “A Delicate Balance” task. She called the process producing the oxygen “photorespiration,” and had to be led to the idea that cellular respiration was responsible for the observation she made. After that she applied the proposition that plants undergo respiration to other scenarios.

Cheryl But the thing is, at night, there’s no stomata open [this is not true]. But plants, I’ve never heard of a plant taking in oxygen before!

Researcher Is there a reaction that a plant undergoes that requires oxygen?
Cheryl Cellular respiration?
Researcher Do plants undergo cellular respiration?
Cheryl Yeah.
Researcher And do they need oxygen for that?
Cheryl Yeah, it’s their electron acceptor.
Researcher Do you think they use oxygen for that in their cells? Do you think that’s what’s causing the oxygen to come in and CO$_2$ to come out?
Cheryl Could be, because in cellular respiration you make carbon dioxide and water.

Chanda arrived at the same conclusion but with less leading. She also seemed to enjoy bridging this gap with little guidance.

Researcher So why would the oxygen still be coming in?
Chanda I don’t know.
[ ] You can’t think of why the CO₂ would be coming out? Is there another process maybe going on...that requires oxygen and puts out CO₂?

Chanda [laughs]

Researcher What are you laughing at?

Chanda Is this cellular respiration [suspecting she is right]?

Carlos bridged his plant respiration gap with some leading as well. Charles was the only participant who immediately understood the phenomenon in the Delicate Balance task to be due to cellular respiration. He even reasoned that it occurs constantly, and that “the net is the other way when the light reactions are happening.” Although Raul accepted that plants undergo respiration, he erred when he said that “if respiration is taking in oxygen and putting out CO₂, then it’s just at night.” This is incorrect since respiration occurs night and day in living cells. Rhyan and Rashad were unable to say that cellular respiration was responsible for the carbon dioxide intake observed at night, although both recognized the conditions as “sugars that are being broken apart again” and “similar to our breathing,” respectively. Caroline did not follow the leading questions smoothly to the conclusion that plants undergo respiration, and Cathy even went so far as to say that plant cells have chloroplasts but not mitochondria. Rhonda did not understand enough to be led to any such conclusions.

Role of water. Another conceptual distance gap emerged with the participants’ inability to distinguish the role of water in a plant cell as a reactant in photosynthesis versus as simply a cellular and extracellular medium. Cathy believes water is stored until needed, as opposed to the view that water is an abundant cellular
medium from which the photosynthetic processes take relatively few water molecules as substrates for photosynthesis.

Researcher: Where is this one [living plant] getting it [water]?
Cathy: Do you water it?
Researcher: Uh huh.
Cathy: Then probably from you. Then it stores it, and if it needs it it uses it.

The amount of water consumed in photosynthesis is negligible compared to that taken into the plant through the roots and lost through transpiration (evaporation through the leaves). This fact may not have been considered by Raul when he was deciding how to get the maximum photosynthesis rate on the simulation. He remembered that relative humidity had little effect on the rate, so he concluded that "water doesn't seem to be very important at all to the process." Similarly, Charles recalled the same low effect of changing the relative humidity level in the simulation when he surmised how Spanish Moss gets its water. Cheryl seemed to misunderstand the role of water as the substrate consumed in photosynthesis as well as a medium when she said, "you put water in. [but] plants don't need water to do any of this [reaction] stuff though." She failed to reconcile this proposition with a conflicting one she held that water is the source of electrons and protons for light reactions. That water is "not very important" to photosynthesis is not an assertion that should be made without qualification. This is because the vast majority of water coming into the plant (as shown on the input meter) is used for turgidity as a cellular medium and, when transpired, as a cooling medium as well. Only a small amount is "consumed" as a substrate in the light reactions.
A different conceptual distance gap mentioned in the introductory paragraph for this section was evident when participants struggled to answer a summative question within “The Electrons” simulation task. The question was: “Do you think there is a link between the reactions producing NADPH and ATP? Why?” Unlike the simple missing link gaps described above, bridging this gap would require more than a simple didactic statement. And unlike the other conceptual distance gaps, a correct response to the question is not as simple as applying information learned earlier in the semester to a new context. Answering this question required thoughtful integration of two complex processes. Although ATP production and NADPH production appear to be conceptually close within the photosynthesis domain, understanding their relationship requires stepping back from the micro frame of reference at which these processes are taught. For these reasons this gap was categorized as a conceptual distance gap. The participants’ responses from the primary data are shown in Table 15.

Most participants did not directly answer the question when it was posed. Chanda and Rhonda were the only two who did, but these direct responses showed much less thought than the others, probably because they treated the question as one requiring a simple answer. The others needed or sought guidance in synthesizing the information to that point. The question was general enough and the processes are so intimately coupled that the question could have been correctly answered several ways. Desirable responses were provided by Charles, Cheryl, Carlos, Caroline, Cathy, and Raul. Some of these (Charles, Caroline, Cathy) were able to provide a response only after Socratic questioning that focused their attention on the most relevant features of
the process. All participants were afforded this opportunity to interact with the researcher in this way. However it is notable that only those with a good base of knowledge base to start with were able to take advantage of this guidance in order to answer the question. The fact that most of Dr. Corey's students and only one of Dr. Reese's students responded satisfactorily is another indicator of better instruction in Dr. Corey's section.

**Biochemical Construct Gaps.**

This category of gaps was identified when participants gave evidence of the state of their development of constructs for abstract biochemical phenomena such as equilibrium, stoichiometry, cycles and coupling. These are constructs that could be regarded as outside of the photosynthesis construct since they are usually taught in chemistry courses in particular contexts, however their propositions are relevant to understanding photosynthesis. These abstract constructs are notoriously difficult for an average freshman to understand much less transfer to a biological context. How well participants applied these concepts of those constructs (with or without their labels) to photosynthesis was an indication of their conceptual development, even though neither significant development of these concepts nor accurate label use is expected at the freshman level. Since these themes play significant roles in meaningful understanding of biochemistry, they may represent critical junctures that gatekeep for success in more advanced courses.

Gaps in understanding of gradients, equilibrium and energy transduction are categorized as *thermodynamics gaps*, and the others (e.g., stoichiometry and coupling) are categorized as *continuity of matter gaps*. 

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Table 15. Statements of relationship between ATP and NADPH production.

<table>
<thead>
<tr>
<th>Chanda</th>
<th>Yes because they are all dependent on the energy of the electrons.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charles</td>
<td>[after review] Yes. The production of NADPH allows protons to cross into the thylakoid, building a free energy gradient. These protons exit through the CF1 complex, and the energy is given to ADP to form ATP.</td>
</tr>
<tr>
<td>Cheryl</td>
<td>The components of water, $H^+$, electrons, etc., are directly related to production of ATP and NADPH. Electrons go to make NADPH and protons go to make ATP.</td>
</tr>
<tr>
<td>Carlos</td>
<td>Yes. Electrons were not pumped in the thylakoid in sufficient numbers to build up the H gradient, which hindered the production of ATP, the NADPH production was directly affected, and the ATP production was indirectly affected.</td>
</tr>
<tr>
<td>Caroline</td>
<td>[after leading] Electron and protons are both coming from water. Electrons are used for the NADPH and the protons are used for the ATP.</td>
</tr>
<tr>
<td>Cathy</td>
<td>[after leading] Yes. The link is protons and electrons, because the electrons are stepping down, the energy is being used to pump protons through, [which then] goes to create ATP and NADPH.</td>
</tr>
<tr>
<td>Rhea</td>
<td>[after leading and review she still did not know how to respond]</td>
</tr>
<tr>
<td>Rhonda</td>
<td>They both need electron flow to do it.</td>
</tr>
<tr>
<td>Rhyan</td>
<td>Yes, the Calvin cycle is directly dependent upon NADPH which in turn produces ADP. ADP is the precursor to ATP. If there is no ADP, the levels of ATP will drop off.</td>
</tr>
<tr>
<td>Randy</td>
<td>[after leading and review she still did not know how to respond]</td>
</tr>
<tr>
<td>Rashad</td>
<td>Yes, because they’re both vital, without them actual synthesis in the Calvin Benson cycle, or the dark reactions, would not take place.</td>
</tr>
<tr>
<td>Raul</td>
<td>The water hydrogen goes to ATP production and the electrons go to NADPH production.</td>
</tr>
</tbody>
</table>

Figure 6. Typology of gaps in biochemical constructs.
Thermodynamics gaps. Gaps in understanding of thermodynamics were instantiated when participants incorrectly explained or applied principles of energy transfer to the context of photosynthesis. These were mostly in their understanding of gradients and equilibrium: the more complex bioenergetic phenomena underlying chemiosmosis and electron transport were not probed since they were not taught to students at this level. Many participants correctly used the term “gradient,” especially Dr. Corey’s students since he used it often in many contexts. As discussed previously, Carlos, Cheryl and Caroline had the view that it was the accumulation of protons on one side of a membrane rather than a condition in which there are unequal concentrations on the two sides of a membrane, a disequilibrium which powers ATP synthesis. Although it would seem that this view of a gradient would interfere with one’s understanding of the energetics of photosynthesis, it apparently did not. However, an *equilibrium gap* related to gradients was apparent when some were asked to explain what would happen to the proton concentration on the inside and outside of the thylakoid membrane at night. In Phase 2’s simulation task, Carlos correctly explained why ATP continued to be made for a short time after electron flow was blocked.

Researcher: Why do you think ATP was being made all that time?
Carlos: I guess it still had hydrogen ions inside the thylakoid membrane, I mean, the thylakoid space.

However an explanation soon thereafter indicated that he believed the gradient became reversed when “all the hydrogen ions leaked outside.”

Researcher: Now that the ATP has stopped, what do you think the concentration of protons is on both sides right now? Do you think there’s still a gradient?
Carlos  No if there’s, well, if all the hydrogen ions leaked outside, then
the gradient, there’s a higher concentration outside the thylakoid
than inside.

Raul showed a similar gap which the researcher helped him bridge.

Researcher  What is going to be the scenario now, now that the flow [of
electrons] has stopped. What do you think the concentration of
protons is inside versus outside? Do you think it’s higher inside?
Raul  It’s higher outside?
Researcher  It’s higher outside? Not equal?
Raul  Hmmm.....
Researcher  ...It only can come to equilibrium. You can’t accumulate more
outside without active transport.
Raul  OK.

Raul’s and Carlos’ predictions were incorrect because a gradient does not reverse on
its own. Rather, the concentration on both sides of the membrane at equilibrium will
come to be equal, as Charles correctly predicted when explaining the fabric model.

This interchange was presented also in the discussion of pH gaps above, and it also
exemplifies the target understanding of gradients and equilibrium.

Researcher  Let’s say the sun is beating down on this model. What would be
the most acidic space? The stroma or the thylakoid space?
Charles  I would say the thylakoid space [correct].
Researcher  What about when the sun’s not shining?
Charles  They would be about equal [correct].
Researcher  About equal. So you don’t think then that if you don’t have an
accumulation of protons, do you think they all go out? Like let’s
say this scenario happens [where electron flow is blocked]
Charles  No I don’t think they all go out.
Researcher  OK, so the endpoint of this
Charles  Would be equilibrium.

Continuity of matter gaps. This set of gaps is one of the largest groups found
in this study. It includes any kinds of gaps that exist because the participant is failing
to regard molecules as an organized structure of atoms bonded together, and that
undergo interconversions. Some instances presented in this section provide evidence
of satisfactory development of these concepts, while others are evidence of gaps. All
participants showed at least one gap in predicting the continuity of the carbon atoms
fixed in photosynthesis, therefore this category of gaps overlaps with sugar fate gaps
discussed above.

The radiolabel task in Phase 1 and the ink-label task in Phase 2 proved to be
especially well suited for revealing the level to which participants understood the flow
of atoms through photosynthesis. Isotopes are atoms of an element with an atypical
number of neutrons in their atomic nuclei. Since these unstable nuclei throw off
subatomic particles and radiation, they can be exploited in research to trace atomic
paths. Isotopes were represented in the simulation as radiolabeled oxygen or carbon
that could be incorporated into a water or carbon dioxide molecule to follow it through
different molecules in the process. As mentioned later in the discussion of graphic-
decoding gaps, few participants recognized the radiolabel icon nor understood what
radioactivity meant. Although some grasped the significance of their observation,
none seemed to have a better understanding of atom tracking after the radiolabel task
in Phase 1. How well participants understood that only a single atom within the water
or carbon dioxide molecule was labeled was an indication of how well they
understood molecular structure. Rhonda clearly had no prior knowledge about even
atomic structure that could help her make sense of the task. Others (Randy, Caroline,
Cathy) accepted at face value that labels could be used to track atomic flow, but did
not indicate that they understood the nature of the atomic label as described above.

A different kind of continuity of matter gap was evident when participants
failed to reconcile two conflicting propositions they held about the fate of the oxygen
in carbon dioxide. All participants correctly interpreted from the simulation’s leaf window that plants take in carbon dioxide and give off oxygen in photosynthesis.

Most descriptions were very similar to Rhyan’s: “It looks like we got carbon dioxide going in, sugar going out, water going in and oxygen going out.” They also had the prior knowledge that these gases are exchanged in the opposite direction in cellular respiration (oxygen in and carbon dioxide out). But Charles and Rhyan also understood that the carbon of the carbon dioxide generated in cellular respiration becomes a component of sugars, and that the oxygen from water generated in cellular respiration is a source of gaseous oxygen released by photosynthesis and consumed in cellular respiration.

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Rhyan</th>
<th>Researcher</th>
<th>Rhyan</th>
</tr>
</thead>
<tbody>
<tr>
<td>What exactly [in that water molecule] is labeled?</td>
<td>[ ] I guess it [the label] would only be on oxygen. If you have water that is radioactive, oxygen is a by-product of this water so that any water that’s broken down to produce oxygen is going to be also radioactive because of that radioactive oxygen in there.</td>
<td>[And what about the label on carbon dioxide?]</td>
<td>I guess it would come out here [points to sugar meter]. [ ] It just means that sugar[s] are organic carbon chains, usually. So if you have a radioactive carbon in there, I guess it’s involved with building the sugar so I guess the sugar is also going to be radioactive.</td>
</tr>
</tbody>
</table>

Rhyan’s explanation of Phase 1’s radiolabel task above exemplified the target understanding of atomic flow in photosynthesis. However some participants instead inferred from the gross gas exchange path (as was the case with scientists historically) that the oxygen in carbon dioxide is the source of molecular oxygen given off, or conversely that atmospheric oxygen is added to carbon in respiration to generate carbon dioxide. Even after completing the simulation’s radiolabel task in Phase 1, Rhea still explicitly stated that the plant “takes the carbon dioxide and changes it to
oxygen and sugars.” When Randy was asked what might happen to oxygen he breathed after it entered his cells, he said “it comes out carbon dioxide.” Rashad also said that oxygen that enters cells “comes out as carbon dioxide.” They made this inference even though they knew that the splitting of water in the light reactions is the source of oxygen. Cheryl noticed in the simulation in Phase 1 that “if you put more carbon dioxide then more oxygen will come out!” Although this is true, it seemed she inferred the oxygen source is carbon dioxide. Raul suggested in the ink-label task that oxygen is converted to carbon dioxide, but qualified his uncertainty.

Raul [It might be] breathed in by somebody and then turn it into CO₂.
Researcher And then turn it into CO₂?
Raul Well loosely speaking, of course.

Charles made several good proposals of paths that oxygen could follow after it leaves a plant cell (seen in second interchange later), but this was only possible after having this carbon dioxide/oxygen gap bridged earlier in that Phase 2 interview (first interchange).

Researcher And then what does it turn into or what molecule might it become a part of if oxygen....
Charles Carbon dioxide maybe?
Researcher Is that what happens?
Charles I have no [idea]....I remember that kind of like I remember this [photosynthesis].
Researcher Well let me remind you.[ ] What happens to the oxygen when it catches the electrons at the bottom [of the chain], does carbon come along, and then it marries and becomes CO₂?
Charles Water [this is correct]?
Researcher Water, OK, so the oxygen that came in is not going out as CO₂?
Charles No.

Charles [The oxygen] might be released into the atmosphere.
Researcher OK, let’s say it’s out in the atmosphere out here somewhere, or outside. Let’s see where it might go next on its trip.
Charles Someone might light a candle, and it might get burned?
Researcher: OK, and what form, what molecule might it end up in?

Charles: Water? [correct]

Researcher: Water. OK.

Charles: It could end up in ozone \([O_3]\), it could end up in, you could breathe it, it could end up in whatever you make it into during respiration [these are all plausible fates].

Charles was able to bridge his gap and incorporate his new proposition into his conceptual framework. Others who continued to have this kind of continuity of matter gap were unable to reconcile two contradictory propositions held in their conceptual frameworks, one of which must be incorrect.

Closed path gaps. These gaps are presumed to exist in students’ conceptual frameworks when they do not explicitly state where atoms go when they go “away.” No data were gathered that are direct evidence of this gap, but several examples are provided that indicated which participants did seem to seek closure when considering continuity of matter.

When attempting to understand in Phase 2’s simulation where the electrons go from the light reactions, Cheryl concluded “they’re not just going to stay there, and they’re not just going to go away, disappear.” In the Phase 2 mapping task Raul recognized the need for a sink for the electrons when he said “the electron gets returned to the chlorophyll, otherwise you’d have permanently ionized leaves I guess.” In Phase 1’s radiolabel task Raul and Charles understood the radiolabeling of oxygen, and made statements that showed that they followed the atomic paths, although Raul made several errors in the paths he envisioned. In a line of questioning about synthesis of new molecules to replace “retired” ones, Rhyan wondered what happens
to atoms in those retired molecules, such as those in proteins marked for degradation.

This further substantiates that he has a good understanding of atomic continuity.

Rhyán So in that case I guess it [the cell] can utilize the carbons there, to make some other type of carbon-containing compound that it needs physically, I mean, in its everyday role. But then [ ] anything else that it [the cell] needs to replace, that carbon [in the retired molecule] has to go somewheres [sic].

Researcher Right.
Rhyán Where does that go?
Researcher Well that gets broken down and salvaged.
Rhyán You don’t see, you don’t see, yeah, but you don’t see, but it’s broken down [stammering].
Researcher They have enzymes that will recycle [parts of the retired molecule].
Rhyán But you don’t see plants giving off waste like [us]!
Researcher Well, no, because they will only produce what they need, in fact they shift their resources into different processes.
Rhyán That is weird.
Researcher So if they’ve got to make a new cell, [then] they’ve got to make a new membrane, new DNA, new mitochondria, new everything.
Rhyán Well those old carbons are broken down, but where do they actually go?

That Charles, Raul, Rhyán and Cheryl contemplated on their own the fate of atoms or particles at all indicates a meaningful understanding of the Law of Conservation of Mass: matter is neither created nor destroyed, but converted into different forms.

Rhyán specifically referred to this Law in a line of questioning following the ink-label task in Phase 2.

Rhyán But we’re talking about conservation of mass. We’re not talking about, I mean, there’s no way that we’re going to be producing more than we’ve already got, I mean...

Researcher So, you think there’s a constant amount of carbon on earth.
Rhyán Definitely, oh definitely. Maybe not a constant amount of carbon dioxide, I mean the levels are always changing.

Some participants’ comments indicate they may have a closed path gap. In the radiolabel task, when the water label appeared in the molecular oxygen, Cathy and
Randy accepted the proposition that it takes water to make oxygen, but did not seem to understand the atomic path behind the observation. When Rhea was challenged to close the atomic path of carbon in sugar broken down in respiration, she was engaged in processing for a few moments before protesting that “you’re making me think too much!”

Contemplation of chicken eggs caused Raul to betray his understanding of conservation of mass. Although Raul knows that mass is conserved in a closed system, he did not invoke this knowledge in the Phase 2 sorting task when he was trying to devise a method to determine whether the egg was living.

