DOCUMENT RESUME

ED 324 204 SE 051 583

AUTHOR	Lawson, Anton E.; And Others
TITLE	A Theory of Instruction: Using the Learning Cycle To Teach Science Concepts and Thinking Skills. NARST Monograph, Number One, 1989.
INSTITUTION	National Association for Research in Science Teaching.
PUB DATE	89
NOTE	136p.
AVAILABLE FROM	National Association for Research in Science Teaching, Department of Science Education, College of Education, University of Cincinnati, Cincinnati, OH 45221.
PUB TYPE	Viewpoints (120) -- Guides - Classroom Use - Guides (For Teachers) (052)
EDRS PRICE	MF01 Plus Postage. PC Not Available from EDRS.
DESCRIPTORS	Cognitive Development; Cognitive Processes; Cognitive Style; *Concept Formation; *Developmental Stages; Discovery Learning; *Elementary School Science; Elementary Secondary Education; Higher Education; *Learning Theories; Misconceptions; Science Activities; Science Education; *Scientific Concepts; *Secondary School Science; Thinking Skills

ABSTRACT

This monograph describes the origins of the learning cycle, related research, and how future research might be conducted to further the understanding of theories of instruction. A wide range of information is synthesized, producing a coherent framework for better understanding the theory of the learning cycle. The monograph identifies various models of the learning cycle, and focuses on a cycle consisting of exploration, term (concept) introduction, and concept application. Topics include: (1) a brief introduction to education goals in general and then to the more specific goals of science education; (2) the introduction of the learning cycle and the fundamental instructional method for teaching science to achieve these goals; (3) the historical origins of the learning cycle method; (4) attempts to provide a theoretical rationale for using the learning cycle method; (5) the nature of the learning cycle and types of learning cycles to show how their use leads to students' acquisition of scientific concepts and the development of creative and critical thinking skills; (6) a review of the empirical research; and (7) suggestions for future research. Appended are the procedures for five science activities that show the use of learning cycle. (KR)

ARST MONOGRAPH, Number One, 1989

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Using the Learning Cycle to Teach Science Concepts and Thinking Skills

Anton E. Lawson
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A THEORY OF INSTRUCTION:

USING THE LEARNING CYCLE TO TEACH SCIENCE

CONCEPTS AND THINKING SKILLS

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The National Association for Research in Science Teaching (NARST) is a professional organization devoted to promoting and disseminating science education research.

To Chet Lawson and Bob Karplus

Thank you

A THEORY OF INSTRUCTION:
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FOREWORD

It is with great pleasure that I write this brief introduction to the first NARST Monograph. The authors have done a splendid job of describing the origins of the learning cycle, related research, and how future research might be conducted to further our understanding of an important theory of instruction.

In reading various drafts and offering comments, I have had the opportunity to watch the development of a document that will surely become an important part of the foundation for future research into how students learn science. This question, it seems to me, is the central question for science education researchers.

All science educators interested in the teaching and learning of science will find this first NARST Monograph valuable in a number of ways. First, it synthesizes a wide range of information into a coherent framework for better understanding the theory of instruction commonly referred to as the learning cycle. For this reason alone it is worth having in one's personal library. Second, it refines and clarifies various terms commonly associated with the learning cycle, such as discovery, invention, concrete and formal operational, etc. In this regard the theory becomes more internally consistent as well as reflective of progress in research on cognition. Finally, this NARST Monograph identifies many areas for future research and raises theoretical issues that must be considered.

I congratulate the authors on a fine piece of work. This NARST Monograph sets a standard for future Monographs that, if met, will ensure a valuable source of science education literature.

Ron Good, Chair
NARST Publications Advisory Committee

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PREFACE

A recent topic of discussion among science educators has centered on a seemingly esoteric question: Is science education a discipline? It can be argued that the central criteria for any discipline is a generally accepted set of principles upon which a field of inquiry has been focused. In other words, a field of inquiry becomes a discipline when, and only when, a theory emerges which satisfactorily explains a substantial number of issues in the minds of researchers such that they agree with one another and can keep others from becoming practitioners in that field until they demonstrate an understanding of those principles. Today, for example, biology is a discipline which has Charles Darwin to thank for providing a generally acceptable set of principles (i.e., the postulates of his theory of evolution through natural selection). Darwin's theory raised the previous hodge podge of disjointed observations about the living world by various naturalists into a cohesive world view of organic change. Today all aspiring biologists and biology students learn about evolution and about Darwin's theory as themes which unify the discipline of biology.

Does science education have such a unified set of accepted principles? Is science education a discipline? We think most observers would have to answer no. However, we also think that our understanding of the nature of scientific knowledge, the child and adolescent, and pedagogy have progressed to the point where such a set of fundamental principles can be offered. Consequently, the primary purpose of this book is to offer those principles. Our hope is that the principles we offer will in time be mutually agreed upon by science educators such that science education will achieve discipline status.

Chapter I begins with a brief introduction to educational goals in general and to the more specific goals of science education. Chapter II then introduces the notion of the learning cycle, the fundamental instructional method for teaching science to achieve these goals. In Chapter III we trace the historical origins of the learning cycle method to the work of Robert Karplus in Science Curriculum Improvement Study program of the late 1950's and early 1960's and to the work of Chester Lawson in biology education during that same time period.

Chapter IV attempts to provide a theoretical rationale for using the learning cycle method by exploring the nature of declarative and procedural knowledge and how these fundamental types of knowledge are acquired. Chapter V then more fully explicates the nature of the learning cycle and discusses types of learning cycles to show how their use leads to students' acquisition of scientific concepts and the development of creative and critical thinking skills. Indeed, proper use of the learning cycle makes students more "intelligent."

Chapter VI reviews empirical research that has been conducted during the past 20-30 years on the effectiveness of the learning cycle and programs that utilize the method. Chapter VII discusses suggested directions for future research.

A few concluding remarks plus a list of the key postulates of the learning cycle theory of instruction that has been introduced are included in a final chapter.

We are deeply grateful to Ron Good, Chair of NARST Publications Advisory Committee, for his encouragement to undertake this project and for his many helpful suggestions on preliminary drafts of the manuscript. Without his leadership this project would not have been undertaken, much less completed. We are also grateful to Publications Advisory Committee members Charles Anderson, James Ellis, Preston Prather, and Russal Yeany; to Patricia Blosser, NARST President, and to NARST Board Members Lowell Bethel, Fred Finley, Robert Sherwood, Emmett Wright, and LeMoine Motz for their support. A sincere thank you is also due Glenn Markle, NARST Executive Secretary, for his efforts in production and distribution of the book and Donna Berlier for her extremely able typing of the all too many preliminary versions of the manuscript. Finally, we would like to thank Charles Kazilek and Mike Junius for preparation of the figures.

A.E.L., M.R.A., and J.W.R.

I. INTRODUCTION

Is this a Dagger, which I see before me,
The Handle toward my hand? Come, let me clutch thee.
I have thee not, and yet I see thee still.
Art thou not fatall Vision, sensible
To feeling, as to sight? Or art thou but
A Dagger of the Mind, a false creation?

"A Dagger of the Mind, a false creation?" Macbeth's mind has created a dagger. Order imposed by the human mind is always a created thing. That construction is found to be true or false by test through behavior. The mind creates from sensory data. The mind then imagines it true to allow the deduction of an expectation and the expectation is then tested. If the expectation is met, the construction is retained. If not, it is replaced. So in lies a statement of how the human mind functions to construct knowledge. Does a theory of teaching follow? We think it does. The primary purpose of this book is to introduce that theory.

In 1961 the Educational Policies Commission of the United States drafted a document entitled *The Central Purpose of American Education* (Educational Policies Commission, 1961). In that document the commission identified the *central* objective of education in America. That objective, in their words, is *freedom of the mind*. Their belief is that no person is born free, thus schools must foster skills required for this essential freedom.

A free mind is one that can think and choose. According to the Educational Policies Commission, there exists rational powers, which if acquired constitute the free mind. These powers allow one to apply reason and the available evidence to ideas, attitudes, and actions, and to pursue better whatever goals he or she may have.

In 1966 the Educational Policies Commission, recognizing the key role which could be played by science education in development of the ability to think, published a second document entitled *Education and the Spirit of Science* (Educational Policies Commission, 1966). In that document they emphasized science not so much as a body of accumulated knowledge but as a way of thinking, a spirit of rational inquiry driven by a belief in its efficiency and by a restless curiosity to know and to understand. They also emphasized that this mode of thought, this spirit, relates to questions people usually ask and answer for reasons which they may think are totally nonscientific - religious, aesthetic, humanistic, literary. Thus the spirit of science infuses many forms of scholarship besides *science* itself.

Although it was recognized that no scientist may fully exemplify the spirit of science nor may their work be totally objective, it is clear that the following key values underlie science as an enterprise.

1. Longing to know and to understand.
2. Questioning of all things.
3. Search for data and their meaning.
4. Demand for verification.
5. Respect for logic.
6. Consideration of premises.
7. Consideration of consequences.

This list, by its nature, insists that students are not indoctrinated to think or act a certain way. Rather, it insists that they acquire the ability to make up their own minds, i.e., to develop freedom of the mind, and to learn to make their own decisions based upon reason and evidence. In this sense, the values of science are the most complete expression of one of the deepest human values -- the belief in human dignity. Consequently these values are part and parcel of any true science but, more basically, of rational thought and they apply not only in science, but in every area of one's life.