Raul: I thought there was a weight difference or something if it’s actually got a chicken growing in there. That would be the simplest way of sorting them out, then you could say, oh that one’s too heavy so it must be alive.

Perhaps he did not know that chicken eggs are a mostly closed system. They do exchange gases with the environment, however exchange of carbon dioxide for oxygen should not lead to the significant net weight gain he envisions in chick development.

Stoichiometry gap. The ratios in which substances chemically react refer to stoichiometry. References made by students indicated their level of understanding of this concept. In Phase 1 Raul and Charles were not satisfied to leave the simulation without attempting to optimize conditions for a maximum photosynthesis rate by “cut[ting] costs” and finding “an ideal amount of water,” respectively. They recognized that water was in excess, and that it would be less wasteful to empirically find the optimum amount of water needed by reducing it until the rate of
photosynthesis decreased. In contrast, Rhyan’s engineering background was evident when he intentionally set the water input level to be in excess, so that this “cheap” resource would not be the limiting reagent (also discussed in Processing Habits later). Caroline interpreted the radiolabel task in Phase 1 somewhat correctly when she concluded that “maybe the same amount [of oxygen in water] taken in, [then] the same amount [of oxygen] produced.” All of the above indicate a developing sense of stoichiometry, although the word was not mentioned by any of them.

Rhyan’s stoichiometric understanding also was apparent when he explained that the commercial plant food provides “an overabundance” of nutrients so that if the plant “is not getting it to the levels it needs to be getting” from its water supply, “this [Miracle-Gro™] is going to give it to them.” The above instances suggest that Rhyan, Raul and Charles do not have a stoichiometry gap. It is assumed that since these instances stood out as remarkable, it is likely that other students have not developed this level of understanding.

Transmutation gap. A corollary of the law of conservation of matter is that the identity of atoms that make up those molecules generally do not change except in nuclear reactors and linear accelerators (e.g., oxygen cannot transmutate to carbon). Randy and Caroline made comments that may indicate they have a transmutation gap, which is a view that atoms can change identity in ordinary chemical reactions, which is not unlike that of alchemists. In the Phase 2 interview Randy was asked about how the growing tomato plant’s cells get new DNA needed when they divide.

Researcher DNA is made of nucleotides, each nucleotide has a nitrogenous base, and
Randy Well, OK, then yes it [DNA synthesis] does [need nitrogen atoms].

Researcher Where does this nitrogen come from to make this new DNA in this new cell in this tomato plant?

Randy From carbon

Researcher Nitrogen can’t come from carbon! It can’t do transmutation!

In Phase 2, when pushed to make a statement about what commercial plant food (whose ingredients are metals) provides the plant, Chanda suggested that “maybe they do substitute for that carbon in the sugar.” Caroline may have made a similar mistake when asked what would happen to the carbon in a sugar molecule made in photosynthesis. When she said, “it would go on to make some oxygen,” she indicated that she thinks atoms can transmute. Perhaps she did not consider the question too carefully and was answering the question “what would happen to the oxygen in a sugar molecule?” If so, then this mistake would instead be indicative of a continuity of matter gap.

Biochemical cycles gap. In freshman biology courses biochemical cycles are usually introduced as chains of chemical reactions (usually enzyme-catalyzed) in which the starting reagent is regenerated and reenters that set of reactions. This level of understanding of cycles was evident with several students. Cheryl recognized that the Calvin cycle “is like regeneration of what you need.” This is similar to Cathy’s understanding of “a cycle, that means it has to have some way to start all over.” But the reason cycles exist escaped Caroline (and possibly Cathy and Cheryl above) who had a dog-chasing-its-tail understanding of cycles as evidenced by her explanation that the sugars produced in the Calvin cycle are used simply “to keep the cycle going.” Rashad’s understanding of biochemical pathways was slightly better developed as he
recognized that they are subject to feedback regulation, usually at an early step: “I
look at most processes as a chain, and the light is one of the beginning steps of the
chain. [ ] There was something about if you turn the first [step of the] chain off,
everything’s turned off.” No participant exhibited the target understanding that a
cycle produces a product, namely in photosynthesis a one three-carbon sugar molecule
(G3P) made in by a net of three “turns” of the Calvin cycle that took in three one-
carbon molecules of carbon dioxide.

Cycles: coupling gap. Reactions or sets of reactions (often cycles) that are
interdependent are said to be coupled if the reactants of one are the products of the
other and vice versa. The fact that NADPH and ATP are made in the light reactions
and used in the Calvin cycle makes the light reactions and the Calvin cycle coupled, or
mutually dependent in this case for energy and electron transfer. More directly, the
reduced NADPH from the light reactions donates its electrons to intermediates of the
Calvin cycle, and ATP from the light reactions releases free energy in its terminal
phosphate bond that is then captured by the Calvin reactions.

In the simulation these reactions are represented as two cycles that
functionally link events at the thylakoid membrane (site of light reactions) and the
Calvin cycle. In Phase 1 Rhea merely saw a “whole bunch of circles” that she tried to
make sense of. She did assume that their arrangement meant that “it all affects each
other.” She was recognizing the phenomenon of coupling, which is a common theme
throughout biochemistry. Charles correctly decoded these relationships from the
simulation in Phase 1.
Charles ...OK...Now I know the relationship between these two [pointing to ATP/ADP in graphic]
Researcher You know the relationship between ATP and ADP?
Charles I think. I think ADP has a phosphate group removed. That’s how you get the energy from the ATP. And then you put a phosphate group back on it.

Another way the light and dark reactions are coupled is that, as Charles alluded to above, the light reactions require the oxidized NADP and dephosphorylated ADP to diffuse back in order to continue. Whether participants recognized this was seen by their predictions in “The Electrons” simulation task. They were to predict the effect of lowering carbon dioxide input on NADPH levels. Only Charles and Rashad made the correct prediction (that NADPH level would increase), and only Charles explained his choice in a way that convinced the researcher that his choice was intentional and not random guessing or a hunch.

Charles I think the level [of NADPH] would increase.
Researcher Why?
Charles Because it’s [NADPH] not going to be used in the dark reactions. because they are not going to happen without CO₂.

Unfortunately Rhyan made an incorrect prediction in spite of the following correct explanation.

Rhyan If [the] flow of electrons were blocked, I’m wondering if everything else wouldn’t be blocked somehow too, or if it’s just like the flow blocked right here. And if that’s the case, if everything else would be staying the same, that would decrease too. Because the reason I’m saying the ATP would decrease too is that NADPH has a part in this cycle here [Calvin], and if electrons were blocked here, it will block off production of NADPH, which this cycle [Calvin] uses to produce ADP. And it seems like the ADP, if this were to shut down or slow down [NADPH cycle], the production [by] this [ATP cycle] would slow down which in turn would slow down the production of the ATP.
The other participants did not see a relationship between the carbon fixation step in the Calvin cycle and the recycling of NADP⁺ to the light reactions, which are, on the surface, separate reactions. Cheryl was enthusiastic when she figured out why the NADPH level increased when carbon dioxide input was zero, but Caroline’s gap persisted because she could not see how these two could be related.

Cheryl OH! Then you can’t use your ATP and NADPH in your Calvin cycle to make your sugars and give off the oxidized molecules. It has nowhere to go! OK! I’ve got it!

Researcher Do you have an explanation of that? Were you right on all of them?

Caroline Nope. NADPH, I said whenever there was less carbon dioxide it [NADPH] would decrease.

Researcher Can you see why that would be, if there’s no CO₂?

Caroline No, um...[long pause]

Researcher Think out loud.

Caroline Well NADPH needs electrons, and protons.

Researcher Here, what does that have to do with CO₂?

Caroline It doesn’t have anything to do with it. I guess I see it as more ‘change’ than increase or decrease.

Not all coupling is related to direct energy transfer via NADPH and ATP. Although it was not intended at the outset, responses to “The Electrons” simulation task highlighted the state of participants’ understanding of coupling in another way.

This task asked participants to predict the effect on oxygen production if electron flow is blocked. Five participants (Raul, Chanda, Charles, Carlos and Cathy) predicted no change, although that was not a choice offered. They made this choice because they had no reason to believe the splitting of water would be affected by electron transport in such a way that blocking the later step (electron transport) would have any influence on the earlier step (water splitting). One example of this thinking is that of Chanda.
Chanda: [rereads question] ‘Will oxygen production increase or decrease if the electron flow is blocked?’ Does it have to be either increase or decrease?

Researcher: Would you rather put that it’s unaffected?

Chanda: Yeah

Researcher: OK, as long as you explain what you mean.

Chanda: I don’t think the oxygen production is affected.

Researcher: Why not?

Chanda: Because the electrons are going through a cycle, or going down a chain, and water [splitting] is separate from this. It comes into the process by bringing photosystem 2 electrons. I guess if this is blocked, then this would decrease, even if it’s not part of the process.

Charles, Carlos, Cathy and Raul (and Cheryl before she changed her final answer) also drew this conclusion when making their predictions. Originally this was considered a simple missing link since the proposition that the two are coupled is not explicitly taught, nor is it self-evident. However the proper category for this gap was reconsidered upon realizing that oxygen production rate is used throughout the simulation as a measure of photosynthetic rate, and therefore the splitting of water to generate oxygen does not occur in the absence of the subsequent reactions. This observation could have helped them conclude that the two reactions are coupled.

Naivete Gaps

This last category of propositional gaps is so named because they seem to be due to lack of experience in the discipline. One could argue that all propositional gaps are due to naivete in the discipline since novices have an underdeveloped sense about what is important to encode about a concept or link. This attention to salient attributes is learned cumulatively with immersion in a discipline. But this category of gaps was evident when the interviewee seemed unaware of the relative significance of some phenomenon in photosynthesis (e.g., photorespiration) or the conventions agreed on
by experts in the field (e.g., criteria and synonyms). For the sake of parsimony and to highlight interesting findings, discussion of the proposed categories of naivete gaps was restricted to relative significance gaps and convention gaps.

Figure 7. Typology of naivete gaps.

Relative significance gaps. These gaps are defined as not understanding the significance of a proposition in spite of knowing the proposition itself. These include the photorespiration gap and role of water gap discussed elsewhere. The simulation’s mechanism window shows oxygen being taken into the Calvin cycle without an explanation. This led all participants to think that oxygen is a requirement of photosynthesis. Without cues from the simulation, participants failed to understand that this oxygen intake is a detrimental, competitive side-reaction that makes photosynthesis much less efficient. All participants had to be debriefed about the relative significance of this oxygen input.

Another example is the role of water gap discussed in the biochemical constructs above. This is a failure to understand the relative importance of water consumption (splitting) as a “drop in the bucket” compared to the volume of water

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moved through plants daily in transpiration. This gap was evidenced by several participants who downplayed the importance of water input.

One other type of relative significance gap is the *anthropomorphism gap* exhibited by Cheryl, who had an otherwise strong conceptual framework for photosynthesis. On several occasions in both the Phase 1 and Phase 2 interviews, she wondered out loud about, for example, what Spanish Moss is “good for” since it apparently doesn’t do anything. By contrast, trees provide oxygen and grass cushions the Earth, she said. This naivete about the natural world should be of concern, especially with an otherwise high-achieving student.

The last type of relative significance gap was witnessed when several participants’ interviews progressed to the point of being asked to consider and comment on an anecdote. The anecdote is about the researcher’s brother who, while a Peace Corps volunteer in Morocco, was warned by his educated Moroccan friends against running at night since plants take up oxygen in the absence of light. When asked if she believed it was true, Rhea said, “well, you said ‘educated friends’,,” and concluded from that that it must be true. Others only said that they had never heard of that before. Those that believe that enough oxygen is removed from the atmosphere to pose a health hazard appear to possess this relative significance gap since they were unable to assess whether the change in oxygen level was negligible. At this point it is worthwhile to note that this anecdote highlights the difficulty of the goal of science literacy, and that a good understanding of photosynthesis and respiration cannot help them evaluate this myth.
Convention gaps. Raul acknowledged that, in science, conventions dictate how members of that discourse community understand one another, even for words like “dead.” This otherwise enlightened metaknowledge did not prevent him from accepting a “spontaneous generation” explanation for the continuity of life through seeds.

Researcher So you’re saying [an item like a seed] can’t be dead and then spring back to life?
Raul I can’t think of any reason offhand why it can’t be that way.
Researcher You mean it can’t be what way?
Raul Can’t be that it, something happens and then it is alive at that point. [spontaneous generation]
Researcher But it’s dead until then?
Raul Well the term [“dead”] doesn’t apply, it’s just a collection of chemicals until then. I mean this is all speculation. It might at most be a matter of standards.

Inability to recognize and discriminate among synonyms is another kind of convention gap. Cathy was confused by the different labels used synonymously for the same ATP synthesizing complex [CF1, ATPase, ATP synthase]. The fact that in the class the terms are used synonymously also had to be explained to Carlos, Chanda and Charles. Although experts in the field finely discriminate between these labels, professors in introductory college courses do not usually make these distinctions explicit, leaving students to wonder if they are synonymous, and if so, why scientists cannot agree on a single label.

Cathy It’s the same thing?
Researcher ATPase, ATP synthase, CF1 complex are all synonyms.
Cathy Did he [Dr. Corey] like say this stuff in class, or is this like a known something that we [are supposed to] just know?

The simulation text referred to the photosynthetic sugar as PGAL (phosphoglyceraldehyde), whereas Dr. Corey and the textbook refer to it as G3P
(glyceraldehyde-3-phosphate), which is another naming convention for the same molecule. Chanda, Caroline and Cathy noticed or asked about these two names.

Researcher  G3P is the same as PGAL.
Cathy  Yeah, I figured it out when I was doing my poster because I was looking at my notes and I was looking at the book, and I kept getting mixed up. I was like, why do they keep putting [PGAL for G3P]!

Other synonyms used (often unconsciously) when teaching about photosynthesis are listed in Table 16. In the interviews 7 of 12 participants specifically commented on use of these synonyms. Several of the other categories of propositional gaps discussed above also seem to be due to naivete. When participants exhibited discrimination gaps they often used terms as though they were synonymous, providing evidence of convention gaps. Furthermore, when the simulation asked which compounds were produced as a result of the light reactions, Chanda knew that ATP was produced, and that it was a molecule, but was not sure whether it qualified as a compound, therefore did not think these were synonymous. Caroline showed a set membership gap in the Phase 2 concept mapping task when she wanted to group the entire set of terms in the sorting task under light dependent reactions, since they all ultimately depend on light.

Table 16. Synonyms questioned by participants.

<table>
<thead>
<tr>
<th>Synonym</th>
<th>Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>oxidative phosphorylation/chemiosmosis</td>
<td>Chanda</td>
</tr>
<tr>
<td>proton/H⁺/hydrogen ion</td>
<td>Rhonda</td>
</tr>
<tr>
<td>Krebs cycle/TCA cycle/Citric acid cycle</td>
<td>Caroline</td>
</tr>
<tr>
<td>Calvin cycle/carbon fixation</td>
<td>Randy</td>
</tr>
<tr>
<td>CF1/ATPase/ATP synthase</td>
<td>Carlos, Cathy, Chanda, Charles</td>
</tr>
<tr>
<td>PGAL/G3P</td>
<td>Caroline, Chanda, Cathy</td>
</tr>
</tbody>
</table>
These examples illustrate naivete gaps since their inability to discriminate molecule from compound, and which reactions are “light-dependent” seem to be due to inexperience in the discipline. Several participants’ understanding of “organic” and “living” as discussed above were also examples of naivete gaps.

Do the Gap Categories Overlap?

As stated previously, one could argue that propositional gaps are ultimately due to naivete. Therefore many of the propositional gaps described in this section also seem to be due to naivete. Readers may also have noticed that some of the propositional gap categories themselves seem to overlap with each other. For example, one discrimination gap (a kind of conceptual gap) about the understanding of the gradient concept seems similar to the thermodynamics concept (a kind of construct gap) about gradients. Similarly, set membership gaps that were exhibited when the chemical composition of a molecule was not recognized seem to overlap with conceptual distance gaps in which participants failed to transfer what was learned earlier in the semester about chemical composition to this specific context (e.g., ATP is a nucleic acid).

It may appear at first glance that these overlap in such a way that separate categories are not justified. Instead, this observation was understood by the researcher to represent a separate emergent overarching theme: there is a continuum of levels at which a concept is integrated throughout one’s conceptual framework, and the three categories of propositional gaps (conceptual, linking and construct) may represent benchmarks in those levels of integration. This notion requires further study, however
at this time it appears that the poles of that continuum may be local to universal integration of the concept across the conceptual landscape.

**Processing Gaps**

The participants thought aloud or explained aloud during most of the clinical interview tasks. The verbalizations made during processing externalized how they applied procedural skills and strategies to the tasks at hand. Errors made in decoding the representations used in the interviews, the graphics in the photosynthesis simulation and fabric model of the chloroplast, led to identification of the majority of the processing gaps, called *graphic decoding gaps*. There were also numerous *procedural habits* and strategies employed by the participants that were relevant to this study. These relevant procedural habits were not gaps *per se*, but were important for understanding how their conceptual frameworks grew and changed as a result of these habits.

It should be stated at the outset that although these gaps are categorized as processing gaps, processing inextricably involves interactions with long-term declarative memory for pattern comparison and with episodic memory for comparison with previous experiences. Therefore the distinction between processing gaps and propositional gaps is not absolute. The researcher chose to categorize them separately since the relevant propositions missing during processing were not in the conceptual framework for photosynthesis *per se*. In the case of graphic decoding gaps, the propositions retrieved from long-term memory during decoding had more to do with the participants' experiences with what icon shape and color represent, for example, than their knowledge of photosynthesis. With respect to procedural habits, the
participants exhibited ways that these habits both helped and hindered their ability to retrieve and use their knowledge to complete the tasks, but were not habits peculiar to photosynthesis. Processing gaps are summarized in Figure 8. When the gaps are listed vertically, their somewhat arbitrary order is simply that in which they are discussed later.

**Graphic Decoding Gaps**

During both clinical interviews participants interacted with the leaf and mechanism windows of the simulation during various tasks. Since no participant had worked with the simulation previously, their explanations in the first interview provided clues to how an uninitiated student working alone on this simulation might decode the graphics in order to encode propositions about photosynthesis. Most of their errors were in icon decoding. Others were in spatial orientation and inferences about single representatives, both of which are more appropriately considered gaps in graphic literacy skills.

**Graphic literacy skills.** Observations of how the participants used graphics indicated how they drew effective and ineffective inferences from them. Many of the propositions they inferred from graphics were defensible, but nonetheless point to gaps in their decoding skills of which instructors need to be aware. Gaps in graphic literacy skills fell into five categories: design convention gaps, representation gaps, orientation gaps, preposition gaps and confidence gaps.
Figure 8. Typology of processing gaps.

Design convention gaps. Participants made numerous inferences about the graphic design conventions (e.g., shape, color, position), and how they came to expect them or permit them as cues. They gave evidence that they expected design features to apply consistently throughout the simulation. When Chanda tried to decode the ATPase block icon, she was reluctant to say it was a channel because she expected the proton flow line to switch from the ATPase to the new channel, which was a reasonable expectation.

Chanda  Well I was going to say that, but then they’re [hydrogen ions] still not moving out, so...
Researcher  You would have expected what to happen?
Chanda  The hydrogen ions to go through that [new channel].
Researcher  For the black and white [flow] line to be able to move?
Chanda  Yeah.

Caroline’s difficulty with orientation also may be related to her expectations of consistency in graphic design. In “A Delicate Balance” she had trouble inferring that carbon dioxide, like oxygen, can enter and exit plants depending on light.
conditions. However the graphic was inconsistent because it showed separate input and output flow lines to and from the oxygen meter, whereas only one flow line was shown for the carbon dioxide meter which merely changed direction according to the net direction of carbon dioxide movement.

Raul also expected consistency in Phase 1 when trying to infer the significance of the proximity of the relative humidity meter to the oxygen input meter in the mechanism window. At the bottom of the same window, the proximity of the water input to the oxygen output is significant. He was misled by trying to apply the same rule when inferring the other could be significant too: "Ah! the relative humidity might control the O₂ up here!" While trying to decode the oxygen flow lines in the "A Delicate Balance" task, Rhyan assumed that consistency of color could be a cue: "Of course black represented protons a little while ago. So I don't know."

Charles inferred that the elongated oval at the bottom of the mechanism window represented the stem instead of the thylakoid membrane. This suggested that he thought it defensible for a graphic designer to mix scale within a single graphic without providing a referencing tool, like telescoping, to guide the user. Perhaps he has had experiences in which this was the case.

Representation gaps. Participants often assumed that the model or graphic they encountered faithfully represented the true number and spatial arrangement of the biological phenomenon under consideration. One manifestation of such face value inferences is the icon decoding gap discussed later in which participants assumed because of the position of the output meter that plants secrete the sugars they produce. Similarly, Randy said "the carbon dioxide is inputted through the side of the leaf,"
somehow through the layers of the leaf,” and that inputs and outputs entered and
exited only on the sections of the leaf where arrows were pointing. In Phase 2, Rhyan
made an assumption that because carbon dioxide and oxygen were illustrated entering
and leaving different stomata shown on the leaf surface that this could mean that
stomata can somehow be specialized to allow in or out only one of the gases.
Likewise, Cheryl’s choice of words when explaining the mechanism window
indicated she may view the positions of the cycles to be fixed where they are in the
representation.

Cheryl OK, this is the thylakoid. What’s happening is, OK, you’ve got
light coming in and you’re beginning your light reactions, and in
your light reactions you make ATP here that’s going in, and you
make NADPH which is coming in this way. So they’re coming
in from opposite ways, they’re going to the Calvin cycle...

Another face value inference Rhyan made was that since the thylakoid in the
mechanism window was elongated, then it must be a stromal rather than granal
thylakoid (Figure 9). In the ink-label task Caroline was asked to follow an imaginary
dot of ink on a carbon atom. When asked whether the ink would stay in the sugar just
produced, she did not go beyond the face value of the graphic when she said “I guess
[it will stay in] sugars. I don’t see any outflow.” It seems part of graphic literacy is
knowing when and how to draw inferences beyond the graphics themselves.

The fabric model of the chloroplast used in Phase 2 also drew face value
inferences. After Chanda incorrectly said that rubisco was in the thylakoid membrane,
follow up questions revealed her reasoning. She believed that rubisco would need to
be in close proximity with the thylakoid in order to use the products of the light
reactions made at the thylakoid surface. Since the fabric model showed the thylakoids

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closely appressed, she assumed that rubisco would have to be found between the thylakoid pouches and therefore falling within the column of a granum. Caroline made a similar inference. She asked whether the close proximity of the thylakoid pouches would not impede the function of the CF1 ATPase, and therefore wondered whether there would be ATPases where the thylakoids are stacked. She did not realize how small these enzymes are relative to membranes, and that "close" is relative. Also, later when Caroline was presented with the fabric model of the chloroplast and was asked how the oxygen gets out, she briefly entertained the notion that it could exit the gap in the membrane left unsewn on the model for the purpose of removing the thylakoid pouches. It was difficult for her to apply what she learned about gas diffusion across membranes to the process of photosynthesis.

Figure 9. Chloroplast ultrastructure.

An inference made about the graphics in the simulation was that a single representative icon means there is but one such structure/event in the real phenomenon. This was designated a single representative gap. Although each icon may be intended to represent hundreds if not hundreds of thousands of the structure it represents, participants do not always make this inference. In Phase 2, Caroline assumed that each thylakoid has "its own ATPase," implying only one per thylakoid. Some students do not seem to have the single representative gap. Rhyan understood
that light entering the plant cell is “hitting all around” but it’s [only] interacting with the pigments. With regard to number, Charles did not exhibit a single representative gap. He readily assumed that a single icon for NADP represented hundreds of thousands of that molecule in a chloroplast. Although the number was much higher than the single icon, he was nonplused: “Nothing sounds big compared to Avogadro’s number.” The following interchange shows that he understands that light is hitting the entire leaf surface and that oxygen exits all over the surface of the thylakoid rather than only at the site of the output meter.

Charles: Well the light’s going right here [points with cursor to light arrow in mechanism window] but I mean presumably it’s not all happening right here for the entire leaf.

Researcher: So you think that this right here [thylakoid] represents the surface of the leaf?

Charles: Yes but just because it looks like this doesn’t mean that it’s happening like this you know. I’m sure oxygen is coming off here [at output meter] but I’m sure it’s coming off here and here [points elsewhere], all over when we saw the whole leaf picture...I mean [switching to leaf window] they have oxygen coming off here [at oxygen meter] but I wouldn’t think it would just come off there.

Researcher: Where else would it come off?

Charles: There, there, there, there, there [points cursor to many places on leaf surface] same place.

Orientation gaps. In the above interchange Charles showed some good graphic literacy skills, however he showed an orientation gap as well (when he thought the elongated thylakoid was the leaf surface). Orientation gaps are defined as the inability to process the information provided in a graphic or between graphics so as to mentally place the interacting structures and processes in a workable arrangement in 3-D space. Similar to Charles in the interchange above, Cathy misunderstood the thylakoid membrane representation in the mechanism window.
Her attempt at visual correspondence between the leaf and mechanism windows led her to believe it represented the stem of the plant. Rhea believed the mechanism window was an overlay of the leaf window, as evidenced by her explanation that the mechanism window portrayed “the same cycle [as the leaf window], it’s just very....thorough now.” When trying to get oriented in the mechanism window she looked for an anchor icon that would let her draw parallels with the leaf window: “Where’s the O₂ that it gives off?” Before Raul clicked the icons representing the photosystems in the thylakoid membrane, he thought that they represented stomata in the leaf surface. This may have been the cause of Charles’ orientation gap as well.

All the participants showed evidence at some point in the interviews that they were not properly oriented. Some may be attributed to simple inattention or impulsive responses. Some evidence is attributable to recognition of a similar form that elicited schemas in another frame of reference. It was frequently necessary to offer suggestions that helped them get oriented. Rhyan showed his graphic literacy skill of drawing preliminary conclusions while immediately orienting himself to the simulation in Phase 1 when he intentionally decoded all the icons: “I see where it’s going, that’s neat. You can vary [these variables]”.

One experience with Caroline indicated that some visuospatial orientation problems are inherent in keeping track (in working memory) of how the involved structures were nested, so that decisions can be made about how they interact across scale. Caroline had an especially frustrating experience when trying to reconcile the features of the simulation graphic with the fabric model. In a plant cell, the thylakoid is a pouch within a chloroplast, and a chloroplast is an organelle within the cell.
Chlorophyll is located in the plane of the thylakoid membrane. There are also three nested liquid media to consider: the matrix within the thylakoid space, the stroma within the chloroplast and bathing the thylakoids, and the cytoplasm, which is the liquid matrix of the cell that bathes the organelles, including the chloroplast (Figure 10).

Figure 10. Relative positions of compartments in plant cells.

As seen in the excerpts later from the Phase 2 interview, Caroline had trouble identifying how the parts represented in the simulation graphic and fabric model were organized with respect to each other in a living plant, especially relating to her concepts of cytoplasm and chlorophyll. She wondered if stroma and cytoplasm were synonymous since they seemed to her to be equivalent. Without this clarification she had trouble getting a cognitive footing on the tasks. The following five quotes are excerpts from a long interchange in Phase 2 about the fabric model.

Caroline And then all of this happens in the chlorophyll, which is in the stroma, or the other way around? The stroma is in the chlorophyll. [incorrect]

Caroline I think this is the thylakoid. I think all of this [interior], well, I guess I’m looking at all this wrong. If it’s the liquid that surrounds the thylakoid, then I think the chlorophyll surrounds the stroma [incorrect].
Caroline: OK, oxygen and carbon dioxide is [sic] going into the cell [incorrect, referring to Calvin cycle in simulation, which is more deeply nested in the chloroplast].

Researcher: What do you think the white [bag] is?
Caroline: um...the cell?
Researcher: The chloroplast.

Caroline: This right here [white felt] is this green [structure in the simulation]
Researcher: No.
Caroline: No? It's the thylakoid [then].

Once she understood that the thylakoid fabric model was green because it contained the chlorophyll, she was able to mentally nest the thylakoid, chloroplast and cell compartments. She suddenly had a need to know more once she got the right orientation, and interrupted to ask questions to further check her new understanding.

Caroline: So the chlorophyll is inside here?
Researcher: It's actually in the membrane...And that's why it's green, because of the chlorophyll.
Caroline: Oh, OK. Because I'm thinking of the whole cell [meaning to say organelle].
Researcher: You're thinking of an organelle. Now a whole cell, if we took this thing [model] and put it in a big plastic bag.
Caroline: Then there would be chlorophyll all over [waves hands around chloroplast].
Researcher: No, that would be the cell. The only place you find chlorophyll is the thylakoid membrane.[ ]
Caroline: Well you know like how in a cell they have all the different little...
Researcher: Organelles?
Caroline: Yeah, organelles inside, and they are in a solution?
Researcher: Cytoplasm?
Caroline: Cytoplasm! [visibly relieved]

Her frame of reference was correctly engaged for understanding the subcellular compartments, but then when asked to reconcile how the leaf and
mechanism windows are related, she still had problems with orientation immediately following the previous interchange.

Researcher  Do you see any cells in this [leaf cutaway view]?
Caroline    Um...well... this right here.
Researcher  The thing [cells] with the little green dots [chloroplasts] on it?
Caroline    Yeah [this is correct].
Researcher  And what do you think the little green dots are?
Caroline    Thylakoids [incorrect].
Researcher  Chloroplasts, which have the thylakoids on the inside.

In this case Caroline’s decoding was aggravated by a subtle change in the graphic design necessitated by the limits of representation. She had only just come to accept that thylakoids are the actual structures in the plant cell that are green. Then the leaf window representation that could not show thylakoids to scale betrayed her understanding by representing the chloroplasts as green discs inside the cell. In Phase 1 Raul also inferred the mesophyll cells in the leaf cutaway were chloroplasts.

Randy’s attempt to visually nest the structures was evident in Phase 1 when explaining where light interacts with the parts of photosynthesis.

Randy      I figure that this [Calvin cycle] is more inside than this is [thylakoid space]. [incorrect]
Researcher More inside what?
Randy      More inside the leaf. Just because it’s a little boxed in area. I don’t know if that’s any good reason, or logic or not. And this, it has to do with more, maybe, like more of the outer layers, not exactly the outside of the leaf, but more outer layers. This is more so the inner layers.

The text of the simulation in Phase 2 explains how the compartments of the cell and chloroplast are nested.

Simulation The chemical substance which gives the plant its green color, the chlorophyll, is concentrated in the chloroplasts. The membranes in the chloroplasts are arranged in pocket-like structures called
thylakoids. The light reactions take place in the thylakoid membrane. Each chloroplast contains many thylakoids.

After reading the passage aloud, Cathy admitted, “That part’s confusing. I have to like write it on paper, everything is inside everything, you know what I mean?” Although she successfully reconciled the fabric model with the simulation graphic by working outward from the innermost pouch (first set of quotes), she later forgot her orientation when asked where oxygen is produced (second set of quotes). These illustrate the difficulty in keeping one’s nesting orientation in working memory.

Researcher So what do you think this bag on the outside is supposed to be?
Cathy Wait, thylakoid, chloroplast...[working way out of fabric model]. Chloroplast [confidently].

Researcher Where is oxygen made?
Cathy Stroma [incorrect, thylakoid space].
Researcher Oxygen’s made in the stroma?
Cathy I know that water’s split in the stroma.
Researcher The water’s split on the inside.
Cathy It is?
Researcher Of the thylakoid.

Rashad made an error seen frequently with students that may indicate failure to regard levels of nestedness. When explaining proton pumping in Phase 1, he said “Protons, I think they are pumped out of the cell.” A similar careless error was made by Chanda when she described protons as being found “in the nucleus of the cell.” Rhea also called protons “parts of the cell that are positively charged.” It seems likely that this misretrieval across scales is due to a cue common to both the cellular and atomic frames of reference (“nucleus”).
Students do not seem to attend to nestedness when leaping across scale. When Rhea was asked where in the leaf is the mechanism of photosynthesis occurring, she was charting new cognitive territory.

Researcher: Can you tell me where this [mechanism] is going on relative to the leaf window? Where is this?
Rhea: Where is it in the leaf?
Researcher: Or where is it happening?
Rhea: In the leaf?
Researcher: In the leaf? OK, just anywhere in the leaf?
Rhea: Um...I’ve never thought about any of these questions before...

After leading questions she was able to say that the mechanism window portrays cellular events. Rhonda, who had the lowest photosynthesis literacy level of all participants, showed her inattention to scale and nestedness when she summarized the events following restoration of ATP synthesis in the Phase 1 simulation as “all just working together, [ ] they just went back to what the plant was.” “The plant” does not identify her level of organization, just as “in the body” fails to identify scale when less mindful students say “where” a particular physiological process occurs.

That students are not accustomed to attending to nestedness is also supported by the observation that when asked to trace the path of oxygen out of the thylakoid membrane, for example, all participants stated that it simply diffused out of the plant’s stomata into the atmosphere. They only followed oxygen’s movement through the nested compartments when pressed to do so, and then never completely. They could follow the oxygen out of the cell, but did not acknowledge the tissue level of the leaf’s organization. Furthermore, no student suggested that oxygen could be consumed by the same cell’s mitochondria. Since oxygen diffuses, it will move to areas of lower concentration. In a plant cell not all the oxygen need leave the cell; it can and does
diffuse to the mitochrondrion where it is consumed during aerobic cellular respiration. Thus the nestedness gap seems to be related to the gas exchange gap discussed above.

Preposition gaps. It was common for participants to use prepositions to describe relative position of structures, although often the usage was ineffective at conveying such relationships. In Phase 2’s co-concept mapping task Caroline explained that protons go “through” the membrane, but she drew a membrane fragment at too fine a grain to provide cues about polarity. Direction of proton pumping in photosynthesis is toward the thylakoid interior, whereas the direction in respiration is “outward” into the intermembrane space of mitochondria. When presented without context clues to establish frame of reference, it is difficult for students to determine from such graphics in which direction protons move. Sometimes the participants’ attempts to use prepositions helped them to resolve conflicting information. When Caroline could not decide whether carbon dioxide entered “through” or “into” the stroma, it indicated that she was confusing the terms stoma and stroma, which carbon dioxide enters “through” and “into,” respectively.

Several participants used prepositions in the same way their textbook graphics graphically represented direction. When Caroline was asked about where electrons go during their transport, she replied, “it looks like it goes down.” Cathy apparently referred to the classic Z-scheme graphic of electron transport while co-concept mapping in Phase 2. In the Z-scheme the Y-axis represents electron volts, or in biological terms, energy, which she had not considered until directly asked.

Cathy OK, the electron goes downhill from here to here to here, and it’s a downhill reaction.
Researcher OK, [writing] 'electrons go downhill,' like in space? They move down physically? Like gravity?

Cathy No.

Researcher What do you mean by downhill?

Cathy That's a good question, like maybe in energy.

She continued to try various linking words to fit energy into her understanding of the graphic. Referring to the same Z-scheme, Carlos said that after the electrons are returned to photosystem 1, they "go straight up." Although he did not indicate he understood this, the graphic should have been interpreted to mean that at the photosystems, light causes the electrons' energy to be raised, or excited. Another textbook graphic was referenced when Carlos said, "hydrogen ions go up" in chemiosmosis.

Preposition use may contribute to failure to completely understand nestedness.

In the simulation's text is the statement that "chlorophyll is concentrated in the chloroplasts." While the statement is true, students need to be reminded to place the chlorophyll within photosystems within the thylakoid membrane within the chloroplast. The simulation's statement above could be construed literally to mean that chlorophyll is loose in the chloroplast.

Confidence gaps. Participants like Cheryl, whose graphic literacy skills have served them well, refer confidently to images from which they have learned. Throughout both interviews Cheryl readily sketched while explaining, sometimes of her own spontaneous design and sometimes recreated from a diagram she spent time understanding. She admitted to being a highly visual learner. On the other end of the confidence spectrum, Caroline had significant difficulty understanding orientation and nestedness as discussed above. Rashad did refer to a graphic of the carbon cycle he
had seen when explaining what photosystem 1 is, but apparently had not learned
enough from it to help him on the task. Carlos was reluctant to reconcile the
simulation graphic with that he learned in class for fear of confusing himself and
interfering with his learning of the graphic for which he would be more accountable.

Carlos: I didn’t think about the diagram [in the simulation] because the
way he [Dr. Corey] had it made more sense to me. I didn’t want
to confuse it trying to match it to this, so I just didn’t worry
about [this one].

In spite of his reticence, he did depend heavily on figures for learning, and admitted to
recopying all of the figures used in class when studying.

Another way confidence plays a role in decoding skills is in trusting that the
representation is scientifically accurate. That assumption allowed all the users to be
confident in the cues they gleaned from the graphics. In Phase 1 when decoding the
simulation graphic, Cheryl was trying to understand the proton flow line when she
stated, “apparently that proton [symbol] there [on the flow line] has got to be there for
a reason.” Similarly, when Rhea witnessed that in the absence of light plants take up
oxygen from the atmosphere (“A Delicate Balance”), she was asked to evaluate the
statement that it’s dangerous to run at night since plants take up oxygen from the air.
When asked whether it was true, she responded, “well, I don’t know why they would
show it if it wasn’t.” At issue in that proposition is whether a plant’s oxygen
consumption is negligible, a propositional gap that is attributed to naivete as discussed
previously.

Icon decoding. During the first clinical interview, participants were asked to
“Describe what you see happening here” each time they encountered the leaf and
mechanism windows. Their responses indicated they had drawn faulty conclusions
drawn about the meaning of the icons and their arrangement in the windows.
Although it is likely that they would have self-corrected upon more careful, persistent
engagement with the simulation, that they made these conclusions at all indicates that
care need be made in using such graphic representation in instruction. To review, in
the leaf window is a cut-away view of the underside of a leaf. Stomata (pores) are
shown, as well as flow gauges for sugar and oxygen production. There are sliders on
the water and carbon dioxide input meters to adjust the amount of them being taken in.
The water and carbon dioxide flow gauges each have a button (empty circle) that, if
clicked, radioactively “tag” the oxygen or carbon atom in those molecules,
respectively. Other features in the leaf window are icons that allow the user to change
light intensity and wavelength, change temperature and change relative humidity.
How these icons were decoded is discussed later.

Radiolabel button. In the first clinical interview when students were asked to
describe what was happening in the leaf window while it was running, several
participants responded “water and oxygen are going into the leaf.” Carlos made that
statement four times in the course of the interview, and it was not obvious to the
researcher why he did so. Then during the water-labeling segment of the simulation
(in which the oxygen in water was radioactively tagged), he realized that the circle-
shaped button in the top corner of the water input meter was a label button, and not
oxygen as he previously thought.

Carlos     See, this is kind of confusing
Researcher You thought it was oxygen?
Carlos     Yeah, I thought it was oxygen
Even after this clarification, when he later was trying to achieve the maximum photosynthetic rate, he was adjusting the water meter as though it was an oxygen meter until he was reminded of the meaning of the icon. This error also was made by Caroline, Rashad, Rhea and Chanda, or five of 12 participants. That the icon was so commonly decoded as oxygen, the graphic designers would do well make that icon look more like a button (perhaps with shadowing) than like an “O.”