What then is being advocated by the Educational Policies Commission is science education not only for the production of more scientists, but for the development of persons whose approach to life is that of a person who thinks creatively and critically (cf., Resnick, 1987). Thus, the central question for the science educator is, how can science be taught to help students become skilled in creative and critical thinking? The answer we believe is by using an instructional method known as the learning cycle. In the following pages we will attempt to substantiate that claim.

We must hasten to point out that we do not believe that creative and critical thinking skills are acquired, nor do they function, independent of specific content; therefore, we must carefully consider the relationship between content and process in thinking and in instruction. Indeed, it will be argued that use of the learning cycle best facilitates both the acquisition of domain specific concepts and conceptual systems and the development of general thinking skills.

II. WHAT IS THE LEARNING CYCLE?

Suppose you are asked to develop a biology lesson on the metabolic activity of an animal such as the water flea (*Daphnia*). Which of the following procedures would you select as most effective?

(a) Provide the students with live *Daphnia*, thermometers, depression slides, and microscopes. Have the students count the number of heartbeats per minute of the *Daphnia* at three different temperatures: 5, 20 and 35 degrees C. Ask them to plot the number of heartbeats versus the temperature on a sheet of graph paper.

(b) Provide the students with live *Daphnia*, thermometers, depression slides, and microscopes, and ask them to find out if different temperatures influence the rate of heartbeat and to explain how variables could account for the differences observed.

(c) Explain to the students that temperature has a general effect on the metabolism of invertebrates. Higher temperature means a higher rate and lower temperature slows down metabolic activity. One rule states that metabolic rate doubles for every 10 degrees increase in temperature. A cold-blooded animal like the *Daphnia* is directly influenced by the environmental temperature. Now have your students go to the laboratory and use live *Daphnia* to verify that what you have explained is correct.

(d) Provide students with live *Daphnia*, a hot plate dexedrin solution, 5% solution of alcohol, a light source, rulers, thermometers, slides, pH paper, balances, graph paper, microscopes, a stirring device and ice cubes. Ask them to investigate the influence of environmental changes on the heartbeat of *Daphnia*, and to search for quantitative relationships among the variables.

Certainly the resources available to you and the preparation of your students will influence your choice. Compare your selection with our comments below

(a) This approach may be effective for students who are somewhat inexperienced in the process of scientific inquiry, as it is fairly directive yet does not spoil student motivation by telling them what they are going to find out. For more experienced students, however, it may be too directive as it limits the scope of inquiry into only one variable (temperature) and fails to justify the selection of three temperatures (i.e., Why are only three temperatures selected? Why were 5, 20 and 35°C selected?).

(b) This approach is very much like the previous one as it focuses on the effect of a single variable although does so without specifying which temperatures to use. This increased nondirectiveness is a strength as it is more apt to cause students to think about what they are doing as it forces them to make their own decisions. If improved skill in thinking is a goal, then some nondirectiveness is essential.

(c) We find little to recommend in this approach as it tells the students what they will find. This has two extremely unfortunate consequences. First, it shifts the motivation for the activity away from satisfying one's curiosity about nature to satisfying the teacher. Second, it shifts the source of authority about what is correct or incorrect from its natural place in data to an authority figure, namely the teacher. Regrettably this approach is the one often taken by teachers. However, in science one tests mental constructions in the empirical world, not in armchairs.

(d) Clearly this is the most nondirective, open-ended of the approaches. It does what approaches (a) and (b) do and more so. For the inexperienced student this nondirectiveness would be difficult to cope with without helpful procedure hints. If frustration is a problem, these hints can be provided to small groups of students working together, or the entire class can be stopped to discuss ideas of ways to get started. For experienced students this approach is highly recommended, as it allows for a variety of paths of investigation which allow considerable opportunity to think and make decisions about what to investigate and how best to investigate it.

The recommended approach in (d) and the somewhat more directive approaches in (a) and (b) are examples of exploratory activities upon which later conceptual understandings can be built. Exploration represents the first phase of the three-phase learning cycle. The three phases of the entire learning cycle were initially called Exploration-Invention-Discovery (Karplus and Thier, 1967). More recently the phases have been referred to as Exploration-Concept Introduction-Concept Application by Karplus, Lawson, Wollman, Appel, Bernoff, Howe, Rusch, and Sullivan (1977) and by Good and Lavoie (1986). Renner, Abraham and Birnie (1985) referred to the phases as Exploration-Conceptual Invention-Expansion of the Idea, while they were referred to as Exploration-Conceptual Invention-Conceptual Expansion by Abraham and Renner (1986) and Exploration-Term introduction-Concept Application by Lawson (1988). Since the choice of terminology is largely one of personal taste, we will simplify matters and hereafter use only the last set of terms to refer to the phases.

During Exploration, the students learn through their own actions and reactions in a new situation. In this phase they explore new materials and new ideas with minimal guidance. The new experience should raise questions or complexities that they cannot resolve with their accustomed ways of thinking. It should also lead to the identification of a pattern of regularity in the phenomena (e.g., heart rate increases with temperature). Approaches (a) and (b) are also considered Explorations although for many students they are not as likely to encourage reflective thought as approach (d).

The second phase, Term Introduction, starts with the introduction of a new term or terms such as metabolism, coldblooded, or poikilotherm, which are used to refer to the patterns discovered during exploration. The term(s) may be introduced by the teacher, the textbook, a film, or another medium. This step should always follow Exploration and relate directly to the pattern discovered during the Exploration activity. The lecture in alternative (c) could be part of a Term Introduction session following laboratory activities like (d). Students should be encouraged to identify as much of a new pattern as possible before it is revealed to the class, but expecting students to discover all of the complex patterns of modern science is unrealistic.

In the last phase of the learning cycle, Concept Application, students apply the new term and/or thinking pattern to additional examples. After the introduction of coldbloodedness, for instance, Concept Application might be concerned with determination of the type of metabolism of other invertebrates or vertebrates such as mice or humans.

The Concept Application phase is necessary for some students to extend the range of applicability of the new concept. Without a number and variety of applications, the concept's meaning may remain restricted to the examples used at the time it was initially defined and discussed. Many students may fail to abstract it from its concrete examples or to generalize it to other situations. In addition, Application activities aid students whose conceptual reorganization takes place more slowly than average, or who did not adequately relate the teacher's original explanation to their experiences.

Note that this phase is referred to as *Concept* Application while the previous phase was labeled *Term* Introduction by Lawson (1988). We are defining a concept as a mental pattern (i.e., a pattern in one's mind) that is referred to by a verbal label (i.e., a term). Thus, a concept is the pattern plus the term. Teachers can introduce terms but students must perceive the pattern themselves. Therefore, we believe Term Introduction is a better label for the second phase than Concept Introduction. Exploration provides the opportunity for students to discover the pattern. Term Introduction provides teachers with the opportunity to introduce the term and provides the students the opportunity to link the pattern with the term (i.e., acquire the concept). Finally, Concept Application allows students to discover applications (and nonapplications) of the concept in new contexts.

Exploration-Term Introduction-Concept Application are phases in a learning cycle. Exploratory sessions frequently require the application of prior concepts while creating a need for the introduction of the new terms. Term Introduction sessions frequently lead to questions best answered by giving students opportunities to work on their own to discover applications of the new concept. Concept Application activities can provide opportunities to use terms introduced earlier and they can permit students to explore a new pattern.

The learning cycle is a very flexible model for instruction. Certainly for young children and for anyone who lacks direct physical experiences with a particular set of phenomena, the exploration phase should involve that direct physical experience. This, however, does not imply that all explorations have to be conducted this way. Indeed, one of the authors had the pleasure of taking a history of science course in graduate school taught using the learning cycle where the exploration consisted of slide presentations, lectures and discussions. The class explored various scientists' ideas and activities in this way and only later "invented" the concept of science. More will be said about the use of different learning formats (e.g., lecture, laboratory, readings, discussions) in different phases of the learning cycle when we review research into the learning cycle. The key point to keep in mind is that one can change the learning format of the three phases of the learning cycle but one cannot change the sequence of the phases or delete one of the phases. If the sequence is changed, or if a phase is deleted, one no longer has a learning cycle.

III. HISTORICAL PERSPECTIVE

All people are teachers during some period of their lives whether professional or otherwise. Thus everyone "knows" something about how to teach. The learning cycle is one method of teaching which purports to be consistent with the way people spontaneously construct knowledge; therefore, anyone who has reflected upon how to teach effectively has no doubt discovered aspects of the learning cycle. For that reason it is not possible to say who first invented the learning cycle. Indeed, it has probably been invented many times by many teachers beginning no doubt before Socrates employed his famous Socratic method to provoke his followers to reflect on the inadequacies of their own knowledge. On the other hand, it would be incorrect to conclude that recent theoretical/empirical work on the learning cycle offers nothing new. The act of teaching involves procedures, thus requires use of procedural knowledge and, as we will see later, procedural knowledge develops not through the abrupt invention of new ideas, but through a gradually increasing awareness or consciousness of those procedures. In a very real sense recent work on the learning cycle represents, not a novel departure from past practices, but a growing awareness of how we should teach and why we should teach in a particular way. Increased awareness should lead to a more consistent use of correct procedures, thus to more effective learning.

Origins of the Learning Cycle in the SCIS Program

Identification of the learning cycle and its three phases can be traced to the early work of the Science Curriculum Improvement Study (SCIS) program on the Berkeley campus of the University of California during the late 1950's and early 1960's (*SCIS Newsletter*, No. 1, 1964 in Science Curriculum Improvement Study, 1973). To be more precise, we can trace its origin to a day in 1957 when a second grade student invited her father, Professor Robert Karplus, a physicist at Berkeley, to talk to her class about the family Wimshurst machine, a device for generating electrical charges. Professor Karplus found the visit enjoyable and so did the children. During the next few months other talks on electricity and magnetism to both elementary school and junior high school students followed. Soon Professor Karplus turned his thoughts to the possibility of developing a program for elementary school science.

With a grant from the National Science Foundation, Karplus prepared and taught three units entitled "Coordinates," "Force," and "What Am I?" during the 1959-60 school year. Although the experience proved interesting, analysis of the trial teaching revealed serious student misconceptions and other weaknesses. The experience prompted Karplus to raise a key question: "How can we create a learning experience that achieves a secure connection between the pupil's intuitive attitudes and the concepts of the modern scientific point of view?"

During the spring of 1960, Karplus continued to familiarize himself with the points of view children take toward natural phenomena as he taught lessons in a first, second and fourth grade twice a week. He also began to develop tentative answers to his question. Following that experience, Karplus was helped by a visit to the research institute of Jean Piaget, the Swiss psychologist and pioneer in the study of how children's thinking patterns and scientific concepts are formed.

When Karplus returned to the United States in the fall of 1961, he returned to the elementary classroom with a plan to stress learning based upon the pupils' own observations and experiences. However, he planned also to help them interpret their observations in a more analytical way than they would without special assistance. During part of that school year, J. Myron Atkin, then a Professor of Education at the University of Illinois, visited Berkeley to share his views on teaching with Professor Karplus. Together Atkin and Karplus formulated a theory of "guided discovery" teaching which was implemented in subsequent trial lessons (Atkin and Karplus, 1962).

The Atkin and Karplus guided discovery approach was designed to be analogous to the way in which scientists of the past invented and used new concepts of nature. In their 1962 paper they offered the example of the ancients' observations and interpretation of the motions of the sun and planets. The geocentric model of the solar system was taken to be a conceptual *invention* following initial observations. The heliocentric concept represents an alternative *invention*. With the help of these inventions, people attempted to *discover* other phenomena besides the ones that led them to propose the inventions in the first place, which could be understood using the invention. These attempts, if successful, led to a reinforcement and refinement of the concept. If they were unsuccessful, they revealed limits of the concept or, in some cases, led to its replacement.

Atkin and Karplus clearly distinguished between the initial introduction of a new concept (called invention) and its subsequent verification or extension (called discovery). They assumed that children are not generally capable of "inventing" the modern concepts of science, therefore, it becomes necessary for the teacher to "introduce" those concepts but making sure that the students' previous observations can be interpreted (or reinterpreted) using the introduced concept. Further, the teacher must follow the introduction with opportunities for the children to *discover* that new observations can be interpreted using the concept. Atkin and Karplus likened the process, in some respects, to the Copernican teacher instructing the students that the sun is at the center of the solar system while almost everyone else in the society **knows** that the earth is at the center. Atkin and Karplus did not introduce the terms *exploration* or *learning cycle* in their 1962 paper, but the phases of *invention* and *discovery* were clearly evident in their discussion and in the example lessons.

During the summer of 1962, Professor Karplus accepted an invitation to work with the Elementary Science Study of the Educational Services Incorporated. There it became clear to him that children need time to *explore* an experimental system at their own pace with their own preconceptions. Only after this initial "exploration" is it wise to introduce a more analytical point of view. Armed with this new insight, Karplus tried out the modified approach the following school year in several public school classes near the University of Maryland where the Science Curriculum Improvement Study was temporarily headquartered. A number of new staff members joined the effort at that time including Dr. Herbert Thier, then Assistant Superintendent of Schools in Falls Church, Virginia. In 1967 Karplus and Thier published a book in which the three phases of the teaching approach are first explicitly stated: "The plan of a unit may be seen, therefore, to consist of this sequence: preliminary exploration, invention, and discovery" (Karplus and Thier, 1967, p. 40).

Origins of the Learning Cycle in Biology Education

Origins of the learning cycle can be found in biology education as well. In 1953 the National Academy of Sciences convened a Conference on Biology Education to examine past teaching practices and suggest alternative approaches. As a result of that conference a project funded by the National Science Foundation, and under the direction of Professor Chester Lawson, a geneticist at Michigan State University, got underway in the fall of 1956. The result of that project, which involved the work of 30 high school and university biology teachers from throughout the country, was a sourcebook of over 150 laboratory and field activities appropriate for use in high school courses (Lawson and Paulson, 1958). Although no explicit statement of teaching method resulted from that work, it provoked Professor Lawson and others to begin a search for such a method. The project also served as the precursor to the well known Biological Science Curriculum Study project.

Professor Lawson, like Professor Karplus, turned his attention to the history of science for insight into the process of conceptual invention. His 1958 book, *Language, Thought and the Human Mind* carefully detailed the nature of scientific invention and identified a general pattern of thought he referred to as "Belief - Expectation - Test" (Lawson, 1958). This pattern can now be seen to be similar to Karplus and Atkins' pattern of invention and discovery as conceptual *invention* constitutes a *belief* which in turn leads to an *expectation* to be *tested* in the real world. If one *discovers* confirming evidence the invention is retained. If not, it is rejected in favor of another belief. We saw this pattern of thought in Macbeth's attempt to test the existence of the dagger which appeared before him.

Following work on the biology sourcebook, Professor Lawson began a careful review of current psychological and neurological research in hopes of developing a comprehensive theory of human learning complete with a model of relevant neurological mechanisms and instructural implications. The theory which resulted from that work stipulated that learning involves (1) attention directed to some undifferentiated "whole", (2) the differentiation of the whole through the identification of its parts, (3) the invention of a pattern by which the parts are interrelated, (4) testing the invented pattern to see if it applies, and (5) use of the new pattern in other similar instances. Lawson's theory would not be published until 1967 (Lawson, 1967); however, his literature search uncovered the Atkin and Karplus (1962) paper to which Lawson had this to say:

> *If we substitute the term "initial unity" for system, "differentiation" for the identification of objects within the system, "pattern or relations" for invention, and "reinforcement" for discovery, we can see the relation of this teaching approach to our theory of learning (p.119).*

Thus the same pattern of instruction had been independently "invented" by Atkin and Karplus and by Lawson. When Karplus, the physicist, needed a biologist to consult in the development of the life sciences portion of the Science Curriculum Improvement Study program he called Lawson.[1] What began for Lawson as a two-week consultation in the summer of 1965 ended with a ten-year job as director of the Life Science curriculum of the SCIS program.

The final product of the SCIS program in the mid 1970's was a K-6 life science and physical science curriculum based on learning cycles. In addition to the efforts of Karplus, Thier and Lawson, Jack Fishleder, Rita Peterson, Robert Knott, Carl Berger, and Marshall Montgomery made substantial contributions as staff members during the development years. Mary Budd Rowe, Stanford Davis, John Renner, Albert Carr and Glenn Berkheimer also made substantial contributions to the development effort as coordinators of trial teaching centers in five locations across the country.

Changes in the Names of the Phases of the Learning Cycle

Interestingly, the term *learning cycle* does not appear in any of the early publications of the SCIS program although the phases of exploration, invention, and discovery are clearly spelled out (cf., Karplus and Thier, 1967; *Science Curriculum Improvement Study*, 1973; Jacobson and Kondo, 1968). First use of the term "learning cycle" appears to be in the Teacher's Guides to the SCIS

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[1] Karplus became aware of Lawson's work through Jack Fishleder who was on the SCIS staff in 1965 and had been a contributing author to the 1958 Lawson directed project.

program units beginning in about 1970 (e.g., *Science Curriculum Improvement Study*, 1970a).

Use of the term *learning cycle* and the terms of exploration, invention and discovery continued by Karplus and others through 1975 (e.g., Collea, Fuller, Karplus, Paldy and Renner, 1975). However, in 1976 and 1977 it became apparent that many teachers were having a difficult time understanding what the terms *invention* and *discovery* were intended to mean in the context of classroom lessons. So, in a series of 1977 publications, Karplus decided to refer to the phases as *exploration*, *concept introduction* and *concept application* (e.g., Karplus, Lawson, Wollman, Appel, Bernoff, Howe, Rusch, and Sullivan, 1977).

Still others, including ourselves, have chosen to modify the terms further. Note that we previously referred to the phases of the learning cycle as exploration, **term** introduction and concept application. This modification is suggested primarily because of our belief that the names of the phases are intended to convey meanings to teachers (not necessarily to students). Teachers can introduce *terms* during the second phase of the learning cycle but they cannot introduce *concepts*. The concepts must be "invented" by students.

IV. WHY USE THE LEARNING CYCLE? THEORETICAL POSITION

Cognitive science distinguishes two fundamental types of knowledge - declarative and procedural. The distinction is essentially between "knowing that" (e.g., I know there are 50 states in the United States, and animals inhale oxygen and expel carbon dioxide) and "knowing how" (I know how to ride a bicycle, count, perform a controlled experiment). Anderson (1980) defines declarative knowledge and procedural knowledge in the following way: "Declarative knowledge comprises the facts that we know; procedural knowledge comprises the skills we know how to perform" (p. 222). Clearly, any theory of instruction must address how it aims to teach both declarative and procedural knowledge. However, before we discuss how use of the learning cycle accomplishes this end, we must consider the nature of these two types of knowledge in more detail.

The Nature of Declarative Knowledge

From the teacher's and curriculum developer's points of view, the declarative aspects of subject matter of the disciplines are composed of a series of concepts of various degrees of complexity, abstractness, and importance. These are generally seen as the primary units of instruction.