Sugar secretion. A feature of the leaf window layout that misled was the flowing arrow from the leaf to the sugar output meter placed outside of the leaf. Several participants perceived this to mean that sugars are secreted from the leaf through the leaf surface (Table 17). Most were reluctant to incorporate the suggestion into their conceptual framework. However Randy did accept this conclusion and referred to it in the second interview when explaining what the fate of sugar would be: “Then it’s gonna travel its way, travel its way out and go in as nutrients into the ground, to the environment around the plant.” Rhonda, Cheryl and Rhyan also retained this interpretation into the second interview. Cheryl corrected this conception for herself while wondering where she ever got such an idea, and Rhyan was “still bugged” by the notion since it challenged his previous conception that plants use the sugars they make. In total, nine of twelve participants at some point made comments indicating they believed the graphic represented sugar being secreted from the leaf.

Photorespiration. In the mechanism window the conspicuous placement of oxygen intake into the Calvin cycle at the top center of the screen was a major source of misretrieval of schemas. Indeed oxygen is consumed in the dark reactions, but in a
wasteful side-reaction in which the primary enzyme rubisco fixes oxygen instead of carbon dioxide. It is this reaction that tropical C₄ and CAM plants adapted to minimize. During Phase 1, every participant saw this prominent oxygen intake and tentatively believed oxygen was a necessary reactant of photosynthesis. Some recovered somewhat quickly or at least recognized the incongruity of their conclusion with their previous decision (Carlos, Cheryl, Charles). This mistake was witnessed much less in Phase 2 interviews, and only with students in Dr. Reese's section (Rhonda, Rhea, Rhyan). Although both professors discussed C₄ and CAM adaptations, only Cheryl (in Phase 2) recognized the oxygen intake icon as such: "Oh, this is photorespiration!!" In Phase 1 interviews, this feature along with the radiolabel button continually reinforced their notion that photosynthesis requires oxygen, which is related to a misretrieval of the cellular respiration schema discussed later.

Table 17. Participant decoding of sugar output in Phase 1 interview.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charles</td>
<td>I'm still not happy with what the sugar is doing...because it looks like it's leaving the leaf through the...leaf.</td>
</tr>
<tr>
<td>Cheryl</td>
<td>I really don't know what the sugar would come in the form of if it's on the outside.</td>
</tr>
<tr>
<td>Carlos</td>
<td>The sugar is...I don't think they're excreted. Like they don't drop a sugar pellet! It's stored in the leaf.</td>
</tr>
<tr>
<td>Caroline</td>
<td>It looks like it but I don't think they are.</td>
</tr>
<tr>
<td>Cathy</td>
<td>The sugar is coming out. It looks like the top of the leaf but I've never noticed sugar coming out of a leaf before.</td>
</tr>
<tr>
<td>Rhea</td>
<td>It's taking in water and carbon dioxide, and, hmph, it's giving off sugars and it's giving off oxygen.</td>
</tr>
<tr>
<td>Raul</td>
<td>...Sugars leaving the leaf, this seems bizarre...I would have thought it would have been kept there.</td>
</tr>
<tr>
<td>Randy</td>
<td>I see water pouring into the leaf, carbon dioxide coming in through the right bottom corner. Sugars look as though they're exiting to the left, and oxygen is also exiting to the upper right.</td>
</tr>
<tr>
<td>Rashad</td>
<td>...It's leaving. ...Where, I do not know.</td>
</tr>
</tbody>
</table>
Oxygen production rate. Most segments of the simulation showed a graph display output while the photosynthesis simulation was running. The title of the graph display was “O2 Production Rate.” When Chanda was asked to interpret the graph, she read the title to be simply “Production Rate.”

Researcher And what is being measured there?
Chanda Production rate of sugar.
Researcher What do you think this means right here in front of ‘production’?
Chanda I’m not sure.
Researcher ...If there was O and a small 2.
Chanda Oh, O2, then I would think it was oxygen.
Researcher So you didn’t think of it as oxygen when you saw it?
Chanda No.

Cathy, Carlos, Randy, Raul and Cheryl also failed to read “O2” as “oxygen,” but they all did after it was suggested that the “2” should be subscripted. Rashad, Rhyan, Rhonda and Caroline did not need the subscript to understand it represented oxygen. Before being debriefed Cheryl assumed that the production rate was of tomatoes and Rhonda assumed it was propagation of the plants. This is a case of design flaw—one in which half of the participants in this study were denied an immediate understanding of the graph by a careless formatting error on the part of the software designer.

Calvin cycle. In the mechanism window there is a dark blue oval which is intended to represented the set of reactions of the Calvin cycle. It was not until Charles suggested that the color represented darkness that the researcher considered that it might represent the dark reactions of photosynthesis of which the Calvin cycle is the major part. Presumably because of the blue color, Rhonda and Randy tentatively believed it represented water input. Because its boundary was construed as
a membrane, Caroline believed it represented the cell, and Rhyan believed on one occasion that it was the thylakoid membrane, and on another that it was a stomate. Randy even used the “little boxed-in area” to make decisions about the nestedness of the Calvin cycle with respect to the thylakoid membrane. Since only one participant correctly inferred the significance of color and shape in that case, and five did not, this indicates that this design feature failed the users.

Flow lines. There are black and white flow lines in the mechanism window’s thylakoid membrane to show proton flow, and in the leaf window to show direction of flow of oxygen and carbon dioxide. In the first case several participants in both interviews construed these to mean electron transport (Cheryl, Chanda, Caroline) when their conceptual framework for chemiosmosis was not well developed. The pop-up for this flow line shows H⁺, which indicates proton flow and helped some participants reconcile their dilemma. In the Phase 2 interview in the “A Delicate Balance” task, Raul called attention to an inconsistency in the graphic design when he wondered why there were two flow lines (in and out) for oxygen, but only one for carbon dioxide (in). After all he had just learned that gas exchange at night in plants is much like that of animals: oxygen is taken in and carbon dioxide is released due to ongoing cellular respiration. This indicates that students constantly seek patterns, then hope they can trust them to understand new scenarios. When the pattern fails to be consistent, the participant may become reluctant to trust her/his ability to decode them. Table 18 summarizes the frequency of errors made while decoding icons in both the leaf and mechanism windows of both Phase 1 and Phase 2 interviews. It is interesting to note that two of these icon decoding gaps (photorespiration and the
radiolabel button) are due to the participants’ erroneous expectation that oxygen input should occur in photosynthesis. This is likely to be related to misretrieval of respiration schema observed frequently in the interviews and discussed in the next section. In addition, four of the six common errors (sugar secretion, oxygen production rate, radiolabel button, Calvin cycle) are due to ineffective or misleading graphic design.

Table 18. Frequency of icon decoding gaps.

<table>
<thead>
<tr>
<th>Icon</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photorespiration</td>
<td>12/12 (100%)</td>
</tr>
<tr>
<td>Sugar secretion</td>
<td>9/12 (75%)</td>
</tr>
<tr>
<td>Oxygen production rate</td>
<td>6/12 (50%)</td>
</tr>
<tr>
<td>Radiolabel button</td>
<td>5/12 (42%)</td>
</tr>
<tr>
<td>Calvin cycle</td>
<td>5/12 (42%)</td>
</tr>
<tr>
<td>Flow lines</td>
<td>3/12 (25%)</td>
</tr>
</tbody>
</table>

ATPase block. In the Phase 2 interviews participants were asked to witness the result of blocking the ATPase in the thylakoid membrane. When a red channel popped up adjacent to the ATPase in the membrane, participants were asked to describe and interpret the red icon that appeared as two parallel lines across the membrane. Their metaphors indicated a great deal about the level to which they understood chemiosmosis (Table 19). It is notable that all the participants from Dr. Corey’s section used metaphors (channel, escape route, alternative pathway) with functional connotations, and they specified proton leakage. This indicated a more complete understanding of the role of proton flow in ATP synthesis. On the other hand, participants from Dr. Reese’s section used non-specific metaphors with fewer references to a three-dimensional structure. To them the channel was merely a hole through which all the thylakoid contents would spill.
It is also notable that Chanda correctly interpreted the icon as a channel, however she was tentative because she expected the black and white flow line that represented proton flow to then begin flowing through the new channel, as mentioned above regarding design conventions. This was important to her on-the-spot decision making, and is another example of how students come to expect consistent patterns in the graphics they use.

The number and kind of graphic decoding errors the participants made begs the question of whether the software designers, the instructors, or the participants themselves deserve to take responsibility for these mistakes. This researcher believes it is all three. Clearly some of the decoding errors were unnecessary, and the graphic designers should address these immediately (e.g., O2 production rate, the blue oval Calvin cycle). However the rest of the decoding errors stem from unavoidable fidelity constraints of graphic representation and the students' poor graphic literacy skills that both instructors and students need to actively address in the course of instruction. Recommendations are discussed further in the Conclusions. The Graphic Decoding gaps are summarized in Figure 11.

Procedural Gaps

Procedural habits that were observed that were relevant to this study also could have been labeled "critical thinking skills." The latter was avoided because of its common usage and "catch-all" connotation for how students think. Procedural habits were evident in the cognitive itineraries participants took when confronted with new information and a task to accomplish. This category emerged by evaluating cases
where participants used their cognitive habits effectively as well as to note cases where they did not.

Table 19. Participant decoding of channel icon after blocking ATPase.

<table>
<thead>
<tr>
<th>Participant</th>
<th>Decoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chanda</td>
<td>Maybe it looks like another pathway for the [hydrogen], [but] nothing’s going through.</td>
</tr>
<tr>
<td>Charles</td>
<td>Is it another pathway? For the hydrogen, the protons?</td>
</tr>
<tr>
<td>Cheryl</td>
<td>It looks like an opening... then your protons could just flow back and forth and you wouldn’t have a gradient.</td>
</tr>
<tr>
<td>Carlos</td>
<td>Well I guess a channel opened up.</td>
</tr>
<tr>
<td>Caroline</td>
<td>A hole?... protons are not going through here, it’s going through there [channel].</td>
</tr>
<tr>
<td>Cathy</td>
<td>It looks like an escape route... they’re leaking through.</td>
</tr>
<tr>
<td>Rhea</td>
<td>It just breaks? It’s a gap?</td>
</tr>
<tr>
<td>Rhonda</td>
<td>[no response]</td>
</tr>
<tr>
<td>Rhyan</td>
<td>A cut in the thylakoid. It looks like all the liquid is spilling out now and the production is going to, I don’t know what’s happening there.</td>
</tr>
<tr>
<td>Randy</td>
<td>It was like it broke... is that what that is? A break in the membrane?... It’s releasing everything outside.</td>
</tr>
<tr>
<td>Rashad</td>
<td>Maybe like a dam?</td>
</tr>
<tr>
<td>Raul</td>
<td>It’s like severing the thylakoid membrane, sort of.</td>
</tr>
</tbody>
</table>

Illustrative case. A look at Charles’ procedural habits as an exemplary case illustrates the processes good thinkers use to complete a task. Evidence for Charles’ good metacognitive skills and the pleasure he derives from learning is presented next in narrative form from both the Phase 1 and Phase 2 interviews.

Gleaning clues. Charles’ Phase 2 interview took place immediately following his class exam that included photosynthesis. Before beginning the tasks he admitted that although he probably made an A on the exam, he felt he “didn’t know it as well as [he] should have.” Although he knows that “if you’re a good test-taker, and with everything else being equal with the other student, you’re going to do better,” he also admits that, “being a good test-taker will not make up for not knowing something.” He believes his test-taking skills play a large part in his success. It was surprising
then to witness in the item sorting task that he did not venture a guess when he really
did not know whether the celery he was holding was undergoing cellular respiration at
that moment. There was no grade at stake, nor were there internal cues he could
exploit as he would on an exam.

Figure 11. Typology of graphic decoding gaps.

Later when using the simulation Charles applied his test-taking savvy to
predict whether blocking electron transport would increase or decrease oxygen
production. He originally wanted to predict “no change” but inferred the information
he was missing (whether water splitting is coupled to electron transport) by the fact
that “no change” was not a choice. He eventually chose the correct response,
“decrease,” by studying what was implied by the choices that were available. From
that he bridged his own gap and concluded that water splitting must be coupled with
electron transport. Other participants who chose “no change” did not consider that the
reason that “no change” was not a choice was because it was not correct.
Acknowledging limits of generalizations. In Phase 1’s term sorting task Charles recognized that photosynthesis is “when green plants, I don’t know if others do it too, it’s what makes them autotrophs.” He showed that during processing he recognizes the possible limits of his generalization that only green plants undergo photosynthesis. In this task he also spontaneously connected terms with photosynthesis although they were not necessarily identified with photosynthesis: “Visible light is the small part of the spectrum that we can see with the naked eye—which is the electromagnetic spectrum. It applies to, it’s necessary for the light reactions to occur.” During co-concept mapping of the terms, he verbalized when he recognized sets of concepts that were and were not exclusively in the domain of photosynthesis:

Charles: I’d say that [this group] is...structures particular to photosynthesis [chlorophyll, stomata] whereas all of this stuff is not necessarily having to do with photosynthesis but used in photosynthesis [glucose, oxygen, protons, ATP, water].

He eventually labeled these groups as “unique” and “not unique” to photosynthesis.

He said the latter group “[doesn’t] necessarily imply photosynthesis.” In another Phase 2 simulation task Charles was asked to name the compounds besides oxygen produced in the light reactions. His first impulse was to write NADPH (which is correct) but hesitated until he asked if NADPH is considered a compound. In most introductory biology courses the term “molecules” is used more often than “compounds.” This showed that he checks the limits of what terms mean in the context they are used.
Putting isolated observations in a context. When explaining the leaf window, he spontaneously placed the leaf in a larger context of the real world when he stated “hmm, it looks like H₂O coming in, through the leaf stem that’s connected to the tree, and O₂ is coming off...” Later in other Phase 1 tasks he spontaneously summarized, drew conclusions, and attended to his own missing information without prompting from the researcher: “I didn’t notice if it [carbon dioxide] was coming from the outside of the leaf or if it was coming from within the process.”

Attending to what’s missing. When asked how Spanish Moss gets what it needs for photosynthesis, Charles was testing a new proposition that it could get moisture from the air. But he recalled from the Phase 1 interview’s simulation that “background water never did make any difference when we changed it,” a memory which affected his decision-making. He and other high ability participants showed the ability to recall specific instances or hold them in working memory so they could check their emerging propositions against them. He also had a keen awareness of which proposition he was missing when he could go no further, in this case during co-concept mapping. A simple answer to his question seemed to open a floodgate of synthesis in his conceptual framework. It is also possible this missing propositional gap represented an “arch” or “strongback” placeholder at the base of an otherwise rich conceptual framework, as discussed previously.

Charles  Can I ask you a question? I can ask [even if you won’t answer]. Is that what H goes through [pointing to CF1 ATPase]?
Researcher  Uh huh.
Charles  OK, so when it’s stepped down in energy, it’s releasing energy, and letting hydrogens through, and this lets them go back across the gradient, and the energy when they go back across, turns
ADP into ATP, and that powers the Calvin cycle which occurs in the stroma and makes the sugars.

Seeking satisfaction. Upon encountering the mechanism window for the first time, Charles showed his pleasure at the challenging complexity of the events portrayed in it: “That’s what I like to see.” He changed his posture to get closer to the screen. He also temporarily ignored the researcher as he became engaged in decoding the graphic for information he was craving. This showed a visceral satisfaction in the challenge, possibly in anticipation of a familiar reward he receives when learning something meaningfully. His tone prior to this experience was that of a skeptical participant who might not have had high hopes for learning from participating in this study. After encountering the mechanism window his subtle body language and comments showed he was less skeptical and more enthusiastic about the possible learning applications of the simulation. For example when shown the radiolabeling feature he enthusiastically wished aloud that “it would be kind of nice if it could have two labels” so that one could simultaneously watch oxygen and sugar labels move through molecules downstream in the process. Once he was engaged in the mechanism window, Charles said, “I wish I could go back and see what a healthy one looked like” (in the mechanism window). In so doing he indicated that he keeps his recent experiences with the simulation in working memory for comparison, a part of pattern-seeking behavior.

Several times in Phase 2 Charles showed his pleasure in making big connections. Charles snickered with a pleased grin when he was reminded (on the simulation) that, on the test he had just taken, he had been able to recognize that
proton flow through the ATPase was an example of facilitated diffusion. This question required integration with a topic taught earlier in the semester. Later in the interview he derived pleasure from following a line of Socratic questioning related to the global carbon cycle to the point of becoming aware of some big connections.

Researcher Where do you think the carbon in this plastic [table top] came from?
Charles Probably fossil fuel.
Researcher And where do you think that carbon came from?
Charles Plants.
Researcher And where did they get the carbon?
Charles CO₂.
Researcher So do you think every organic molecule on the face of the earth was once in G3P?
Charles Oh sure, now [I do].
Researcher So is photosynthesis important?
Charles [laughs] yeah.
Researcher I just love to do that to premed [ical students who think photosynthesis is not important].
Charles I'm thinking of picking up a biology area of concentration.
Researcher You mean for your...
Charles Chemistry.
Researcher You mean straight chemistry?
Charles Chemical engineering. I want to teach, and I need to know how many hours you have to have in something before you can teach it.

Procedural habits. In this section several kinds of habits of mind evident in the participants' verbalizations will be discussed. The habits themselves are in and of themselves neither beneficial nor detrimental since in some cases a habit led to a better solution to the task, and in others it did not.
Reliance on prior knowledge. It was no surprise that all participants showed the tendency to refer to prior knowledge when faced with a new problem. This was observed in several ways: reliance on anchor propositions, influence by life experiences, and retrieval of similar schemas.

Some participants showed a tendency to rely on "anchor" propositions, or trustworthy propositions learned in their classes that they recalled readily and which were for some reason vivid in their memories. It was not always obvious why some of these anchors were so vivid. On more than one occasion Rhyan made apparent reference to a statement made by Dr. Reese in his lecture on biomolecules when discussing lipids. Afterward, Rhyan used this proposition in Phase 1 to identify carotenoids in the term-sorting task.

Rhyan  Carotenoids, those are lipids that give color to certain things, such as carotene is a carotenoid. It gives orange in carrots and flamingos it gives a pink color.
Rhyen also had an anchor proposition about the order in which electrons entered the photosystems. The numerical naming of the photosystems is a historical artifact: electrons move through photosystem 2 before photosystem 1. Since on the surface this is contrary to logic, its novelty made this memorable proposition an anchor for Rhyen: “I know that photosystem 2 in the book is in front of photosystem 1. I was wondering why that was...”

Rashad referred to ATP on multiple occasions throughout both interviews, as if its role as an energy molecule was central to his conceptual framework in multiple contexts. It thus served as an anchor proposition for him. Cheryl’s anchor proposition about ATP was evident when she compared ATP’s apparent role in the Calvin cycle with what she meaningfully learned from a college level biology workbook in which ATP’s role in linking anabolic and catabolic processes was represented graphically.

When explaining water intake from the roots, Rhea recalled that hydrogen bonds played a role in this process. Cheryl and Rhyen readily transferred their chemistry understanding to many of the tasks. For example Cheryl recognized equilibrium in the simulation: “...And it always gets constant after a while too. We’re on equilibrium right now in chemistry, so I [notice that stuff].” In the Phase 1 interview, Rhyen, who had already completed both semesters of organic chemistry, did not recognize what glyceraldehyde-3-phosphate’s role was in photosynthesis, but he predicted its structure based on nomenclature. He also correctly applied his knowledge of redox (oxidation and reduction) to photosynthesis.