Adequately defining the term *concept* is no simple matter Nevertheless, the following definition should prove sufficient. A concept has been formed whenever two or more distinguishable objects, events or situations have been grouped or classified together and set apart from other objects, events or situations on the basis of some common feature, form or properties of both (after Bourne, 1966, p. 2). A concept can be considered to be a unit of thought which exists in a person's mind. We typically use terms to refer to these units. This does not deny the existence of nonverbalized knowledge yet we choose to think of concept formation as involving both the recognition of some common form, or feature(s) from some phenomena plus the addition of some term or a combination of terms to refer to that which is common to the otherwise varied phenomena. Chairs, dogs, atoms, democracy, hunger, love and so on all are terms to which meaning has been attributed. Hence these terms represent concepts.

Concepts do not stand alone. Rather, they are related into meaningful systems often with hierarchical structure of subordinate and superordinate concepts (cf., Ausubel, 1963; Bruner, 1963; Gagné, 1970; Lawson, 1958; Novak, Gowin, and Johansen, 1983; Okebukola and Jegede, 1988; Preece, 1978; Suppes, 1968). We choose to call these systems of interrelated concepts "conceptual systems." An example of such a conceptual system is the ecosystem from ecological theory. This conceptual system consists of concepts such as trees, sunlight, frogs, producers, consumers, food webs, community, environmental factors, and ecosystem itself. The hierarchy of concepts with the basic units of trees, frogs, sunlight and so on at the bottom and ecosystem at the top form the conceptual system known as ecosystem. The concept ecosystem is all inclusive.

All of the previously mentioned concepts are mentally integrated under the term "ecosystem." Figure 1 shows a number of the subordinate concepts which must be interrelated to form the inclusive concept of ecosystem.

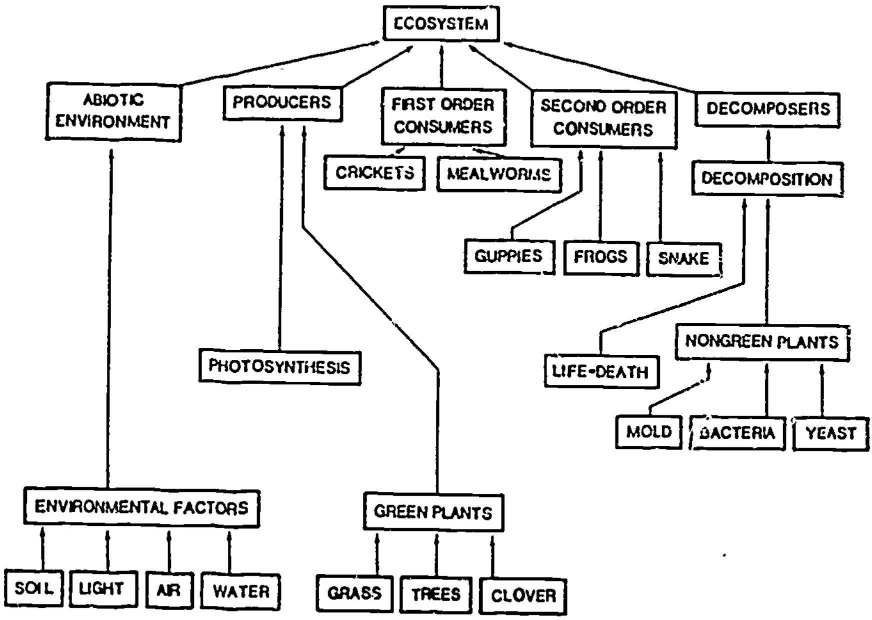


Figure 1. A number of interrelated concepts which are subordinate to the inclusive concept of "ecosystem." Interrelationships among subordinate concepts are complex, yet generally hierarchical.

As previously defined, a concept refers to some pattern (regularity) to which a term or terms have been applied. Terms fall into different types according to the different sources of meaning. There are, we believe, at least three major ways in which meaning can be derived. Hence, there are three major types of concepts.

One can have concepts about immediately sensed input such as the color green, hot-cold, sharp-dull, internal states such as hunger, thirst, tiredness and so on. The complete meaning of such terms is derived immediately from the internal or external environment. The term *blue*, for example, derives its meaning from something that is immediately apprehended. Thus, concepts *by apprehension* are the first major type of concept (Northrop, 1947).

The second type of concept we call *descriptive*. Objects such as tables, chairs, other persons, the room; events such as running, resting, playing, eating; situations such as on top of, before, under, next to, and so on are not immediately apprehended. The meaning of such terms must come through direct interaction with the "world out there." Babies are not born with the ability to perceive objects in their environment as they perceive them later on (Piaget, 1952). As Northrop (1947) said, "perceptual objects are not immediately apprehended factors; they are postulates of common sense so thoroughly and frequently and unconsciously verified through their deductive consequences that only the critical realize them to be postulated rather than immediately apprehended" (p. 93). In other words, even tables and chairs are mentally constructed entities. Yet we lose sight of this fact in that we have gathered so much data to support their presumed existence. We will return to this important point when the process of concept acquisition is discussed.

Descriptive concepts also refer to perceived relations of objects and events. Taller, heavier, wider, older, on top of, before, under, are all terms that derive meaning from a direct comparison of objects or events. To understand the meaning of such terms, the individual must mentally construct order from environmental encounters. However, his mental constructions can always be compared with and thus verified or falsified by direct experience. Such descriptive concepts allow us to order and describe direct experience.

The third type of concept we distinguish is one that is also produced by postulation. However, they differ from descriptive concepts in that their defining attributes are not perceptible. The primary use of these concepts is to function as explanations for events that need causes but for which no causal agent can be directly perceived. Fairies, poltergeists and ghosts fall into this category. Common examples from science are genes, atoms, molecules, electrons, natural selection, etc. We have named these concepts *theoretical concepts*. The reason for the existence of theoretical concepts of imaginary objects and interactions lies in a basic assumption humans make about the universe - that is, events do not occur without a cause. Thus, if we perceive certain events but cannot perceive objects or processes that cause such events, we do not conclude that the events are spontaneous and without cause. Instead we invent unseen objects and interactions that explain the events in perceptible causal terms.

Because theoretical concepts are imagined and function to explain the otherwise unexplainable, they can be given whatever properties or qualities necessary in terms of the theory of which they are a part. That is, they derive their meaning in terms of the postulates of specific theories (Lawson, 1958; Lewis, 1980; 1988; Northrop, 1947; Suppes, 1968).

Of significance to the educator attempting to teach theoretical concepts such as the electron, a young child may be quite capable of imagining tiny particles and calling them electrons, if the teacher wishes, but with little or no awareness or understanding of (1) the theoretical system of which they are a part and in fact from which they derive their importance, (2) the empirical situation(s) which led to the postulation of the existence of these "tiny particles" in the first place, and (3) the evidence which supports the existence of the particles. To the young child with no understanding of the nature of theoretical systems and their relationship to empirical data, the idea of the electron and other theoretical concepts must seem to have derived meaning as if by magic or perhaps by decree of some omniscient scientist. In short, one cannot fully comprehend the meaning of any single theoretical concept without some appreciation and awareness of the theoretical system of which it is but a part and of the empirical data upon which that system is based (cf., Lawson and Karplus, 1977; Shayer and Adley, 1981).

Conceptual Systems - Concepts by apprehension, descriptive concepts, and theoretical concepts are the bricks that, when cemented together, make up the conceptual systems that represent our knowledge of the world and universe, the conceptual systems that make up the laws of the land, the philosophies and religions that guide human lives - in short, the contents of human minds.

Basically, conceptual systems are of two types, descriptive or theoretical, depending on the nature of the concepts which comprise the system. A descriptive conceptual system is composed of concepts by apprehension and descriptive concepts only. A theoretical system is composed of concepts by apprehension, descriptive concepts, and theoretical concepts.

Examples of descriptive conceptual systems are: human anatomy, early Greek cosmology, taxonomies, and games such as chess, football and baseball. Each of these systems consists of concepts about perceivable objects and the interactions of these objects.

Theoretical conceptual systems are exemplified by atomic-molecular theory, Mendelian genetics, Darwin's theory of evolution through natural selection and so on. In atomic-molecular theory, the atoms and molecules were imagined to exist and to have certain properties and behaviors, none of which could be observed. However, by assigning certain properties to atoms that included combining with each other to form molecules, observable chemical changes could be explained. In the same manner, Mendel imagined genes to exist that occurred in pairs, separated at the time of gamete formation, combined when egg and sperm united, and determined the course of development of the embryo. By assuming the gene to exist and to have certain properties and behavior, Mendel could explain the observable results from crosses of plants and animals.

Each conceptual system is composed of a finite set of basic postulates that taken together define the system and certain basic concepts of that system. For example, the basic postulates of classic Mendelian genetics are as follows:

1. Inherited traits are determined by particles called genes.
2. Genes are passed from parent to offspring in the gametes.
3. An individual has at least one pair of genes for each trait in each cell except the gametes.
4. Sometimes one gene of a pair masks the expression of the second gene (dominance).
5. During gamete formation, paired genes separate. A gamete receives one gene of each pair.
6. There is an equal probability that a gamete will receive either one of the genes of a pair.
7. When considering two pairs of genes, the genes of each pair assort independently to the gametes.
8. Gene pairs separated during gamete formation recombine randomly during fertilization.

These postulates, when taken together, constitute the essence of a theoretical conceptual system (i.e., a theory) used to explain how traits are passed from parent to offspring. Concepts such as gene, dominance, recessive, independent assortment and segregation derive their meaning from postulates of the system. When the postulates of a theory such as Mendel's theory become widely accepted, the theory is referred to as an "embedded" theory and its postulates take on the status of "facts." The postulates of many important scientific theories have been identified by Lewis (1980; 1987; 1988).

How Are Descriptive Concepts Formed? The Constructive Process

To acquire a sense of how the formation of descriptive concepts takes place, consider the drawings in Figure 2. The first row of Figure 2 contains five "creatures" called Mellinarks (Elementary Science Study, 1974). None of the creatures in the second row are Mellinarks. From this information try to decide which of the creatures in the third row are Mellinarks.

The problem of deciding which of the creatures in row three is/are Mellinarks is an example of descriptive concept formation. If you correctly identified the first, second and sixth figures as Mellinarks you have formed a "concept" (schema) for the term Mellinarks. How did you do it? Outdated theories of abstraction (Locke, 1690; Hume, 1739) would claim that you "induced" a set of specific characteristics and generalized it to other instances. Modern theories, on the other hand, emphasize the importance of hypothesis generation and the predictive nature of concept formation (e.g., Bolton, 1977; Holland, Holyoak, Nisbett and Thagard, 1986; Mayer, 1983). Also recall Lawson's model of Belief-Expectation-Test (Lawson, 1958):

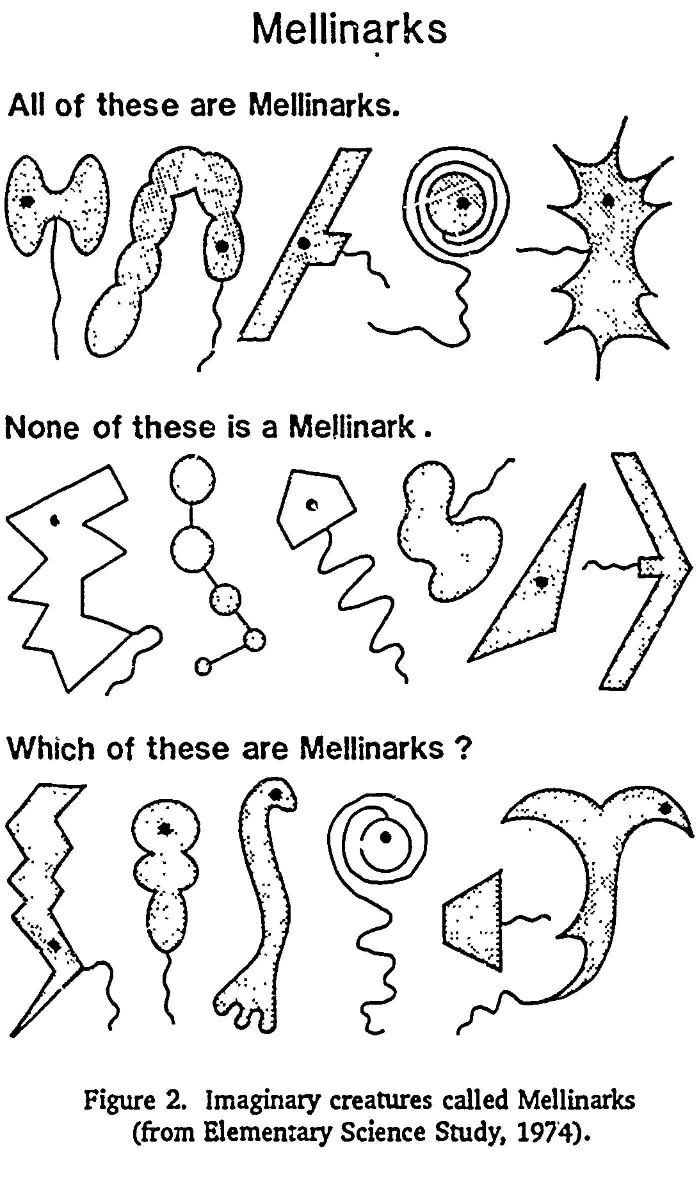


Figure 2. Imaginary creatures called Mellinarks (from Elementary Science Study, 1974).

Let us consider a solution employing the more modern notion of hypothesis generation and testing. A glance at row one reveals several features of the Mellinarks. They have tails. They contain one large dot and several smaller dots. They have an enclosed cell-like membrane that may have curved or straight sides. If we assume that features such as these are crucial, then which ones? The nature of the membrane (curved or straight) can be eliminated immediately as both membrane types exist in row one. The importance of the other three features can be tested easily starting with some hypotheses as follows. Mellinarks consist of creatures with:

1. one large dot only
2. several small dots only
3. one tail only
4. one large dot & several small dots
5. one large dot & one tail
6. several small dots & one tail
7. one large dot & several small dots & one tail

Hypothesis 1 would lead one to predict that all the creatures of row one and none of the creatures in row two would contain one large dot. Since this is not the case, the prediction is disconfirmed and the hypothesis that Mellinarks are creatures distinguished solely by the presence of one large dot is also disconfirmed. The same pattern of hypothetico-deductive reasoning leads one to disconfirm hypotheses 2 through 6 as well, leaving hypothesis 7, that Mellinarks are defined by the presence of all three features, as "correct." Thus only the first, second and sixth creatures in row three are Mellinarks.

Concept formation, seen in this light, is not viewed as a purely abstractive process but rests on the ability to generate and test hypotheses. In this sense one's conceptual knowledge (an aspect of declarative knowledge) depends upon one's procedural knowledge. As one gains skill in using these hypothetico-deductive procedures, concept formation becomes easier. More will be said about this later when we discuss the development of procedural knowledge. In the case of the Mellinarks, the concept formed is a descriptive one as its defining attributes are directly perceptible. We may continue to use the term *induction* to refer to this process of concept formation provided we do not view induction as purely abstractive.

The Role of Chunking in Higher-Order Concept Formation

The human mind at any one moment is able to mentally integrate or process only a limited amount of information. Miller (1956) introduced the term "chunk" to refer to the discrete units of information that could be consciously held in working memory and transformed or integrated. He cited considerable evidence to suggest that the maximum number of these discrete chunks was approximately seven.

Clearly, however, we all form concepts that contain far more information than seven units. The term ecosystem, as mentioned, subsumes a far greater number of discrete units or chunks than seven. Further, the term "ecosystem" itself is a concept, thus it probably occupies but one chunk in conscious memory. This implies that a mental process must occur in which previously unrelated parts -- that is, chunks of information (a maximum of about seven chunks) - are assembled by the mind into one higher-order chunk or unit of thought. This implied process is known as chunking (Simon, 1974).

The result of higher-order concept formation (chunking) is extremely important. It reduces the load on mental capacity and simultaneously opens up additional mental capacity that can then be occupied by additional concepts. This in turn allows one to form still more complex and inclusive concepts (i.e., concepts which subsume greater numbers of subordinate concepts). To turn back to our initial example, once we all know what a Mellinark is we no longer have to refer to them as "creatures within an enclosed membrane that may be curved or straight, one large dot and several smaller dots inside and one tail." Use of the term Mellinark to subsume all of this information greatly facilitates thinking and communication when both parties have acquired the concept. See Ausubel (1963) and Ausubel, Novak and Hanesian (1968) for details of the subsumption process.

How are Theoretical Concepts Formed?

The preceding discussion of descriptive concept formation leaves two important issues unresolved. How does concept formation take place when the defining attributes are not directly perceptible, that is when the concept in question is a theoretical one? And what takes place when the theoretical concept to be acquired contradicts a previously acquired concept?

Again let us consider these issues through the use of an example. The example is that of Charles Darwin as he changed his view from that of a creationist to that of an evolutionist. Further he invented a satisfactory theory of evolution through natural selection. Note that the concepts of creationism, evolution, and natural selection are all theoretical, according to our previous definition.

Let us consider the process of conceptual change first. How are inappropriate theoretical concepts modified or discarded in favor of more appropriate theoretical concepts? This is a difficult question to answer, primarily because the process takes place inside people's heads away from the observer and often at a subconscious level. Thus it is not only hidden from the researcher, but often hidden from the subject as well (cf., Finley, 1986).

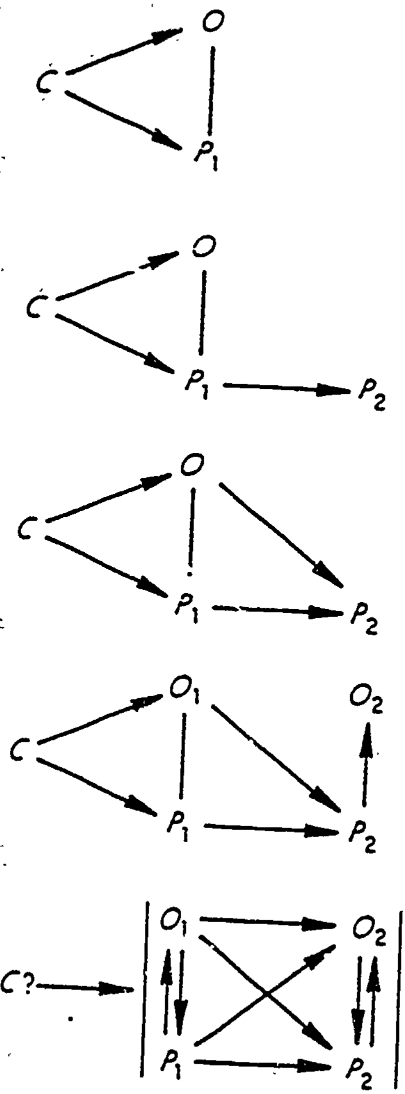
Conceptual Change

To get a handle on this problem, Gruber and Barrett (1974) analyzed Darwin's thinking during the period 1831 to 1838 when he underwent a conceptual change from a creationist theory of the world (a misconception in today's scientific thinking, to that of an evolutionist (a currently valid scientific conception). Fortunately for Gruber and Barrett and for us, Darwin left a record of much of his thinking during this period in copious diaries. Figure 3 highlights the major changes in his theoretical conceptual system during this time.