It was interesting to note instances in which participants’ responses seemed to have been influenced by their life experiences. As mentioned previously in the
discussion of role of water gaps, Rhyán and Raul made slightly different choices when maximizing photosynthesis rate that reflected their academic backgrounds. While Raul, the physics major, spent extra time trying to optimize water input stoichiometrically (to “cut costs”), Rhyán allowed the maximum water input to make sure it was in excess, probably because water is a cheap resource from an engineering and manufacturing perspective. In addition, Rhyán revealed his process manufacturing viewpoint when he explained his predictions in “The Electrons” simulation task.

Rhyán: If flow of electrons were blocked, I’m wondering if everything else wouldn’t be blocked somehow too, or if it’s just like the flow blocked right here. And if that’s the case, if everything else would be staying the same, that would decrease too, because the reason I’m saying the ATP would decrease too is that NADPH has a part in this cycle here [Calvin], and if electrons were blocked here, it will block off production of NADPH, which this cycle [Calvin] uses to produce ADP. And it seems like the ADP, if this were to shut down or slow down [NADPH cycle], the production [by] this [ATP cycle] would slow down which in turn would slow down the production of the ATP.

Rhyán’s was the most thorough explanation offered by a participant for why blocking electron transport will affect NADPH and ATP production. The interchange above was also provided in the discussion of coupling gaps.

Carlos: Most produce is still alive, like herbs and stuff.
Researcher: What about a potato?
Carlos: Yeah, a potato is still alive.
Another life experience apparently influenced Charles when he said that carbon dioxide entering the Calvin cycle is “going on a golf tour.” In Phase 2 Cathy, the cheerleader, was asked what might happen to a G3P sugar molecule when it arrives in one of her cells from the food she eats. “Could it make lactic acid?” she suggested, since she is familiar with the burn due to this product of anaerobic respiration in animal muscle. Some participants referenced conversations with peers when remembering propositions relevant to the task at hand. Cheryl recalled that organic chemistry was based on carbon because of her friend’s comments.

Cheryl [My friend] just says ‘I took a whole year learning about carbon. You get sick of carbon after a while.’ So that’s what I think of when I think about ‘organic’ because I’ve never learned a whole lot about it.

Similarly Raul remembered conversations with an old girlfriend that taught him that nitrogen fixation was carried out by soil or root bacteria, and provided nutrients to plants. One of the few concepts in photosynthesis that Raul understood was active transport, which may be attributable to a physics professor’s work he admired that applied physics to understanding membrane pumps and channels. On the other hand, hearsay did not serve him well when he remembered learning as a second grader that “Spanish Moss suffocates trees.” A humorous moment came in Phase 2
when, upon being reminded that plants take up oxygen from the air at night, he
recalled a movie that addressed this.

Raul There's a scene in the movie ['Secret of my Success'] where Michael
J. Fox just chauffeured the boss' wife home [ ]. And she's
commenting how she doesn't like all the trees around the mansion
because they suck up all the oxygen. So actually he tells her [],
'actually they make the oxygen.' And then she said, 'Oh really,'
eactly the way you just said it.

Retrieval. As participants verbalized during tasks, several observations were
made that may shed light on the strategies students use to retrieve information from
memory. One observation was that most of the participants from Dr. Corey's section
who knew the light reactions well seemed to retrieve these propositions for the
concept map temporally, or in the order in which the steps are thought to occur in
time. In fact, before the participants were asked to make relationships in the map,
they were first asked to sort the terms in the set into "those related to the light
reactions." "those related to the dark reactions," "those related to both," and "those
related to neither." Upon doing so it was evident that some participants were mentally
going through the steps in order to sort the terms. Cheryl even commented that it was
harder to sort them into light and dark reactions than to map them (temporally).

Another habit observed in Dr. Corey's students was the tendency to add extra
concept labels to their maps (Appendix H). Although the cyclic and noncyclic
pathways and the acceptor molecules of the electron transport chain were not included
in the set of seed concepts, most of Dr. Corey's students added them in. It seemed
that these details helped their temporal retrieval of their light reactions schemas.
Without the details they may not have been able to link distant concepts in which these intermediate molecules’ and processes’ roles were not explicit.

Charles was the only student from Dr. Corey’s section whose understanding of photosynthesis did not come directly from studying in class. During his map construction he did not temporally reconstruct the set of events. As a high-ability student he has honed his test-taking and other processing skills in a way that he learns in class only what he feels he needs to do well. These skills allow him to find and integrate all cues provided by careful reading of text or decoding of graphics and to keep recent conclusions in working memory for evaluation. His heavy dependence on cues was evident once when he was unable to draw a relationship between electron transport and ATP synthesis. He was attempting to understand a graphic in the simulation that oversimplified chemiosmosis by showing only the source of protons from the splitting of water, when in fact electron transport uses energy from light to pump protons into the thylakoid space as well.

Researcher Had you made that connection before the test?
Charles Yes.
Researcher You did, but you just weren’t thinking under those terms?
Charles Right, because they were...using different representations?
Researcher Very different.
Researcher [ ] By them simplifying, oversimplifying what happens in here, just brushing over it, it doesn’t give you the cues.
Charles You don’t realize why the hydrogen comes across.
Researcher Yeah, they make it look like it’s just from the splitting of water, but it’s the combination.

Another observation seems related to the anchor propositions. It appeared that during retrieval, participants showed preference for the construction in which they learned the concept(s) most meaningfully. Cathy referenced her image of the posters
she designed, Carlos and Caroline referred to the diagrams Dr. Corey drew in his lectures, and Cheryl referenced the graphics she studied in her book and workbook. In the fabric model task she was holding the model but she did not refer to it to answer the questions about where the components of the process took place. She showed a strong preference for her own construction. When trying to solve a task, Rhyan said, "I’m [mentally] going back to my notes.” Chanda was one of the few who said that she thought about the simulation she worked with in Phase 1 when she was learning about photosynthesis in class. Perhaps this is because she learned meaningfully during the Phase 1 interview. None of the participants from Dr. Reese’s section showed evidence of a particular experience they referenced during retrieval, probably because there was relatively less emphasis on photosynthesis in his lectures.

The most common and perhaps most significant retrieval error was participants responding in tasks as if the questions were about cellular respiration instead of photosynthesis. This misretrieval is not unexpected since the same biochemical themes play roles in both processes, and it is more likely that cellular respiration was taught to them in high school than photosynthesis. As discussed previously in the graphic decoding gaps section, this schema misretrieval was exacerbated by other features of photosynthesis, and the graphic representation of it in the simulation. Table 20 summarizes these types of errors.

Carlos in his Phase 2 interview was especially prone to misretrieval of the respiration schema, which accounted for 10 of the 35 errors documented. Some participants were quickly aware of their misretrieval and self-corrected. Several commented specifically on their confusion.
Rhea  ...Wait! I think I’m thinking of respiration.

Charles  I’m getting it confused with respiration.

Rashad  That’s one of the most confusing things about a lot of this is that a lot of things seem similar to me in cellular respiration.

Table 20. Summary of propositions misretrieved from respiration schema.

<table>
<thead>
<tr>
<th>Error</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Photosynthesis</strong></td>
<td></td>
</tr>
<tr>
<td>Oxygen is required</td>
<td>11</td>
</tr>
<tr>
<td>Carbon dioxide is produced</td>
<td>6</td>
</tr>
<tr>
<td>ATP is a product of the Calvin cycle</td>
<td>3</td>
</tr>
<tr>
<td>Sugar is required</td>
<td>1</td>
</tr>
<tr>
<td>Thylakoids are in the mitochondria</td>
<td>1</td>
</tr>
<tr>
<td>Three protons are pumped per ATP</td>
<td>1</td>
</tr>
<tr>
<td>Oxygen serves as a final electron acceptor</td>
<td>1</td>
</tr>
<tr>
<td>Protons are pumped between nine electron acceptors</td>
<td>1</td>
</tr>
<tr>
<td>Chlorophyll is in the mitochondrial matrix</td>
<td>1</td>
</tr>
<tr>
<td>Oxygen is the primary electron acceptor</td>
<td>1</td>
</tr>
<tr>
<td><strong>Respiration</strong></td>
<td></td>
</tr>
<tr>
<td>Oxygen is produced</td>
<td>1</td>
</tr>
<tr>
<td>Sugar is produced</td>
<td>1</td>
</tr>
<tr>
<td>Calvin cycle is in respiration</td>
<td>1</td>
</tr>
<tr>
<td><strong>General</strong></td>
<td></td>
</tr>
<tr>
<td>Calvin cycle confused for Krebs cycle</td>
<td>4</td>
</tr>
<tr>
<td>“Photosynthetic respiration”</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

Proposition generation and evaluation. All participants were observed generating propositions in an attempt to link the concept under consideration to their prior knowledge. In a pilot study it appeared that the participant constructed a temporary schema for the purpose of completing the task (e.g., exam or diagnostic instrument), and the student seems to construct it with the requirement that it be
internally consistent (Griffard & Wandersee, 1999b). They use available clues internal to the instrument to supplement their understanding. While participants in this study were not directly observed constructing temporary schemas, they generated propositions in order to complete the tasks. They would then test the propositions later in other contexts, but sometimes forgot their tentative conclusions. This was evident in three kinds of observations: Recidivism (i.e., rapid forgetting of earlier conclusions); Etymological approach as a default, and Reaching when they had no helpful propositions to draw from. Even when participants generated propositions they accepted previously that would help them in a future task, they exhibited cognitive recidivism when they “fell off the wagon” and fell back on older, “anchor” propositions they relied on more readily regardless of their correctness in the context. It seemed as though newly generated propositions were conceptually linked only to the situation in which they formed, or that insufficient time or experience prevented indexing that could be used during elicitation. In the photosynthetic item-sorting task Rhyan had concluded that Spanish Moss undergoes photosynthesis. However when asked later about it he couldn't recall whether Spanish Moss was a plant or a fungus, although in the previous interview he was clear that fungi do not undergo photosynthesis. So he apparently forgot the propositions he accepted earlier.

The following long passage shows how rapidly a “told” proposition is forgotten. After Rashad had correctly explained several features of cellular respiration, he was asked about the fate of the photosynthetic sugar, and he correctly predicted the events of respiration. However he could not label that process \textit{respiration} even after the word was provided for him. This was in spite of his
apparently good grasp of the possible fates of the sugar. This is also an example of a
respiration gap discussed above in conceptual distance gaps.

Researcher: What’s going to happen to that G3P that just got made?
Rashad: The sugar?
Researcher: Yeah.
Rashad: The sugar can be either used by a person like me, like as a
source of energy [ ]. Sugar could also be, I guess you can build
on it, you can make bigger sugars.
Researcher: Like?
Rashad: Like, I think sucrose is glucose and fructose [correct]. You can
also break that sugar down if you want.
Researcher: What do you mean by break down?
Rashad: Uh, catabolism.
Researcher: Catabolism, but cellular respiration? [Here he is being led so
that the gap can be investigated]
Rashad: Cellular respiration.
Researcher: Can break down sugars?
Rashad: Uh huh.
Researcher: OK, so where is the C going to end up, that C with the ink on it
that’s part of the 3-carbon sugar there? It’s just going to jump
into cellular respiration? Where’s the C going to end up?
Rashad: If I eat it I’m going to end up breathing it out.
Researcher: In the form of?
Rashad: Uh, in the form of a gas. [ ] I can probably break down
something like glucose.
Researcher: In what process?
Rashad: In photosynthesis I believe the equation is C6H12O6 plus light
energy plus 6 water.
Researcher: So photosynthesis uses glucose, or makes it?
Rashad: Uses it, no makes it, makes sugars.
Researcher: And what breaks it down? What reaction has glucose on the
left side of the equation?
Rashad: On the left side....
Researcher: Like you were just saying it.
Rashad: It’s on the tip of my tongue, I just don’t know it.
Researcher: ...Cellular respiration.

Although Rashad accepted the proposition that what he was describing was cellular
respiration, he quickly forgot it, indicating that such “told propositions” typical in
classroom lectures are only weakly incorporated into their schemas at best.
Even after being corrected so that simple icon decoding gaps would not stand in the way of collecting other data, some participants still reverted to their incorrect decoding. After being corrected that the circle in the water input meter represented a radiolabel and not oxygen, Carlos and Chanda continued to make this error in the Phase 1 interview. Carlos also continued to assume the oxygen input into the Calvin cycle represented a necessary requirement of oxygen for the process rather than the detrimental side reaction of photorespiration that it is.

When confronted with a new word, most participants took an etymological approach to proposition generation. This seemed to be a default approach tried when no viable propositions could be retrieved to help them. Some had an even more shallow default setting that was echoic rather than etymological. Words that sound the same very often misled the participant into the wrong schema. The most common retrieval error was mistaking stoma and stroma. Another was Rhyan thinking about the concept for anabolic when the target concept was anaerobic. Raul, the physics major, relied heavily on etymological clues when generating propositions, especially when trying to reach for the meaning of unfamiliar terms in the term-sorting tasks. In almost all cases he did not have enough background propositional knowledge for his strategy to help him.

Raul: Chemiosmosis—I recognize the words and root words, but I can’t think of what it would be exactly. Osmosis having something to do with chemicals.

In contrast, when trying to get clues about the set membership of abbreviated terms (e.g., NADPH, ATP), some participants were helped when they were given the extended names. Raul was able to identify rubisco as a protein upon being told it is an
abbreviation for ribulose bisphosphate carboxylase. He said, “that’s the standard, to call enzymes ‘-ases’.” and therefore placed rubisco in the protein category. Cheryl was one of the few to categorize ATP as a nucleic acid, which she realized upon extending the abbreviation: ATP is adenosine triphosphate.

Researcher Why did you put it under nucleic acid?
Cheryl I don’t know, that’s the first thing I think of, Adenine, it’s a nucleic acid, A, adenine.

Reaching was a habit witnessed when participants were pressed to generate a proposition when they lacked knowledge to do so. Reaching resulted in somewhat outlandish propositions that can only be attributed to generating a proposition on the spot to attempt to explain a phenomenon that had never been considered before then. Caroline suggested that Spanish Moss may be “part of the tree, and then branches off.” Chanda had never considered what a plant does with the sugar it produces when she generated the proposition that the sugars go into the shriveling cotyledons (on the bean plant present), in essence to produce new beans. With an opportunity to more carefully examine her proposition she should be able to realize that beans develop from fertilized eggs in flowers.

Sometimes the questioning led the researcher to propose implausible scenarios to which the participants would react. Caroline and Randy were among the most suggestible participants. When Caroline was asked whether the carbon in new DNA came from photosynthetic sugar or from a separate carbon fixation process, she believed the latter was possible. When Randy was asked whether sugar is excreted from the leaves as it appeared in the graphic, he not only accepted that it was possible, but then used the proposition as an anchor on two occasions in the next interview.
Randy: Now I'm thinking that either the plant reuses the sugars that it produces, or it disperses them into the ground as nutrients. You know, revitalizes.

Researcher: Which one do you think it is? Or do you think it could be both?

Randy: I think it could be both, but probably more so it's to revitalize the ground its roots are in, maybe.

Randy: OK, with the sugars it's replenishing the soil.

Regardless of the way the proposition was generated, when given the opportunity the participants followed that by testing his/her new proposition and evaluating whether to discard it or accept it (When this did not happen, participants were debriefed at the end so that the faulty conceptions were corrected). Sometimes evaluation was in the form of "test-driving" the proposition for a while in the context to see if it "worked." In Phase 2 Cheryl was trying out different ideas in the process of deciding to which category she should assign the term ATPase. After initially assigning the ATPase to the process category, a comment from the researcher prompted her to not only place it in the molecule category, but to further identify its biochemical composition as protein. This "test-drive" allowed her to confirm her decision when she realized that the channel [CF1] had an enzyme component [ATPase] and that enzymes are proteins as well.

Cheryl: It's a protein.

Researcher: Why do you say it's a protein?

Cheryl: Because it is. Proteins are what help move the particles [in] facilitated diffusion.

Researcher: So when you've got something in the membrane, those are all proteins?

Cheryl: Yes

Researcher: When you have a channel or a pump or something?

Cheryl: So your enzyme [ATPase part] would probably be a protein too.
Awareness and Self-Monitoring. Participants varied in their attention to available cues during the tasks. As discussed above, Charles is acutely aware of cues that may help his processing. On the other hand, Cathy often did not attend to helpful features of the simulation. In the simulation during the Phase 1 interview, she observed that the ideal temperature was twenty-five (25) degrees. She later stated that she remembered that the photosynthesis rate was higher in cold weather, indicating that she failed to notice the temperature was in Celsius. In a similar scenario she failed to notice that to grow tomatoes the photosynthetic rate had to be at least 60. From that she assumed that sixty was ideal and was frustrated when making adjustments to light and water, for example, brought the photosynthetic rate higher than sixty, and she assumed this would not produce a good tomato yield.

Evidence that participants were cognitively engaged in tasks at hand included noting when the participant’s speech or reading rate slowed (especially with fast-speaking Cheryl and Cathy) or when reading was punctuated with pauses (Randy) or passages were reread more slowly (Charles). In Charles’ case he reread when he realized he didn’t have enough information, as if in search of more embedded cues.

A hallmark of metacognition is monitoring of one’s learning. This self-monitoring took the form of summarizing, making conclusions, generating and checking propositions, and testing predictions without prompting from the researcher. Charles, Cheryl, Chanda and Rhea, all above-average students, showed specific instances in which they spontaneously summarized or verbalized conclusions as they went along to clarify their ideas for themselves. For example, after explaining the leaf window in Phase 2, Cheryl spontaneously summarized when she said, “so this one is
just saying that the water and carbon dioxide come in and the sugars and oxygen come out.”

Most participants were able to catch themselves as they made errors, and some were able to catch errors as they compared and reconciled new statements with statements made in other tasks. For example, Raul and Rhea seemed to have kept their previous decisions in working memory or were able to retrieve them for comparison. In the Phase 2 co-mapping task, Raul could not decide whether ATP was a reactant or a product in the Calvin cycle. Later in the interview after reading in the simulation that “the high energy and reducing agents ATP and NADPH are formed,” he said, “oops!” He then remembered at the end of the interview to amend his map. When deciding whether the egg had a living cell Rhea said, “Well this [egg] might [have a living cell], but that would contradict what I just did [when I said it was never living].”

Raul and Rashad had experiences in which the researcher’s line of questioning raised their awareness of their contradictions. Raul confronted his conflicting ideas when asked about whether Spanish Moss was undergoing photosynthesis, whereas Rashad accepted his inconsistency by shrugging off his earlier position.

Researcher  If I just plucked it off of a tree, fresh, and brought it in, do you think it would have cells undergoing photosynthesis?
Raul  I don’t even know if it has cells to undergo photosynthesis.
Researcher  So it may not even have cells?
Raul  No, it has cells.
Researcher  OK.
Raul  I’ve never heard of an organism larger than a virus that didn’t have cells [laughs].
Researcher  All of these have one living cell in them?
Rashad  Uh huh. One living cell. OK [reconsidering], I don’t think the bean has one living cell, or the acorn, or the peanut, or the egg, and neither this [Miracle-Gro™], but I do think the moss does.

Researcher  OK, so you had it in nonliving before, and now you’re going to put one living cell in it...?

Rashad  Yes.

Another metacognitive trait observed was wanting to know more about the criteria or expectations before completing the task. When asked to sort the items into living and nonliving, Rhyan asked, “as far as composition?”

Satisfaction and confidence monitoring. A reward for good cognitive habits, as seen with Charles previously, seems to be a giddy satisfaction in getting it right. Charles and others not only derive pleasure from learning, but monitor their pleasure as a gauge of their learning. Sighs (of relief) and smiles were also evidence of this.

Cheryl  Oh! So ATP has a correlation with the oxygen production rate which I didn’t know! I like!

A corollary of this is that Cheryl (and probably others) feels great discomfort when she doesn’t understand. as much as she feels satisfaction when she does.