Darwin's theory in 1831 has been described by Gruber and Barrett (1974) as one in which the creator made an organic world (O) and a physical world (P). In this view, the organic world was perfectly adapted to the physical world (see A of Figure 3). This view of the world served Darwin well and his thoughts and behavior were consistent with this view.

Although Charles Darwin was most certainly a creationist in 1831 he was well aware of evolutionary views. In fact, Darwin's own grandfather, Erasmus Darwin, published a work entitled *Zoonomia: or the Laws of Organic Life* that contained speculative ideas about evolution and its possible mechanism. Nevertheless, Charles Darwin on that day in 1831, when he boarded the H.M.S. Beagle as the ship's naturalist, was seeking an adventure - not seeking a theory of evolution.

During the first two years of the voyage on the *Beagle*, Darwin read some persuasive ideas about the modification of the physical environment through time by Charles Lyell in his two volume work entitled *Principles of Geology*. At each new place Darwin visited, he found examples and important extensions of Lyell's ideas. Darwin was becoming increasingly convinced that the physical world was not static - it changed through time. This new conception of the physical world stood in opposition to his earlier beliefs and it created a serious contradiction. If the organic world and the physical world are perfectly adapted, and the physical world changes, then the organic world must also change. This, of course, is the logical extension of the argument. Its conclusion, however, was the opposite of Darwin's original theory that organisms did not evolve.



a. 1832 and before: The creator (C) made an organic world (O) and a physical world (P); O was perfectly adapted to P. Mental equilibrium exists.

b. 1832-1834: The physical world undergoes continuous change, governed by natural forces as summarized in Lyell's *Principles of Geology*. A logical contradiction is implied which induces a state of disequilibrium.

c. 1835: Activities of organisms contribute to changes in the physical world (e.g., coral reefs). Disequilibrium persists.

d. 1836-1837: Changes in the physical world imply changes in the organic world if adaptation is to be maintained; the direct action of the physical environment "induces" organic adaptations. Equilibrium is partially restored.

e. 1838 and after: The physical and organic worlds continuously interact and induce reciprocal changes to maintain adaptations. The role of the creator is unclear. He may have set the system into existence yet stands outside. Mental equilibrium is restored at a higher more complex plane.

Figure 3. Charles Darwin's changing world view from 1832 to 1838 as an example of mental equilibration (after Gruber & Barrett 1974).

This contradiction of views put Darwin into what Piaget has called a state of mental disequilibrium because Darwin did not immediately accept the logic of this situation and conclude that organisms must also change. In fact, it was not until 1837, after his return to England, that he was converted to the idea of evolution of species (Green, 1958). It seems unlikely that it would require this amount of time for Darwin to assimilate the logic of the situation, but the fact of the matter is that in the 2,000 pages of geological and biological notes made during the voyage, there is very little discussion of the evolution of organisms. What little there is opposes the idea.

Precisely how and why Darwin changed his view is, of course, not known. Figure 3, however, appears to be a fairly accurate summary of his changing world view. Smith and Millman (1987) have also carefully examined Darwin's notebook (particularly the B notebook) and have characterized Darwin's mind as in a state of "exploratory thinking" meaning that, rather than accepting any particular theory, Darwin was considering various views (alternative hypotheses) to explain the situation as he saw it. If we assume that the weight of accumulating evidence forced a rejection of special creation (e.g., physical change, intermediate "forms" of organisms, untold diversity of species = more than could reasonably be held on Noah's ark), then this exploratory thinking was aimed primarily at explaining evolution. Figure 3e thus represents the partial restoration of mental equilibrium as it eliminates the logical contradiction implied in Figure 3b.

Piaget refers to the process of moving from a mental state of equilibrium to disequilibrium and back to equilibrium as equilibration. Therefore, an initial answer to the question how does conceptual change occur is through the process of equilibration. The necessary conditions for conceptual equilibrium to take place appear to be: (1) data which are inconsistent with prior ways of thinking, (2) the presence of alternative conception/hypotheses (the hypothesis of evolution), and (3) sufficient time, motivation and thinking skills to compare the alternative hypotheses and their predicted consequences with the evidence (cf., Poser, Strike, Hewson and Gerzog, 1982; Hewson and Hewson, 1984; Anderson and Smith, 1986; Lawson & Thompson, 1987).

The Use of Analogy

Once Darwin had accepted the alternative hypothesis that organisms evolve, the question of "How?" immediately arose. Of course his answer was through a process called natural selection. Thus, natural selection represents a theoretical concept employed by Darwin. Further, unlike the example of our formation of the descriptive concept of Mellinarks, the defining attributes of the concept of natural selection are not visible. By what intellectual process did Darwin come to use the concept of natural selection? How, in general, are theoretical concepts formed?

According to the record (e.g., Gruber and Barret, 1974; Smith and Millman, 1987; Green, 1958), Darwin's search for a theory to explain the evolution of organisms involved a number of initially unsuccessful trials and a good deal of groping until September of 1838 when a key event occurred. Darwin read Thomas Malthus' *Essay on Population*. Darwin wrote, "I came to the conclusion that selection was the principle of change from the study of domesticated productions; and then reading Malthus, I saw at once how to apply this principle" (Green, 1958, pps. 257-258). Darwin saw in Malthus' writing a key idea that he could *borrow* and use to explain evolution. That key idea was that *artificial* selection of domesticated plants and animals was *analogous* to what presumably occurs in nature and could account for a change or evolution of species. As Gruber (1974, pps. 118-119) points out, Darwin had read Malthus before but it was not until this reading that he became conscious of the import of the artificial selection process.[2] But once it had been assimilated, Darwin turned to the task of marshalling the evidence favoring his theory of descent with modification. He turned to the facts known about plant and animal breeding, to the evidence which had first led him to doubt the fixity of species, namely the facts concerning the geographic distribution of organic forms, and to the creatures of the Galapagos Islands. He discovered support for his ideas in the geological, anatomical, ecological, and embryological records of the time and by the year 1842 he was ready to commit a rough draft of his entire theory to paper (Green, 1958).

The example of Darwin's use of the analogous process of artificial selection suggests that analogy plays a central role in theoretical concept formation. The "idea" or pattern that allowed Darwin to make sense of his data was analogous to the pattern inherent in the process of artificial selection. Hanson refers to this process of the borrowing of old ideas and applying them in new situation as "abduction" (Hanson, 1947). Others have referred to the process as analogical reasoning (Karplus, 1979; Lawson & Lawson, 1979) or analogical transfer (Holland, Holyoak, Nisbett and Thagard, 1986).

Examples of abduction are numerous in history of science. Kepler borrowed the idea of the ellipse from Appolonious to describe planetary orbits. Mendel

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[2]One might well ask why did Darwin not recognize the importance of the selection process when he first read Malthus. Of course, no one knows the answer to this question for certain but it is clear that the concept of natural selection assumes awareness of prior concepts such as limiting factors, variation and biotic potential. If Darwin was not aware of these ideas, or if they were not near his plane of consciousness when he read about artificial selection, it would seem unlikely that the importance of the idea in evolution would be recognized.

borrowed patterns of algebra to explain heredity. Kekulè borrowed the idea of snakes eating their tails (in a dream!) to determine the molecular structure of benzene, and Coulomb borrowed Newton's ideas of gravitational attraction to describe the electrical forces which exist at the level of atomic particles.

Abduction, the use of analogy to borrow old ideas and apply them in new situations to invent new concepts and new explanations, is all-pervasive. According to Pierce (quoted in Hanson, 1947):

> *All the ideas of science come to it by way of Abduction. Abduction consists in studying the facts and devising a theory to explain them. Its only justification is that if we are ever to understand things at all, it must be that way. Abductive and inductive reasoning are utterly irreducible, either to the other or to Deduction, or Deduction to either of them.... (p. 85).*

Thus, the answer to the question of how theoretical concepts are formed is by applying a previously acquired pattern from the world of observable objects and events to explain unobservable events. The scientist must discover the analogy for him or herself while the student in the classroom can be assisted by having the teacher point out the relevant analogy.

The General Pattern of Concept Formation and Conceptual Change

Upon reflection we can identify a general pattern which exists in both processes of concept formation (whether one is forming descriptive concepts via induction or theoretical concepts via abduction) and conceptual change. The pattern exists in both because what we are considering in concept formation and change are not really two different processes but two ends of the same continuum. As Piaget reminds us, every act of assimilation to a cognitive structure is accompanied by some accommodation of that structure. No two experiences are ever identical, therefore pure assimilation is not possible. Likewise, pure accommodation presumably does not take place because that would imply that a cognitive reorganization has taken place without any input from the environment. Thus, at the concept formation end of the continuum we have the dominance of assimilation over accommodation and at the conceptual change end of the continuum we have a dominance of accommodation over assimilation.

The general pattern is shown in Figure 4. Box A represents the question which was been prompted due to some experience (e.g., what is a Mellinark? How did the diversity of species arise?) Box B represents alternative hypotheses which have arisen either by the selection of perceptible features of the problem situations (induction) or via analogical reasoning (abduction) from either one's own memory or that of others (e.g., in books). The use of analogical reasoning is an important component of what is often referred to as creative thinking. Importantly the subconscious mind plays an important role in the generation of novel ideas.

To test alternative hypotheses some experimental and/or correlational situation must be imagined which allows the deduction of the ideas' logical consequences (Box C). The logical consequences (predictions) are then compared with the actual results of the test which are represented by Box D. If the predicted results and the actual results are essentially the same then support for the hypothesis has been obtained. If not, the hypothesis has been weakened and others should be generated and tested until a reasonable agreement is obtained. Note how the words if...and...then and therefore tie the elements of the hypothetico-deductive process together into a reasonable argument for or against any particular hypothesis or set of alternatives.

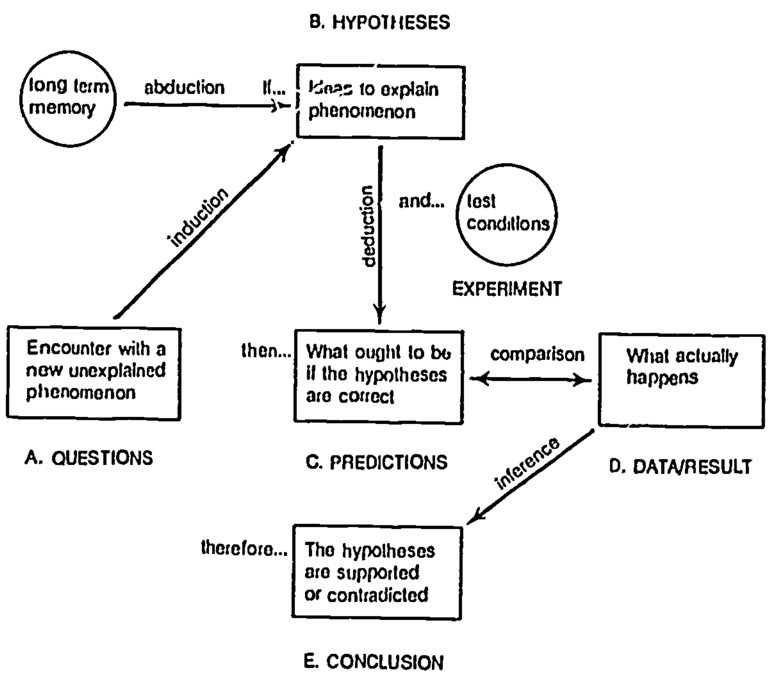

Figure 4. The basic pattern of hypothetico-deductive thinking.

The acquisition of declarative knowledge is very much a constructive process which makes either implicit or explicit use of the procedural knowledge. Of course students can memorize, in a rote fashion, aspects of declarative knowledge but such learning by rote will not assist in the improvement of the procedural knowledge. The pedagogical task is to teach in such a way that students participate in the constructive process because doing so improves meaningfulness and retention of the declarative knowledge and increases consciousness and generalizability of the procedural knowledge. Before we turn to a discussion of how use of the learning cycle accomplishes this task, we will take a closer look at the nature of procedural knowledge.

The Nature of Procedural Knowledge

Figure 4 depicted the way in which concept formation occurs, i.e., the way people learn about their world. The result of this learning process is conceptual/declarative knowledge. The procedures one uses to generate that declarative knowledge are collectively known as procedural knowledge. Thus the boxes of the figure represent various aspects of declarative knowledge (questions, hypotheses, predictions, results, and conclusions) while the arrows (from box to box) represent various procedures (abduction, induction, deduction, and inference). Various reasoning patterns (cognitive strategies) such as combinatorial reasoning (the generation of combinations of alternative hypotheses) the control of variables (experimenting in a way which varies only one independent variable) and correlational reasoning (comparing ratios of confirming to disconfirming events) are embedded in the process.

Because of the central importance of procedural knowledge in science and in creative and critical thinking in general, psychologists and educators alike have attempted to identify its components with as much precision as possible. One of the early attempts to do so contained eight central skills and several subskills (Burmester, 1952). A modified list of those skills appears below grouped into seven categories intended to be easily relatable to the general pattern of thinking depicted in Figure 4. The seven categories are:

1. Skill in accurately describing nature.
2. Skill in sensing and stating causal questions about nature.
3. Skill in recognizing, generating and stating alternative hypotheses and theories.
4. Skill in generating logical predictions.
5. Skill in planning and conducting controlled experiments to test hypotheses.
6. Skill in collecting, organizing and analyzing relevant experimental and correlational data.
7. Skill in drawing and applying reasonable conclusions.

Some of the above skills are creative, while others are critical. Still others involve both creative and critical aspects of scientific thinking. We are defining a skill as the ability to do something well. Skilled performance includes knowing what to do, when to do it, and how to do it. In other words, being skilled at something involves knowing a set of procedures, knowing when to apply those procedures, and being proficient at executing those procedures. The seven general skills listed above can be further delimited into the following subskills:

1.00 Skill in accurately describing nature.
- 1.10 Skill in describing objects in terms of observable characteristics.
- 1.20 Skill in seriating objects in terms of observable characteristics.
- 1.30 Skill in classifying objects in terms of observable characteristics.
- 1.40 Skill in describing, seriating, classifying and measuring objects in terms of variables such as amount, length, area, weight, volume and density.
- 1.50 Skill in identifying variable and constant characteristics of groups of objects.
  - 1.51 Skill in identifying continuous and discontinuous variable characteristics and naming specific values of those characteristics.
  - 1.52 Skill in measuring, recording and graphing the frequency of occurrence of certain values of characteristics in a sample of objects.
  - 1.53 Skill in determining the average, median, and modal values of the frequency distribution in 1.52 above.
- 1.60 Skill in recognizing the difference between a sample and a population and identifying ways of obtaining a random (unbiased) sample.
  - 1.61 Skill in making predictions concerning the probability of occurrence of specific population characteristics based upon the frequency of occurrence of those characteristics in a random sample.

2.00 Skill in sensing and stating causal questions about nature.
- 2.10 Skill in recognizing a causal question from observation of nature or in the context of a paragraph or article.
- 2.20 Skill in distinguishing between an observation and a question.
- 2.30 Skill in recognizing a question even when it is stated in expository form rather than in interrogatory form.
- 2.40 Skill in distinguishing a question from a possible answer to a question (hypothesis) even when the hypothesis is presented in interrogatory form.
- 2.50 Skill in distinguishing between descriptive and causal questions.

3.00 Skill in recognizing, generating and stating alternative hypotheses (causal explanations) and theories.
- 3.10 Skill in distinguishing an hypothesis from a question.
- 3.20 Skill in differentiating between a statement that describes an observation or generalizes from the observation and a statement which is an hypothesis (causal explanation) for the observation.
- 3.30 Skill in recognizing the tentativeness of an hypothesis or theory.
- 3.40 Skill in distinguishing between a tentative explanation for a phenomenon (hypothesis) and a term used merely to label the phenomenon.
- 3.50 Skill in systematically generating all possible combinations of generated hypotheses.

4.00 Skill in generating and stating logical predictions based upon the assumed truth of hypotheses and imagined experimental conditions.
- 4.10 Skill in differentiating between hypotheses and predictions.

5.00 Skill in planning and conducting controlled experiments to test alternative hypotheses.
- 5.10 Skill in selecting reasonable alternative hypotheses to test.
- 5.20 Skill in differentiating between an uncontrolled observation and an experiment involving controls.
- 5.30 Skill in recognizing that only one independent factor in an experiment should be variable.
  - 5.31 Skill in recognizing the independent variable factor and the dependent variable factor(s).
  - 5.32 Skill in recognizing the factors being held constant in the partial controls.
- 5.40 Skill in recognizing experimental and technical problems inherent in experimental designs.
- 5.50 Skill in criticizing faulty experiments when:
  - 5.51 The experimental design was such that it could not yield an answer to the question.
  - 5.52 The experiment was not designed to test the specific hypotheses stated.
  - 5.53 The method of collecting the data was unreliable.
  - 5.54 The data were not accurate.
  - 5.55 The data were insufficient in number.
  - 5.56 Proper controls were not included.

6.00 Skill in collecting, organizing and analyzing relevant experimental and correlational data.
- 6.10 Skill in recognizing existence of errors in measurement.

6.20 Skill in recognizing when the precision of measurement given is warranted by the nature of the question.

6.30 Skill in organizing and analyzing data.

6.31 Skill in constructing tables and frequency graphs.

6.32 Skill in measuring, recording, and graphing the values of two variables on a single graph.

6.33 Skill in constructing a contingency table of discontinuous variables.

6.40 Skill in seeing elements in common to several items of data.

6.50 Skill in recognizing prevailing tendencies and trends in data and to extrapolate and interpolate.

6.60 Skill in applying quantitative notions of probability, proportion, percent, and correlation to natural phenomena and recognize when variables are related additively or multiplicatively setting up simple quantitative equations describing these relationships.

6.61 Skill in recognizing direct, inverse, or no relationship between variables.

6.62 Skill in recognizing that when two things vary together, the relationship may be coincidental, not causal.

6.63 Skill in recognizing additional evidence needed to establish cause and effect (see 6.62 above).

7.00 Skill in drawing and applying reasonable conclusions.

7.10 Skill in evaluating relevancy of data and draw conclusions through a comparison of actual results with predicted results.