Cheryl  When we [you and I] were talking about the molecules [in the term sort in Phase 1], remember how I said I didn’t know what those things were?

Researcher  Right, and it drove you crazy?

Cheryl  Yes!

Researcher  And was it a comfort when you found out what they were?

Cheryl  Yes, because I know they had to be there for some reason.

Cheryl’s anxiety and frustration about trying to understand photosynthesis in Phase 1 was at least as evident as her comfort in her understanding in Phase 2.

Confidence was an indicator many participants mentioned during tasks, although this was not always a reliable indicator since some participants, especially women, regularly expressed self-doubt regardless of the likelihood of correctness. At times
participants had uncertainty that they knew what “was wanted.” Several students (Chanda, Rhea, Rashad) assumed that the answers they were first inclined to provide couldn’t possibly be what was wanted; they assumed the correct response was more complex than that. In the Phase 1 simulation tasks, the simulation points out its graphic feature by telling the user to notice what happens when the light intensity is lowered. When the background turned dark, Rhea did not believe that was the observation they intended her to make.

Researcher  Did you see what happened to the air around the leaf when you raised the light?
Rhea  On the leaf?
Researcher  Undo what you just did. Do the slider down again. I don’t remember what the number was, but just pull it down. What happened?
Rhea  The only thing I noticed is it got darker [the intended observation].

Summary

The above results suggest numerous heretofore unrecognized gaps that exist in college biology students’ conceptual frameworks. A full emergent typology of these propositional gaps and processing gaps is presented in Figure 13. As discussed in this section, the gaps are related to each other in various ways. The think aloud interview tasks allowed both propositional and processing gaps to be detected as well as evidence of cognitive interplay between them. Cross-links could have been drawn in the typology to illustrate this interplay between the categories and subcategories, however they would have quickly made the graphic unreadable. The fourth level of gaps in the “gap map” is abbreviated relative to the individual micro-maps to provide a single illustrative example of each of the tertiary categories in order to anchor the
categories for the reader. The typology's implications for teaching and learning are discussed in the Conclusions.
Figure 13. Full typology of gaps found in this study
CONCLUSIONS AND RECOMMENDATIONS

Answering the Research Questions

The main research question addressed in this study was: What gaps in biochemical understanding are revealed by a range of university introductory biology students as they work through a critically acclaimed multimedia program on photosynthesis, and what are the corresponding implications for elaboration of the Ausubel-Novak-Gowin Learning Theory (Human Constructivism)? An underlying assumption of the entire study is that one’s knowledge can be viewed as a conceptual framework that is a hierarchical semantic network of interrelated propositions.

This study looked for gaps in 12 students’ conceptual frameworks for photosynthesis as well as studied the processing habits that they engaged in during task completion that externalized these conceptual frameworks. Since a richly integrated conceptual framework is a characteristic of expertise, the gaps uncovered in this study should not necessarily be considered personal deficiencies. Rather they simply represent a set of missing propositions in typical students at this level that should be considered in instruction. This study begins to raise awareness of these gaps, which will allow professors to help their students progress from nominal to multidimensional literacy. But these findings also contribute to what is known about how one’s personal knowledge grows with increasing expertise or literacy. The subquestions of the main question are answered next.

The first question was: What gaps in biochemical understanding can think-aloud protocols, videotaped program-path analyses, and pre- and postinstruction
Clinical interviews uncover as these college students work through an acclaimed multimedia program on photosynthesis? Clinical interviews using a computer simulation and other tasks revealed numerous gaps in the participants’ conceptual frameworks for photosynthesis, as discussed in the Results. Sorting tasks, co-constructed concept maps, and explanations provided additional instantiations of gaps and the habits learners engage in during processing. The subquestion related to the first was: Can a typology of the emergent biochemical gaps be constructed? Evidence of gaps was identified in multiple passes through the interview protocols and indexed into an emergent typology using NUD.IST™. The gaps identified in videotaped verbalizations during the tasks were categorized over numerous iterations until the typology (the "gap map") shown in Figure 13 was developed. There were multiple levels of organization in the hierarchy proposed, though four are shown in Figure 13.

In the typology the gaps were broadly categorized as propositional gaps and processing gaps. Four categories of propositional gaps were identified. Three of these were categorized on the basis of whether the gap existed at the level of the concept, proposition, or construct, which are three levels of organization of conceptual frameworks. Conceptual gaps describe cases of incomplete development of a concept, and include discrimination gaps (inability to distinguish meaning of two concepts) and set membership gaps (inability to identify to which category a concept belongs, such as a process or a molecule). Linking gaps describe cases where a proposition has failed to form due to a missing link between two concepts, and these may be between conceptually close concepts (simple missing link gaps) or conceptually distant
concepts (conceptual distance gaps). Gaps in biochemical constructs describe underdeveloped abstract understanding of major constructs that underlie biochemistry understanding, such as continuity of matter and thermodynamics.

The fourth category of propositional gaps, naivete gaps, includes missing propositions about conventions and relative significance that are bridged with experience in the discipline. It could be argued that all gaps can be due to naivete in the discipline since knowing what to encode about a concept or link is learned cumulatively with immersion in a discipline. However the role of naivete was clearest when gaps were evident in the students' understanding of the relative significance of propositions or the meaning of synonyms, and were thus categorized separately.

It is important to note that several categories of propositional gaps described previously were predicted at the start of the study. They were theorized to exist based on the propositional view of knowledge organization. One of these categories, the simple missing link gaps, is important because although it was theorized to exist, there was not a lot of empirical support for it in the secondary data. A methodological constraint that may have hindered finding interesting simple missing links was that it was the participants with good understanding of photosynthesis who provided the most data for the entire study. Simple missing links were not evident in those with poor understanding because holes were difficult to detect and isolate in a jumble of confused propositions. The fact that few simple missing links were found among the ones with good understanding could be due to them simply not having simple missing links.
However this researcher prefers an alternative explanation: that meaningful learning provides for placeholders when simple links are missing, and these placeholders, like architectural arches and strongbacks, allow for superordinate knowledge construction around the gap. This would also make these simple missing link gaps more difficult to witness directly. Therefore this gap map itself has a gap. The theory would predict this category but data to support it were not strong. This is not unlike the chemist Mendeleev who, when constructing the periodic table based on then-current atomic theory (1869), left gaps in it until the missing elements were discovered.

The major category of processing gaps was graphic decoding gaps. Because participants made numerous errors in decoding representations (e.g., icons in the simulation) and orienting themselves in the windows, it is apparent that their graphic literacy skills (and probably those of most undergraduate science students) could be significantly improved with explicit attention to developing their graphic literacy during their education. Several participants’ inability to mentally orient the image to scale in space and time was noted, especially when they were asked or expected to mentally nest or jump across frames of reference. Other graphic decoding gaps were in their ability to infer what was represented by a single representative icon for light, ATPase, and water, for example.

A close look at the thought processes of participants during these tasks revealed their relevant procedural habits and strategies. Metacognitive habits such as monitoring satisfaction, situating the problem in a context, and testing propositions...
generated were evident especially in above average students. These participants also
seemed to be better at “multi tasking,” or keeping numerous propositions or episodic
memories in working memory for simultaneous processing activities such as
comparison and evaluation, making them more likely to be aware of and reconcile
conflicting propositions they held. Another habit noted with participants at both
ability levels was a tendency to spontaneously and preferentially refer to particular
propositions. Understanding how these “anchor propositions” come to earn a central
place in the learner’s framework could lead to improvements on current theories about
conceptual change.

Another question asked in this study was: Do the gaps identified correspond
with instruction? The participants were recruited from two different sections of the
same course. The data in Tables 7, 11, 14, 15 and 19 indicate that the participants
from Dr. Corey’s section had a much better understanding of photosynthesis as
evidenced by fewer propositional gaps seen in their concept maps, their predictions, or
the depth of the questioning that was possible with them. On the whole Dr. Corey’s
students’ postinstruction literacy levels (scored from their concept maps) were higher
(Table 7). All participants from his section were engaged in all of the tasks, spent
more time in the interviews, and followed the lines of questioning intently. In this
researcher’s opinion, this is evidence that the instruction delivered by Dr. Corey
predisposed them to such engagement. He spent more time on the topic, he attended
to how students learn, and he was able to weave earlier learned information into the
topic under study. He also had a more engaging style and challenged students in class
and on exams by expecting them to bridge conceptual distance gaps. Since his challenging exams direct his students' learning to a higher level, this is probably a case of "the (assessment) tail that wags the (learning) dog."

It is possible that Dr. Reese has a belief that he has little control over student learning, therefore spending extra time on each of the topics is not justified. It seemed that he moved through the basic concepts to get them out of the way, possibly in order to address more interesting, rich topics for him to teach, such as those related to his research. Since the researcher did not attend lectures after those on photosynthesis, she cannot rule out that Dr. Reese consciously integrated these basic concepts when teaching about a more complex biological process. There were no trends noted with regard to graphic decoding gaps between the sections, although in this researcher's opinion Dr. Corey did use graphics more effectively in lecture to orient the students to his frame of reference.

In spite of the above comments, it is not justified to say unequivocally that the participants' disparate performance on the interview tasks was due to instruction. First of all, several participants from Dr. Reese's section were somewhat atypical. For example, this was Rashad's third time to take the course, and Rhonda's and Raul's GPAs were poor indicators of their literacy levels. Another factor that diminishes the differences between the instructors is the timing of instruction relative to the interviews. In Dr. Corey's section photosynthesis was taught immediately before the Phase 2 interviews, which in turn took place immediately before the course exam on photosynthesis. In contrast, in Dr. Reese's section, photosynthesis was the first topic
to be taught among those tested on the second course exam. For these participants the motivation to use the clinical interview as a check on their knowledge before the exam was not as great. Meaningful learning has a longer "shelf-life" than rote memorization, so if the disparate performance of the students from the two sections was indeed due to the time lag then this could indicate that Dr. Reese's students did not learn photosynthesis meaningfully. This could be at the root of Dr. Reese's students' lower level of engagement in the tasks as well.

The final question posed at the start of this study was: If such a typology can be constructed, how can it be integrated with ANG learning theory? The lens through which the data generated in this study were analyzed was that of the Human Constructivist view of ANG learning theory (Mintzes et al., 1997; Mintzes & Wandersee, 1998). As discussed earlier, this theory explains that learning is the result of meaningful incorporation of new concepts and propositions into an existing framework of hierarchical, interconnected propositions between concepts. and that prior knowledge figures significantly in the construction of these frameworks.

The findings of this study support the theory in several ways. First, all students consulted their prior knowledge either intentionally or implicitly when completing these cognitive tasks. It was interesting that some propositions were favored over others (i.e., preferentially retrieved). Those they learned meaningfully (processed more deeply) in the recent or even distant past were more readily elicited than those they were told or those they accepted for themselves earlier in the very same interview. The preferred anchor propositions were relied upon over others,
regardless of correctness. Another way participants relied on prior knowledge was in making decisions apparently influenced by their life experiences with jobs and friends.

Second, the alternative conceptions movement in part influenced by ANG learning theory during the 1980's generated a rich literature base on the ways natural phenomena are misunderstood. The findings here show that some of what appear to be "prescientific conceptions" in the literature may at least in part be due to missing propositions (gaps) in learners' conceptual frameworks. The instruments used in many of those studies diagnosed alternative conceptions as robust errant frameworks, whereas these clinical interviews were able to detect and isolate specific erroneous or missing propositions (or gaps) that exist in the participants' conceptual frameworks. These gaps could cause them to respond incorrectly to items on a traditional diagnostic instrument or even in a short clinical interview designed *a priori* such as those relied upon during that era.

Third, another aspect of the theory is that meaningful learning is significantly enhanced by metacognition, or learning about one's learning. Metacognitive habits were very evident among the meaningful learners in this study. It also seemed that "zooming in" on just the part of the construct needed to complete tasks was less difficult for those with good metacognitive skills. Regardless of their academic ability the participants also seemed to have benefited from having to externalize their knowledge and make relationships explicit in mapping and other tasks. It seemed that this was the first experience most had had verbalizing their thinking. Their authentic engagement in interview tasks and Socratic questioning provided them with
experiences and satisfaction that they may refer to as they develop their metacognitive
skills further: they have learned what it feels like to learn, and it feels good. The
results gave evidence of a visceral satisfaction when making connections during
meaningful learning. This is another feature of meaningful learning that has not been
studied to a great degree.

Fourth, an outcome of the ANG learning theory-driven research tradition has
been the development of graphic organizers such as concept maps, concept circles and
Vee diagrams. This study used concept maps as a way for participants to represent
their knowledge, and used other representations (e.g., simulation graphics, fabric
model) as cognitive probes. The value of graphic organizers like concept maps is well
documented, however it has been shown that their value to learning and research lies
in the skill level and experience of the mapper. This study benefited from using co­
constructed concept maps to overcome this limitation, and this application of concept
mapping served this research purpose very well.

Because of its identification with such graphic organizers, it seems natural that
ANG theory be expanded to fully address other issues related to visual aspects of
cognition. A valuable visual referent that was well-exploited in this study was the
fabric model of the chloroplast that the participants could manipulate in order to gain
orientation and notions of nestedness. This is another representational form that has
not been widely exploited to date at this level although the data reported in this study
indicate a need for such visual orientation tools.
Another aspect of visual cognition that has not been directly incorporated into current learning theory is the role of graphic representation. Although use of graphic representation in life science instruction is ubiquitous, the data presented here indicate there are serious gaps in learners' ability to decode them effectively. The assumption that proper decoding and orientation is an automatized procedural skill among college students seems to be widespread, but it is contradicted by the data presented here. ANG learning theory can be expanded to explain how learners use graphics and models during knowledge construction.

Fifth. ANG learning theory is identified with the reception learning paradigm which values carefully crafted instruction over pure discovery learning in the construction of new knowledge. Since the phenomenon of photosynthesis is understood to a much greater degree than is possible to convey with discovery learning approaches alone, this researcher is convinced that for college level instruction in this topic, the balance is tipped in favor of the reception paradigm. Observations in this study support this as well. For example, some participants tended to incorporate extra details sequentially and logically into the “story” they told as they mapped. This seemed to make it easier for them (especially those from Dr. Corey’s section) to recall the events and players in photosynthesis. In addition, an above average participant’s (Charles’) effort to understand a schematic diagram in the simulation was stymied because it lacked cues he was seeking. These indicate that “dumbing down” (providing fewer details) hinders learning since doing so omits cues and relevance. A reasonable amount of detail, presented logically and in sequence, seems to make it
easier to remember propositions, just as story-like mnemonic techniques use details to make lists, for example, easier to recall. This may also be at play behind successful interventions based in situated cognition (e.g., Jasper Woodbury Project, (Bruer, 1993)).

In addition, proponents of discovery learning historically have paid more attention to cognitive processing (critical thinking skills) than to the knowledge framework that results from it. This study did make note of such processing habits in order to understand how the participants accessed and used knowledge from their conceptual frameworks. The findings of this study support the notion that thinking is the set of meaning-making processes that necessarily consult, act upon, and modify propositional knowledge, but that thinking is not possible without knowledge to “think with.”

Discovery learning approaches do provide learners with propositions (e.g., blue light causes more bubbles to be produced than green light). So do “told propositions” that are often delivered in traditional lecture settings. How does a proposition earn a readily accessible position in a conceptual framework? In other words, which become anchor propositions? The former is more likely to do so unless the proposition is “told” in a way that is plausible, fruitful, and logically woven into a bigger picture. This can be accomplished through active classroom techniques (e.g., concept maps, discussion, case study). It appears that discovery learning (labs) as well as classroom active learning strategies both generate trustworthy propositions upon which more knowledge can be built. However the rate at which this new knowledge is
built in laboratory settings at the college level is too slow compared with what is possible with active classroom strategies. This leads this researcher to recommend that college level science laboratory classes should be committed to providing students with authentic inquiry experience: direct investigative experience with experimental and naturalistic approaches of the scientific method to study nature is preferred over confirmatory labs. Confirmatory experiences should be offered as demonstrations in lecture in order that propositions they offer are incorporated as anchor propositions.

Other Findings

The participants in this study were diverse with regard to gender, academic ability, career plans and ethnicity. The gap in metacognitive skills was the only one identified that seemed to correspond with academic ability. The graphic decoding gaps, conceptual distance gaps, and even continuity of matter gaps cut across ability. Another way that ability made a difference was in the depth of questioning that was possible during the interviews. All participants were pushed to the limit of their understanding until gaps were evident. The above average students revealed as many or more of the gaps than average students did because their rich conceptual frameworks and their awareness of their processing made these participants easier to study. This suggests first of all that everyone has gaps, and secondly that looking for them only in a sample of above average students could be justified in future research.

In addition, evidence of participants' gaps also varied because of their other psychosocial characteristics, such as how impulsive, suggestible, or extroverted they were. There was also variety in how much control they sought: Some wanted control
while others came to expect assistance, for example, in reinterpretation of the text-based instructions in the simulation tasks.

No trends were noted with regard to ethnicity, however one gender difference was obvious. In the clinical interviews all the women were concerned to some degree about the correctness of their responses and sought feedback from the researcher during the tasks. The men rarely sought feedback about their responses. This observation, combined with this researcher's experience in scientific research, suggests that the way women prefer to negotiate meaning is by direct interaction with others. One could speculate that this may be part of the reason fewer women choose science careers. It was probably a factor in this researcher's decision not to pursue a scientific research career. Gender differences alternatively may be explained by propensity for risk-taking in the interview setting.

One aspect of this study was the use of BSCS's biological literacy levels to denote the participants' levels of understanding of photosynthesis. BSCS has not set guidelines for what constitutes literacy within individual topics in biology, however they have set forth a framework, a rubric, which can be used by practitioners to evaluate learning. In this way the definitions of the literacy levels were useful in this study. The findings presented here indicate that some of the gaps found may be typical for various literacy levels. BSCS states that the third level, structural literacy, is a reasonable goal for college students, and that the fourth and highest level, multidimensional literacy is typical of experts in the field. This raises the question of how experts who were once college students progressed from structural to
multidimensional literacy. It would appear that without instruction that explicitly addresses gaps, propositions (e.g., conceptually distant propositions) that enrich one's "big picture" are bridged slowly through experience. Science professors, who are multidimensionally literate, have admitted this did not happen until they were instructors themselves. Since BSCS and the reform movement have a goal of literacy for all, how will the majority of students who will not have a future in science develop their "big picture?" This study suggests that attending to gaps in their propositional knowledge is called for rather than waiting for literacy to happen, and that the BSCS literacy model may be improved by such attention. Another improvement would be to understand the process by which one progresses to higher literacy levels. This will be difficult research to conduct since learning of propositions interacts with existing knowledge structure iteratively, and documenting every event of these iterations continues to be the challenge to educational psychology.

Limitations of the Study

This study was limited by assumptions built into its design. Among these assumptions is that the linked network view of a conceptual framework is valid. The schema view of knowledge organization is widely accepted among educational psychologists and experts on memory (Searleman & Herrmann, 1994) as well as science educators (Novak & Gowin, 1984). If this view prevails it is reasonable to study gaps in these schemas or conceptual frameworks.

Another assumption is that a gap can be studied in a clinical interview without bridging it. Upon tentatively identifying a gap, this researcher attempted to understand
the knowledge structure that circumscribed the gap. If a gap is an unconsidered or missing proposition, then an inherent problem is that the interview questions designed to probe this gap would call attention to it and perhaps prompt consideration of it. The alert mind is a natural meaning-maker, thus care was taken during data collection to look for relationships in the participant’s knowledge structure without suggesting any up front. Probing of their cognitive structure facilitated learning even though that was not an explicit goal of this research. It has been found that the mere act of self-explaining can enhance learning (Chi et al., 1994). Each line of questioning in the Phase 2 interviews was continued until it was clear that the limit of the participant’s understanding had been reached. The line of questions then continued in a Socratic way, and was expressly intended to draw their attention to the target concepts and constructs. Some participants responded eagerly to the opportunity to bridge their gaps and seemed to enjoy the intellectual stimulation of the activity (Rhyan, Cheryl, Charles, Chanda) and others were grateful for the clarification (Randy, Caroline, Cathy). Other participants seemed to perceive this extension of the questioning as fatiguing or tangential (Rhea, Rashad). Raul and Carlos accepted that the line of questions was part of the research, and Rhonda’s understanding was so limited that questioning was not extended beyond that planned in the interview guides.

A major assumption of this research was that meaningful learning generates a knowledge structure, and that the retrieval process during the clinical interviews does not hinder or distort it. Any method for studying conceptual structure requires that the research participant retrieve and externalize this knowledge, a process which is not
well understood and is still a subject of debate (Anderson, 1983; Anderson, 1997). The external representations of internal knowledge structure are the only access researchers have to knowledge structure. This consideration makes confidence in any findings contingent on a more widely accepted view of how humans retrieve information from memory. Although there are quantitative research methods in use to study knowledge structure (e.g., Pathfinder analysis), they may underestimate the modifying role that retrieval may play. For this reason the study described here did not incorporate such methods and instead relied on complex qualitative data resulting from interactions between researcher-participant and simulation-participant.

Although this idiographic study aimed to understand participants' knowledge on its own terms, the students' knowledge was compared with the target knowledge presented by their professors, the textbook, and with the knowledge of the researcher, herself an experienced instructor of college biology and former doctoral candidate in biochemistry. Therefore another assumption that may be a limitation of the study is that the researcher's own conceptual framework for photosynthesis is at least as scientifically accurate and integrated as a college introductory biology instructor's knowledge should be. In spite of general agreement between her personal understanding of photosynthesis and that of the professors and textbook writers, the data were necessarily evaluated from the researcher's point of view. It is recognized that what is valued in the meaningful learning of photosynthesis set forth in this study was likewise influenced by the researcher's background.
Implications for Future Research

The above findings suggest several lines of scholarly inquiry that could build on this study. If one's view of a conceptual framework is that of a linked hierarchy, then seeking, identifying, and categorizing gaps that exist in propositional knowledge of other science domains is in order. It would be important to study whether other categories emerge in those as well, with an ultimate goal of building a more comprehensive typology.

There may be value in future research directed at revealing whether gaps are at the root of some of the alternative conceptions documented in the literature. For example, the literature indicates that students believe plants get their food from the soil (Wandersee, 1983). Research could look into whether this alternative conception is due in part to a conceptual gap about how the meaning of "plant food" changes with context, and a relative significance gap due to undervaluing the role of minerals in plant nutrition.

There was some indication in this study that factors may influence the sequence in which propositions are accepted (and therefore which gaps are bridged). Understanding these factors can extend understanding of how biology knowledge grows (Abrams & Wandersee, 1995), and supplement what has been proposed about viability of propositions in one's "conceptual landscape" and how knowledge is restructured over time (Strike & Posner, 1992; Pearsall, Skipper, & Mintzes, 1997). It may be that one constructs knowledge by first seeking anchor propositions from her/his framework which s/he trusts. These anchor propositions may then serve as
nucleation sites for new knowledge construction. The participants in this study showed trust of the accuracy of the simulation graphics and any text before them. Therefore "told" propositions offered by authority figures (researcher, professors, textbooks) are trusted, but may not be memorable enough to serve as anchors. Future research can be directed to further understand how propositions become favored over others as one's personal knowledge grows. In particular, the roles that anchor propositions and trustworthiness of propositions play is in need of more exploration. Also the role that graphics and examples play in qualifying a proposition to be an anchor could be investigated.

The findings of this study about varied levels of metacognitive development could be further explored with a longitudinal study of several learners' metacognitive skills, and which subskills or habits develop in which order. Findings about satisfaction monitoring in this and another study (Griffard & Wandersee, 1999a) suggest a connection between visceral reward and meaningful learning. Both suggest that satisfaction may be an important motivating factor that enhances metacognition. A systematic look at how satisfaction with one's understanding affects the quality of learning that results seems in order. A corollary is that attending to discomfort or anxiety about one's understanding may serve as a metacognitive monitor as well.

This study indicated a need to better understand how learners develop graphic literacy skills. This could be done by studying a cross-age or cross-literacy samples of learners using classic life science-related graphics. Additional research could be directed at how instructors use graphics effectively to enhance learning of declarative
content knowledge and procedural graphic literacy skills. Many of the faulty assumptions the participants made (e.g., decoding icons) were defensible given their prior knowledge. These problems indicate a need for research into graphic integrity in instructional artwork (e.g., textbooks, computer simulations, 3-D models). Such findings may prompt adopters of textbooks to hold publishers accountable via the market for the instructional value of their designs. However, this study identified some shortcomings in the photosynthesis simulation that are due to inevitable constraints of graphic design. Thus students must rely on their own agency (Brown, 1988) in using graphic representations, and research into how they learn these skills would advance what little is known about development of science graphic literacy.

In contrast to the “less is more” mantra dominating science education today, given what was noticed in this study about the value of details in making a “story” more memorable, future research could look more closely at whether details improve understanding. If so, one could postulate that the value of many effective instructional interventions (e.g., direct lab experiences, computer simulations, metacognitive organizers, theatric analogy (Griffard & Wandersee, 1995)) lies in their ability to make the propositions more memorable. credible or plausible so that the propositions will become anchors that can be woven into a rational story. Since pictures can represent a large number of propositions, learning activities based on graphics or animation (e.g., flip books (Griffard, Flanagan, & Wandersee, 1999c)) may also make such propositions more memorable.
Implications for Teaching

Construction of knowledge in many classrooms today seems to be distinct from genuine meaning-making. Learners develop coping skills (e.g., memorizing) (Bereiter & Scardamalia, 1989; Griffard & Wandersee, 1999a) in the absence of true concept development, which requires exposure to multiple examples necessary for pattern recognition. They also fall back on such methods when they do not get sufficient experience and feedback to trust their interpretations of the patterns they do perceive. These students prefer rote instruction and are reluctant to transfer knowledge on their own perhaps because they have not developed a trust of their ability to do so, and have erred in doing so previously. In such education settings students have actually “succeeded” by using labels without having concepts for them (Griffard & Wandersee, 1999a). They have also gotten by only knowing concepts are related but not stating explicit links between them.

The continuity of matter gaps and conceptual distance gaps discussed above should be of particular concern, and it is opinion of this researcher that they deserve urgent attention. The inability to view matter as continuous and to envision how it flows through biochemical processes is not only a major hindrance to understanding biology, but it may also be at the root of documented alternative conceptions in chemistry as well. Bridging this gap can be facilitated by having students pose (and be accountable for) a scenario in which they follow the path of an oxygen atom through several trajectories through the oxygen cycle. The same should be done for the carbon cycle at the least, and other cycles if possible (nitrogen, phosphorus).
Conceptual gaps are in urgent need of bridging by making explicit how the basic concepts of transport, pH and chemical composition learned in an overgeneralized context, usually early in a semester, play roles in more complex processes. Without this opportunity to transfer these basic concepts, they remain so basic that they are inert and therefore irrelevant to anything else. ANG learning theory values repeated exposure to concepts in various contexts so that the learner can perceive regularities among them. Rich concept development is not possible by teaching only about a single prototypical example or focusing only on the big ideas without grounding them with real world examples.

Considering the paucity of attention to graphic literacy in science education, it would appear that most instructors (professors and teachers) assume their students are able to extract information from graphics. Few seem to model or explicitly teach how to interpret graphic representations, and thus are not fully availing themselves of these powerful teaching aids.

The findings of this study indicate that attention in classrooms to graphic decoding skills is needed. Findings in situated cognition suggest that such instruction should be given in the content area rather than in context-free “study skills” settings (Brown & Palincsar, 1989; cf. Siegel, 1988). In addition, instructors need to listen to themselves with learners’ ears and take time to further explain graphics, synonyms, conventions, and relative significance as they go along. Understanding the gaps identified in this study may help professors guide instruction so that the big picture
they claim their students lack is accessible earlier, and thus would enhance their progression to higher literacy levels.

The goal of Human Constructivist learning theory is to support knowledge construction by enhancing concept, proposition and construct development. Gaps in these forms of knowledge will persist until bridged by personal experience and instruction. Bridging many kinds of gaps will require that instructors traverse the "muddled middle," which here is defined as the conceptual territory between major topics in a domain. For example, few students are asked to ponder how the starch grains (so prominent in "typical" plant cells) get "out" for respiration or biosynthesis, or how ubiquitous Spanish Moss gets its food. Why do students skip (middle) levels of organization when explaining what structures oxygen encounters as it diffuses from the plant? Why do so few students wonder why plants bother with respiration if the light reactions provide ATP, or how classical and molecular genetics are related (Griffard & Wandersee, 1998)? Are students not asked to consider these fundamental (middle) questions in their education because the middle is assumed to be too self-evident or mundane? Instructors who are aware of gaps can help their students traverse this muddled middle which seems to be missing in instruction and textbooks. Knowing how to do so should be considered a form of pedagogical content knowledge (Anderson & Mitchener, 1994).

It is hoped that modifying instruction to address the diverse set of propositional and processing gaps in learner's conceptual frameworks will speed the rate at which these gaps are bridged, and thus provide the satisfaction of meaningful
learning more expediently to all students of science. Identifying these gaps was the goal of this study, and improving instruction to nurture this satisfaction will continue to be the goal of this researcher. At the Underground rail stations in London, one is constantly reminded, both visually and aurally, to “Mind the Gap!” While that directive refers to the potentially dangerous gap between the platform and the train car, this study has shown that gaps in understanding biology can also have important consequences.
REFERENCES


THINKING SIDE

Focus Question: What gaps in biochemical understanding are revealed by a range of university introductory biology students as they work through a critically acclaimed multimedia learning program on photosynthesis, and what are the corresponding implications for elaboration of Ausubel-Novak-Gowin Learning Theory? Subquestions are:

a) What gaps in biochemical understanding can think-aloud protocols, videotaped program-path analyses, and pre- and post-instruction clinical interviews uncover as these college students work through an award-winning multimedia program on photosynthesis?

b) Do the gaps identified correspond with instruction?

c) Can a typology of the emergent biochemical gaps be constructed?

d) How can the typology be integrated with ANO learning theory?

DOING SIDE

VALUE CLAIMS
Attention to gaps in propositional knowledge and processing skills (especially graphic literacy) can improve instruction. Instructional artwork should take graphic decoding gaps into consideration. BICS literacy model is a good start but does not consider how gaps can be bridged.

KNOWLEDGE CLAIMS
Introductory biology students have propositional and processing gaps in their understanding of photosynthesis. Gaps exist in students' development of concepts, links, and constructs. Metacognition, prior knowledge, and graphic decoding influence processing during meaningful learning. One cause of gaps is naïveté. ANO theory is supported. Some "alternative conceptions" may be due to gaps.

EVENTS/OBJECTS

1. Choose commercial multimedia photosynthesis package.
2. Develop and refine the actual tasks to be accomplished by the participants during the clinical interviews.
3. Proceed technology to record student think-aloud processes during use of software.
4. Identify two intro bio professors with whom to work, attend their lectures, interview re important photosynthesis concepts. Make short recruitment presentation on first class day.
5. Identify and recruit 12 students from each of the professors' sections (2 sections a 2 each of hi, avg ability level, randomized for race, gender).
6. Meet with and orient students; conduct pre-task interview including co-concept maps or card sorting to determine prior knowledge.
7. Conduct in-depth clinical interviews: Phase 1 (pre-instruction), Phase 2 (post-instruction), and Phase 3 (backup session, extra data collection). Includes think-aloud data during computer simulation in COE Lab.
8. Analyze transcripts of Phase 1 and 2 interviews using NUD-IST. Index instantiations of emerging gaps to codes.
9. Refine typology of gaps form the hierarchy of nodes that emerged using NUD-IST for coding/indexing.
APPENDIX B

FLOW CHART OF RESEARCH

August 1993
Begin developing theoretical framework

December 1995
Choose and refine research questions

Spring 1996
Begin literature review

Fall 1997
Write research prospectus

January 1998
Recruit applicants; get consent for IRB

February-March 1998
Students receive regularly scheduled instruction in photosynthesis in Bio 1201 course

May 1997
Complete Science Education coursework

Fall 1997
Get approval of course coordinator, professors

February 1998
Purposely select 12 full participants

March 1998
Review participants' exams and lecture notes with them

Phase I interviews x12: sorting tasks, co-concept mapping; think-alouds during introduction to photosynthesis simulation

Phase II post-instruction, pre-exam interviews x12: co-concept mapping; think-alouds during higher level activities in photosynthesis simulation

Phase III: participants answer exam questions from other professor; complete two-tier diagnostic while thinking aloud.

April 1998
Propose typology of gaps; analyze sources; propose instruction to address gaps

Legend

- events or activities
- data collected
- decisions
- analysis

Researchers' notes from professor lectures
Field notes from lecture observations
Students' lecture notes and exams
Course textbook

Think-aloud protocols
Co-concept maps

Verbal analysis; document analysis; NUD*IST

Verbally analyze; document analysis; NUD*IST

Digital analysis; document analysis; NUD*IST
Title of Research Study: Gaps in College Biology Students’ Understanding of Photosynthesis: Implications for Human Constructivist Learning Theory and College Classroom Practice

Project Director: Student Investigator: Phyllis Baudoin Griffard, Doctoral Candidate of Biology Education, LSU; Advisor: Dr. James H. Wandersee, Professor of Biology Education, LSU

Purpose of the Research: The researchers hope to reveal, categorize and attribute reasons for gaps in college biology student’s understanding of some biological processes. We hope that findings will improve instruction with regard to this and related topics, as well as to advance theory of human learning.

Procedures of the Research: If you are selected and you participate fully, you can expect to meet with and interact with the researcher on three occasions on campus during this semester, each lasting one to two hours. During these meetings you will perform simple tasks and answer questions related to biology, as well as work with a computer simulation of biological and biochemical processes. You will also be asked to submit your lecture notes and course examinations and assignments for review by the researcher.

Potential Risks: There are no medical, personal, social or academic risks anticipated with this study. Nonetheless participants are welcome to contact the researcher at any time to discuss concerns about perceived risk. Your grade in this course or any other will not be adversely affected by participation in this project.

Potential Benefits: Benefits of your participation in this study include:
1. An improved understanding of photosynthesis and related topics in this course, improved cognitive and study skills, improved visual learning skills, and thus possibly a better grade in the course.
2. A contribution to the effort to improve college biology teaching at LSU and elsewhere.
3. Compensation in cash (Federal minimum wage rate) as well as a stipend awarded at the completion of the project at semester’s end if you participate fully as described above.
Alternative Procedures: There are no alternative procedures for collecting this data. Your participation is entirely voluntary. You may withdraw consent and terminate participation at any time.

Protection of Confidentiality: Sessions will be videotaped for the purpose of data collection. After transcription and coding, the recordings will be in the sole possession of the student investigator named above. Transcriptions and all subsequent analysis and public presentation of the data (in journals or presentations) will use non-identifying pseudonyms. At the completion of the project, you will be asked, but not required, to grant us permission to use video segments in academic presentations which may or may not include your likeness. In this case the only identifying information will be your likeness, since pseudonyms will still be in use.

I have been fully informed of the above-described procedure with its possible benefits and risks and I give my permission for participation in the study.

__________________________________________  ____________________________
signature                                      printed name

__________________________________________
date
APPENDIX D

APPLICATION

- Only ten to fifteen subjects will be selected for the full study. In recognition of the time required by students who agree to participate in the study, those students will be offered compensation by the researcher (at least at the Federal minimum wage rate) for their participation in the study.

- Your signature below gives me, Phyllis Baudoin Griffard, permission to view your academic records at LSU. This will help me select participants appropriately and get other needed data. You will also be asked to submit your lecture notes, assignments and examinations for review.

- If you are selected, you may be contacted anytime between now and Spring Break. Questions may be addressed to the researcher, Phyllis Baudoin Griffard, at 504-866-3571 or email: griffardp@aol.com

Signature of applicant __________________________ Date __________________________
Printed name of applicant __________________________ Social Security No. __________________________
Phone number(s) __________________________ Email address (if applicable) __________________________
declared major __________________________ current career goal __________________________ current GPA __________________________
Sex ______ Race ______ High School graduated from __________________________ HS GPA __________________________

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How often did you use a computer last semester?

___ Not at all  ___ Once or twice  ___ Once a week  ___ Every few days  ___ Daily
APPENDIX E

INTERVIEW PROTOCOLS

Interview Protocol: Phase 1

I. Introductions

II. Share agenda for interview and provide information/agreement sheet with information about the study

III. Think-aloud warm-up/literacy level: Material sorting task (rock, seashell, loose green leaves (pitispormum), dried basil, dried Shiitake mushroom, young red bean plant, dried wood, sweet potato, baker’s yeast, cabbage) (10 min.)

A. Sort the 10 items into living (or once-living) and non-living and explain why.

B. Sort the 10 items into photosynthetic and non-photosynthetic and explain why.

IV. Card-sorting task/modified co-concept mapping (10 min.)

A. Choose the concepts from this stack of adhesive notes that you recognize.

B. Give a simple oral definition of each of these.

C. Now I’ll help you to produce a map that shows how you think about the concepts and how they are related to each other. Take the cards and put the most important, or “biggest idea” one on top. Now, take the others and group them as “next biggest ideas” under that, etc.

D. Write a linking word or phrase between each pair of words that tells the relationship between the cards.

E. Are there any changes you’d like to make in your map (links, concepts, arrangements)?

V. Introduction to computer simulation of photosynthesis
A. Engage in the introductory section that has you manipulate variables. (15-20 min.). When you encounter speaker icons and “hot words” in blue, click them. Speak out any thoughts you are having as you go through the introduction.

B. I will explain a few features not made explicit by the program and answer their questions about what the icons represent (wavelength slider, CO₂ and water input, humidity slider, stomate size, and popups for equations (mechanism window). You can refer to the marked pages in the user’s guide if you’d like.

C. Now go back to the “for the birds” window since it has an output graph. I’d like you to try to get the maximum photosynthesis rate you can, and please think aloud as you make decisions. I’ll only interrupt to ask you to think aloud, and I’ll only answer questions about the graphics and what they represent, not suggestions for how to proceed.

VI. Summary and Transfer of graphic concepts to living plant:

A. If you had to summarize the overall process of photosynthesis, what would you say is required (inputs) and what is produced (outputs). You may refer to the simulation. Now show me where the inputs and outputs “come into” and “go out of” the reaction in both the leaf and mechanism windows (5 min.).

B. Look at this plant. Do you think photosynthesis is going on right now? Why or why not? Where is this plant getting the inputs it needs for photosynthesis? What is it doing with the products of photosynthesis? (10 min.)
VII. Map changes: Are there any changes you’d like to make in your concept map?

Are there any words in the rest of the deck you now recall or recognize? (If so, use new sheet of easel paper.)
Interview Protocol: Phase 2

I. Icebreaker (2 min.)

II. Agenda for interview (1 min.)

III. Think-aloud warm-up/literacy level: Material sorting task (using 10 new items) (10 min.)

IV. Card-sorting task/modified co-concept mapping (start with their map from Phase 1, ask for changes.) (10 min.)

V. Tasks using computer simulation of photosynthesis: “I’ll interrupt to ask you to think aloud, and I may ask you questions along the way and afterward.”

A. Do the “A Delicate Balance” section while thinking aloud. Afterward I will ask questions related to the think-aloud protocol (“What happens to oxygen and carbon dioxide flow when light intensity is zero? Explain”) (10 min.)

B. Do the “Electrons” section while thinking aloud. Afterward I will ask questions related to the think-aloud protocol (e.g., “Why does NADP turn to NADPH at this point?”) (20 min.)

C. (Prediction) Now I’d like you to pretend you are growing a plant in the presence of carbon dioxide in which carbon-12 is replaced with radioactive isotope, C-14. Which product will be radioactive? What about replacing water with some in which the oxygen is labeled? Which output will be labeled? Run the simulation with labeled inputs and test your prediction. Explain why you were right or wrong. (10 min.)

D. (Prediction) Predict what will happen in the mechanism window if you use the blocker tool and block the ATPase. Run the simulation, then evaluate your prediction. (10 min.)

VI. Transfer of graphic concepts to living plant:
A. (Conversation) You have said that photosynthesis makes “food” for a plant. Do you think this plant is undergoing photosynthesis? What does that mean at a cellular level? What is the “food” made in photosynthesis? What happens to it after it’s made? (10 min.)

B. (Conversation) Did you know that this Spanish Moss is a vascular green plant? If I tell you it is, can you figure out how it gets what it needs to photosynthesize? Explain which parts of the photosynthesis simulation apply to this Spanish Moss. (10 min.)

C. Ask participant about his/her lab experiences with photosynthesis.

VII. Map changes: Are there any changes you’d like to make in your map? Are there any words in the rest of the deck you now recall or recognize? (If so, use new sheet of easel paper)
APPENDIX F

QUESTIONNAIRE

• You are asked to answer the following questions for research purposes. Answering them is optional, however your doing so will help us better understand how college students learn biochemistry.
• Your responses will not affect your exam grade in any way.
• Circle your choices directly on this sheet, not your scantron.
• You are encouraged to jot notes, diagrams or questions in margins of each question as you think about them.
• Answer only those you feel you have sufficient time to think about. It is better to leave an item blank than to answer without reading it.

1. Which is NOT a possible fate of a sugar molecule produced by a plant cell in photosynthesis?:
   a. a caterpillar can eat the leaf and the caterpillar’s cells’ mitochondria can oxidize the sugar in respiration for ATP production
   b. the leaf cell can convert it to sucrose, which travels to nonphotosynthetic cells, which then can oxidize it in respiration.
   c. the leaf cell’s enzymes can convert the sugar to glucose, then cellulose or starch
   d. the sugar can directly provide energy for endergonic cellular processes such as active transport
   e. the leaf cell converts the sugar to an amino acid that gets incorporated into ribosomal protein

2. What happens to the oxygen made when water is split in photosynthesis?
   a. it combines directly with carbon to make carbon dioxide, and is used in the Calvin cycle
   b. it immediately diffuses out of the cell, the leaf and into the air
   c. it accumulates in the thylakoid
   d. it diffuses to areas of lower concentration, such as the mitochondria where it is used in respiration.

3. What is the pH of a leaf cell’s thylakoid space when the plant is in full sunlight?
   a. acidic
   b. basic
   c. neutral
   d. acidity is of no relevance to photosynthesis

4. Chemiosmosis involves two types of transport across membranes. The electron transport chain moves protons by ____ and ATPase (or F1 complex) moves protons by _____.
   a. active transport, active transport also
b. facilitated diffusion, facilitated diffusion also
c. facilitated diffusion, active transport
d. active transport, facilitated diffusion
e. proton movement does not occur by either of those transport mechanisms

Use the following choices (a-e) to identify the chemical composition of the components of photosynthesis (1-7) below:
a. protein  b. lipid  c. carbohydrate  d. nucleic acid  
e. a mixture of more than one of the above

1. thylakoid  ____  2. CF1 ATPase  ____
3. chlorophyll  ____  4. rubisco  ____
5. G3P sugar  ____  6. ATP  ____
7. NADPH  ____  8. photosystems  ____

Please tell me about yourself:
_____________________________________________________________________
Name (optional if you are not participating in my study)

__________
SS#

Fr  Soph  Jr  Sr  Classification  Major  Career goal  GPA  Grade on first test

__________
Grade you think you made on this exam

Comments about questions above:
_____________________________________________________________________
_____________________________________________________________________

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### APPENDIX G

**PRIMARY DATA FROM PHASE 1**

**Summary of Phase 1 Sorting Task: Living (L) vs. Nonliving**

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**Summary of Phase 1 Sorting Task: Photosynthetic (P) vs. Nonphotosynthetic**

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PHOTOSYSTEM 2

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HETEROTROPHS
| CARBON FIXATION
NADPH
| CHEMIOSMOSIS|
ATPSYNTHASE]

Chanda’s Phase 1 concept map

RECOGNIZED
BUTNOT 1NCORTORATED
INTO SUP
THYLAKOIDMEMBRANE
CYCLIC PHOTO
PIIOSPIIORYI-ATION
ELECTROMAGNETIC
SPECTRUM
STOMATA PROTONS
CHLOROPHYLL NADP
REACTIONCENTER
WAVELENGTH
OXYGEN11MESOPHYLL|
VISIBLEUGIH | ATP|
PHOTONS GLUCOSE
LIGHT
REACTIONS RUBISCO
CAROTENOIDS
NONCYCLIC PHOTO
PHOSPHORYLATION

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Charles's Phase 1 concept map
Cheryl's Phase 1 concept map
PHOTOSYNTHESIS

direct needs

PHOTOSYSTEM PHOTOSYSTEM II PHOTOSYSTEM III parts

indirect energy

WATER ATP SYNTHASE

main require

PHOTOSYSTEM LIGHT REACTIONS ATP NADPH needs yields

substage

CALVIN CYCLE PRIMARY ELECTRON ACCEPTOR factor REACTION CENTER

products of Calvin Cycle

CAROTENOID
STOMA(TA)
GLYCERALDEHYDE-3-PHOSPHATE

HETEROTROPHS products
AUTOTROPHS

DON'T RECOGNIZE
CYCLIC PHOTOPHOSPHORYLATION
NONCYCLIC PHOTOPHOSPHORYLATION
PHOTOPHOSPHORYLATION
MESOPHYLL
THYLAKOID MEMBRANE
CARBON FIXATION
ATP SYNTHASE
CHEMIOSMOSIS

Carlos' Phase 1 concept map
PHOTOSYNTHESIS

all (below are) part of

AUTOTROPHS
HETEROTROPHS

ATP SYNTHASE

PROTONS
PHOTONS

PRIMARY ELECTRON ACCEPTOR

WAVELENGTH
VISIBLE LIGHT
LIGHT REACTIONS

MESOPHYLL
CHLOROPHYLL

ELECTROMAGNETIC SPECTRUM
CARBON FIXATION
CALVIN CYCLE

needs

produces

OXYGEN
GLUCOSE
WATER

comes in through
TIYLA KOID MEMBRANE

DON'T RECOGNIZE
GLYCERALDEHYDE-3-PHOSPHATE
PHOTOSYSTEMS
PHOTOSYSTEM 1
PHOTOSYSTEM 2
CHEMOSMOSIS
CAROTENOIDs
RUBISCO
PHOTOPHOSPHORYLATION
CYCLIC PHOTOPHOSPHORYLATION
NONCYCLIC PHOTOPHOSPHORYLATION
REACTION CENTER

Caroline's Phase 1 concept map
Cathy's Phase 1 concept map

**CALVIN CYCLE** takes place in **PHOTOSYNTHESIS** and are made in **NADP**, **ATP** (is related to) **ATP SYNTHASE**. **VISIBLE LIGHT** is needed for **LIGHT REACTIONS** and is a part of **ELECTROMAGNETIC SPECTRUM**.

**CHEMIOSMOSIS** and **PHOTOSYSTEMS** are **PHOTOSYSTEM 1** before going to **PHOTOSYSTEM 2**. **DONT RECOGNIZE** **REACTION CENTER**

**THYLAKOID MEMBRANE** and **CYCLIC PHOTOPHOSPHORYLATION**.

**NONCYCLIC PHOTOPHOSPHORYLATION** and **PHOTOPHOSPHORYLATION**.

**GLYCERALDEHYDE-3-PHOSPHATE** and **RUBISCO**.

**STOMATA** and **CAROTENOID**.
Rhea’s Phase 1 concept map
GLYCOLYSIS are involved in
ATP SYNTHASE GLUCOSE
NADPH GLYCERALDEHYDE
ATP 3-PHOSPHATE
PRIMARY ELECTRON ACCEPTOR

GLYCOLYSIS
CAROTENOID
HE ADDED
GLYCOLYSIS
LIGHT
PLANT FUNCTIONING
REFINED PHOTOSYNTHESIS
DON'T RECOGNIZE
RUBISCO
PHOTOSYSTEM 2
PHOTOSYSTEM 1
PHOTOSYSTEMS

LIGHT
are related to
ELECTROMAGNETIC SPECTRUM
WAVELENGTH
VISIBLE LIGHT
PHOTONS

PLANT FUNCTIONING
(are related to general)
HETEROTROPHS
AUTOTROPHS
CARBON FIXATION
CYCLIC PHOTOPHOSPHORYLATION
NONCYCLIC PHOTOPHOSPHORYLATION
CHEMIOSMOSIS

REFINED PHOTOSYNTHESIS
(CALVIN CYCLE)
WATER
CHLOROPHYLL
REACTION CENTER
PHOTOPHOSPHORYLATION
STOMATA
OXYGEN
LIGHT REACTIONS
THYLAKOID MEMBRANE
PHOTOSYNTHESIS
MESOPHYLL
PROTONS

Rhyan's Phase 1 concept map
PHOTOSYNTHESIS

Plants use it for

LIGHT REACTIONS

types of light used

ELECTROMAGNETIC SPECTRUM

VISIBELIGHT

how light is dispersed

WAVELENGTH

PHOTONS

ATP (is)

ENERGY

CHLOROPHYLL

ATP SYNTHASE

NADPH

AUTOTROPHS

HETEROTROPHS

CARBON FIXATION

HEADED

ENERGY

PRIMARY ELECTRON ACCEPTOR

OXIGEN

Randy's Phase 1 concept map
Rashad's Phase 1 concept map
APPENDIX H

PRIMARY DATA FROM PHASE 2

Summary of Phase 2 Sorting Task: Living (L) vs. Non-living

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Summary of Phase 2 Sorting Task: Item has a Living Cell (C) or Does Not

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### Summary of Phase 2 Sorting Task:
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**Living Cell is Undergoing Photosynthesis (P) or Is Not**

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* indicates supramolecular complexes that justifiably may be categorized as a molecule or a subcellular component.
### Participants' Phase 2 Term Sorting Results

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**Charles: Score 18/20**

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**Cheryl: Score 19/20**

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Note: The table represents the sorting of molecules and processes in cellular biology. The entries are marked with asterisks to indicate specific components or reactions.
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*CO₂, ATP, NADPH categorized simply as organic
PHOTOSYNTHESIS

1st part is LIGHT DEPENDENT REACTIONS
2nd part is CALVIN CYCLE

events are occurs in

SUNLIGHT
THYLAKOID
STROMA

CARBON DIOXIDE

from atmosphere starts off with

CHLOROPHYLL is in PHOTOSYSTEMS excites provides ELECTRONS go through ELECTRON TRANSPORT pumps produces PROTONS NADPH

provides e to make ATP

CHEMIOSMOSIS CF1 COMPLEX

process is RUBP considered [is] [needed for]

CARBON FIXATION

SUGARS RUBISCO

OXYGEN

2c3, 3p

RUBP catalyzed by +rubp

Chanda's Phase 2 concept map: Score 51
PHOTOSYNTHESIS

LIGHT DEPENDENT REACTIONS
- requires LIGHT
- requires ELECTRONS
- occurs in THYLAKOID
- contains PHOTOSYSTEMS

ELECTRONS
- get passed around & stepped down in THYLAKOID
- pass e- to (cyclic) PHOTOSYSTEMS if noncyclic
- provides e- to CHLOROPHYLL
- powers CARBON DIOXIDE

WATER
- PROTONS moves across & release energy at CF1 COMPLEX
- NADPH moves across & release energy at CF1 COMPLEX

NADPH
- pass e- to reduce NADP+

ATP
- made from ADP
- powers CF1 COMPLEX

STROMA
- SUGARS
- makes CALVIN CYCLE

CALVIN CYCLE
- occurs in STROMA

First part is LIGHT DEPENDENT REACTIONS
Second part is CALVIN CYCLE

Charles's Phase 2 concept map: Score 53
The image contains a concept map explaining the process of photosynthesis. The map shows the light-dependent reactions and the Calvin cycle. The process begins with sunlight on chlorophyll, which is converted to electrons. These electrons are then used in the electron transport chain to generate NADPH and ATP. The water is also used to generate oxygen. In the Calvin cycle, these molecules are used to fix carbon dioxide, converting it into sugars. The map includes detailed nodes and arrows indicating the flow of reactions and the participation of various molecules and components.
Photosynthesis

Light Dependent Reactions

1st part is

- Sunlight
- Water
- Oxygen
- Electrons

2nd part is

- Carbon Dioxide
- ATP
- NADP

Calvin Cycle

Stroma

Carbon Fixation

[Stromal Carbon Fixation]

Calvin Cycle

Carbon Dioxide

Carbon Dioxide

Photosynthesis

Photosynthesis

Photosynthesis

Carlos' Phase 2 concept map: Score 60
PHOTOSYNTHESIS

LIGHT DEPENDENT REACTIONS

SUNLIGHT

需要光

PHOTOSYSTEMS

需要光

CO2 enters in form of fixation

CARBON DIOXIDE

CARBON FIXATION

需要

CARBON DIOXIDE

SUGARS

CHOLOPHYLLE

ELECTRON TRANSPORT

ATP/NADPH

HER DRAWING HERE
PHOTOSYNTHESIS

LIGHT DEPENDENT REACTIONS

THYLAKOID

CYCLIC

SUNLIGHT

PARES

NONCYCLIC

TRACTION CENTER

PHOTOSYSTEMS

CHLOROPHYLL

LIGHT

ELECTRONS
to

ELECTRON ACCEPTOR

[FD]

[PS II]

[PS I]

LOSSING ENERGY ELECTRONS GO DOWNHILL

CHEMOSMOSIS

TRANSPORT

PROTONS

provide energy to make

PSI

ATP FROM ADP

[CF I COMPLEX]

[GOES through]

[XYTOSCHROMES]

[HY]
PHOTOSYNTHESIS

first part is LIGHT DEPENDENT REACTIONS
second part is CALVIN CYCLE

STROMA needs WATER goes through SUNLIGHT energy passes through CHLOROPHYLL energy products (are) gives off NADPH uses ATP need CALVIN CYCLE

RUBISCO is an enzyme that takes CARBON DIOXIDE and makes SUGARS

PHOTOSYSTEMS

DIDN'T INCLUDE CHEMIOSMOSIS ELECTRON TRANSPORT CARBON FIXATION CF1 COMPLEX ELECTRONS PROTONS

Rhea's Phase 2 concept map: Score 16
PHOTOSYNTHESIS

1st part is

LIGHT DEPENDENT REACTIONS

produce

require

OXYGEN
WATER

SUNLIGHT

CARBON DIOXIDE
ELECTRONS
PROTONS
CHLOROPHYLL

2nd part is

CALVIN CYCLE

produces

SUGARS
RUBISCO

THYLAKOID
ATP
ELECTRON TRANSPORT
CHEMIOSMOSIS
NADPH

CARBON FIXATION
STROMA
PHOTOSYSTEMS
CF1 COMPLEX

Rhonda's Phase 2 concept map:  Score 8
PHOTOSYNTHESIS begins with light-dependent reactions that use raw materials. The Calvin cycle follows, using carbon dioxide and raw materials. Photosystems produce oxygen, while the electron transport chain produces ATP and NADPH. The Calvin cycle produces sugars and takes part in the production of products.
PHOTOSYNTHESIS

LIGHT DEPENDENT REACTIONS

THYLAKOID
- uses SUNLIGHT to excite WATER
- produces OXYGEN

CHLOROPHYLL
- uses NAD+
- uses ADP
- produces ATP and NADPH

CALVIN CYCLE

STROMA
- uses CALVIN CYCLE

THYLAKOID
- is in

CHLOROPLAST
- is filled with CARBON DIOXIDE

RUBISCO
- uses enzyme to produce SUGARS

HE DID NOT INCLUDE IN FIRST MAP
- CARBON FIXATION
- CF1 COMPLEX
- ELECTRON TRANSPORT
- CHEMIOSMOSIS

HE ADDED
- PROTONS
- MOLECULES

MOLECULES
- CHLOROPLAST
- ADP
- NADP+

ELECTRONS
- are in all MOLECULES

Randy's Phase 2 concept map: Score 41
Light Dependent Reactions

First part is split, second part is needed to make...
PHOTOSYNTHESIS
1st part is LIGHT DEPENDENT REACTIONS
2nd part is CALVIN CYCLE

STROMA occur in PROTONS are EVERYWHERE

SUNLIGHT is incident upon CHLOROPHYLL

PHOTOSYSTEMS some subset is CHLOROPHYLL CHEMIOSMOSIS catalyzes synthesis of

PHOTOSYSTEMS some subset is ELECTRONS

PHOTOSYSTEMS

HE ADDED EVERYWHERE NADP+

PRIMARY ELECTRON ACCEPTOR

SOME ELECTRONS transferred to ELECTRON TRANSPORT

NADPH donates e for SUGARS

WATER source of H for OXYGEN

CARBON DIOXIDE releases its undergoes

NADPH

CARBON FIXATION to make ATP could be

RUBISCO an enzyme involved in synthesis from adp

DIDN'T KNOW THYLAKOID

Raul's Phase 2 concept map: Score 44
Summary of Predictions Made in the Phase 2 Simulation Task "The Electrons"

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Note: Prediction of No Change was accepted as correct in the first condition. See text for rationale.

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VITA

Phyllis Baudoin Griffard was born in southern Louisiana to Andrew Ray Baudoin and Cynthia Arabie Baudoin, both of Cajun ancestry. After being educated in public schools in Louisiana and Mississippi, she graduated *magna cum laude* with an Honor's Baccalaureate Degree in Zoology from the University of Southwestern Louisiana in 1983. Her love of life sciences led her to pursue a doctoral degree in biochemistry at Purdue University. After completing all her course work and qualifying exams, she spent several years conducting doctoral research in carcinogenesis. When her vision of the life of a research biochemist began to pale in comparison with working in village development in Africa, she elected to complete her studies at Purdue in 1987 with a master's degree in her home department of medicinal chemistry. She worked with village mothers and supported indigenous extension agents in the West African country of Mali in 1989. She returned to the United States in 1990 to resume her career in science, this time on the biology faculty at Xavier University in New Orleans. Her commitment to excellence in teaching was supported and enriched by this institution so successful in educating young African-American science students. She began her doctoral studies in science education at Louisiana State University. In 1995 she was awarded the L.S.U. Alumni Fellowship to support her studies.

Phyllis currently lives in Houston, Texas, with her husband Pete, their children Emile and Gabriel, and their dog Wulu, on a homestead that includes a highly photosynthetic centenarian Live Oak tree. She is on the faculty of the Natural
Sciences Department at the University of Houston-Downtown where she teaches biology and is interim director of the Science Learning Center. She expects to be awarded the degree of Doctor of Philosophy in Curriculum and Instruction in December 1999 from Louisiana State University.
DOCTORAL EXAMINATION AND DISSERTATION REPORT

Candidate: Phyllis Baudoin Griffard

Major Field: Curriculum and Instruction

Title of Dissertation: Gaps in College Biology Students' Understanding of Photosynthesis: Implications for Human Constructivist Learning Theory and College Classroom Practice

Approved:

[Signatures]

EXAMINING COMMITTEE:

[Signatures]

Date of Examination:

August 27, 1999