7.11 Skill in differentiating between direct and indirect evidence.

7.12 Skill in recognizing data which are unrelated to the hypotheses.

7.13 Skill in recognizing data which support an hypothesis.

7.14 Skill in recognizing data which do not support an hypothesis.

7.15 Skill in combining both supportive and contradicting evidence from a variety of sources to weigh the likely truth or falsity of hypotheses.

7.16 Skill in postponing judgement if no evidence or insufficient evidence exists.

7.17 Skill in recognizing the tentativeness inherent in all scientific conclusions.

7.20 Skill in applying conclusions to new situations.

7.21 Skill in refraining from applying conclusions to new situations which are not closely analogous to the experimental situation.

7.22 Skill in being aware of the tentativeness of conclusions about new situations even when there is a close parallel between the two situations.

7.23 Skill in recognizing the assumptions which must be made in applying a conclusion to a new situation.

These skills function in concert in the mind of the creative and critical thinker as he or she learns about the world. They include key steps and the key words "if...," "and...," "then...," "therefore...." as depicted in Figure 4. The skills are, in essence, learning tools essential for success and even for survival. Hence, if you help students improve their use of these creative and critical thinking skills you have helped them become more intelligent and helped them "learn how to learn."

Stages in the Development of Procedural Knowledge - Piaget's Theory

A great deal has been written about the development of procedural/ operative knowledge within the Piagetian tradition (e.g., Collette and Chiappetta, 1986; Collea et al., 1975; Inhelder and Piaget, 1958; Karplus et al., 1977). Piaget's stages of sensory-motor, preoperational, concrete operations, and formal operations are well known. Little argument exists over the validity of the notion of levels or phases in the development of procedural knowledge but considerable controversy exists regarding the details.

In Piaget's theory the child at birth is in a stage called sensory-motor. During this stage, which lasts for about 18 months, the child acquires such practical knowledge as the fact that objects continue to exist even when they are out of view (object permanence). The name of the second stage describes the characteristics of the child: *preoperational* – the stage of intellectual development before mental operations appear. In this stage, which persists until around seven years of age, the child exhibits extreme egocentricism, centers his attention only upon particular aspects of given objects, events, or situations, and does not demonstrate conservation reasoning. In other words, the child's thinking is very rigid. The major achievement during this stage is the acquisition of language.

At about seven years of age the thinking processes of children begin to "thaw out"; they show less rigidity. This stage, called *concrete operational*, is marked by the development of operations. Concrete operations are defined as mentally internalized and reversible systems of thought based on manipulations of classes, relations, and quantities of objects. The child can now perform what Piaget calls mental experiments; he can assimilate data from a concrete experience and arrange and rearrange them in his head. In other words, the concrete operational child has a much greater mobility of thought than when he was younger.

The name of this stage of development is representative of the type of thinking of this type of learner. As Piaget explains this stage, "The operations involved ... are called 'concrete' because they relate directly to objects and not yet to verbally stated hypotheses" (Piaget and Inhelder 1969, p. 100). In other words, the mental operations performed at this stage are "object bound" – operations are tied to objects.

The potentiality for the development of what Piaget calls *formal operational* thought develops between 11 and 15 years of age. For Piaget, the stage of formal operations constitutes the highest level in the development of mental structures. A person who has entered that stage of formal thought "...is an individual who thinks beyond the present and forms theories about everything, delighting especially in considerations of that which is not" (Piaget, 1966, p. 148).

Presumably there is nothing genetically predetermined in this sequence of development of mental structures. Rather, as Inhelder and Piaget state, "...maturation of the nervous system can do no more than determine the totality of possibilities and impossibilities at a given stage. A particular social environment remains indispensable for the realization of these possibilities" (Inhelder and Piaget, 1958, p. 337). Piaget chose the name *formal operational* for his highest stage of thought because of his belief that thinking patterns are isomorphic with rules of formal propositional logic (cf., Piaget, 1957). This position is perhaps the most problematic in Piaget's theory. A long line of research indicates clearly that, although advances in reasoning performance do occur during adolescence, no one, even professional logicians, reason with logical rules divorced from the subject matter (Griggs, 1983; Lehman, Lempert, and Nisbett, 1988; Nisbett, Fong, Lehman, and Cheng, 1987; Wason and Johnson-Laird, 1972).

Reflectivity and the Internalization of Patterns of Argumentation

If the acquisition of formal rules of logic do not differentiate the thinking of the child from that of the adolescent, then what does? Lawson, Lawson, and Lawson (1984) hypothesized that the important shift is one towards greater reflectivity due to the adolescent's ability to ask questions, not of others, but of oneself and to reflect on the correctness or incorrectness of answers to those questions in a hypothetico-deductive manner. This internalized hypothetico-deductive question asking and answering behavior involves the acquisition of linguistic skills associated with hypothesis testing and leads ultimately to the development of hypothesis testing schemes and patterns of argumentation. In other words, prior to adolescence the child raises questions, generates answers, yet has no systematic means of asking him/herself if his answers are correct or not. He/she must rely on others for this so when left on his/her own he/she simply generates ideas and for the most part uses them for better or for worse.

Without such a reflective ability children confronted with complex tasks simply choose the most obvious solution that pops into their heads and conclude that it is correct without consideration of arguments in its favor or disfavor.

Kuhn, Amsel, and O'Loughlin (1988) reached a similar conclusion regarding the differences between child-like and adult-like thinking. They identified three key abilities that are acquired by some adults. First is the ability to think about a theory rather than thinking only with a theory. In other words, the reflective adult is able to consider alternative theories, and ask which is the most acceptable. On the other hand, the intuitive thinker does not consider the relative merits and demerits of alternative theories (hypotheses), he/she merely has a "theory" and behaves as though it was true. Chamberlain (1897) referred to these are ruling theories.

Second is the ability to consider the evidence to be evaluated as distinct from the theories themselves. For the child, evidence and theory are indistinguishable. In our experience perhaps the most difficult distinction to be made in the classroom is that between the words *hypothesis*, *prediction* and *evidence* (Lawson, Lawson and Lawson, 1984). Presumably this is the case because the words are essentially meaningless if one has never before tried to decide between two or more alternative explanations, thus has never before considered the role played by predictions and evidence. Third is the ability to set aside one's own acceptance (or rejection) of a theory in order to objectively evaluate it in light of its predictions and the evidence.

Lawson, Lawson, and Lawson (1984) hypothesized that the ability to reflect on the correctness of one's theories arises as a consequence of the internalization of patterns of external argumentation which occurs with others when alternative theories are proposed. This hypothesis appears to be in essential agreement with Piaget's earlier thinking. Piaget (1928) advanced the hypothesis that the development of advanced reasoning occurred as a consequence of "the shock of our thoughts coming into contact with others, which produces doubt and the desire to prove" (p. 204). Piaget went on to state:

> *The social need to share the thought of others and to communicate our own with success is at the root of our need for verification. Proof is the outcome of argument...*
>
> *Argument is therefore, the backbone of verification. Logical reasoning is an argument which we have with ourselves, and which produces internally the features of a real argument. (p. 204).*

In other words, the growing awareness of and ability to use the pattern of hypothetico-deductive thought during adolescence (defined as the ability to ask questions of oneself, generate tentative answers, deduce predictions based upon those answers, and then sort through the available evidence to verify or reject those tentative answers, all inside one's own head), occurs as a consequence of attempting to engage in arguments of the same sort with other persons and listening to arguments of others in which alternative propositions (theories) are put forward and accepted or rejected as the basis of evidence and reason as opposed to authority or emotion.

This position also seems consistent with that of Vygotsky (1962) who views speech as social in origin and only with time does it come to have self-directive properties that eventually result in internalized verbalized thought. This position is also similar to that of Luria. According to Luria (1961) the progressive differentiation of language to regulate behavior occurs in four steps. First, the child learns the meaning of words; second, language can serve to activate behavior but not limit it; third, language can control behavior through activation or inhibition via communication from an external source; and fourth, the internalization of language can serve a self-regulating function through instructions to oneself.

Even Piaget (1976) proposed a similar three-level theory of procedural knowledge development. The first level (sensory-motor) is one in which language plays little or no role as it has yet to be acquired. The child learns primarily through sensory-motor activity and knowledge is that of action. The second level is characterized by the acquisition of language. The child is able to respond to spoken language and acquire knowledge transmitted from adults who speak the same language. To learn, the child is able to raise questions and have adults respond verbally to those questions. Of course, this is not to say that all adult responses are understood; nonetheless, a new and powerful mode of learning is available to the child. The essential limitation of this level is that the use of language as a tool for reflection and as an internal guide to behavior is poorly developed. Thus reasoning at this level is essentially intuitive. The final level begins at the moment at which the individual begins to ask questions, not of others, but of himself, and through the gradual "internalization" of elements of the language of argumentation acquires the ability to "talk to himself" which constitutes the essence of reflective thought and allows one to internally test alternative hypothetical statements and arrive at internally reasoned decisions to solve problems.

Recently Voss, Greene, Post and Penner (1983) have characterized advanced thinking in the social sciences as largely a matter of constructing proposals for action that conform to many of the classical principles of rhetorical argumentation. Likewise, Lawson and Kral (1985) view the process of literary criticism as mainly a process of argumentation using these classical forms of argumentation.

No distinct age norms are suggested for the passing from one level of thinking to the next, yet we see no biological or psychological reason why a child as young as say six years old could not begin to internally reflect upon his own thoughts given an environment in which such reflective behavior was strongly encouraged. Of course this represents just a beginning and one would still require considerably more time and experience to internalize the language of argumentation and develop the associated hypothesis testing schemes. On the other hand, a dogmatic environment in which the relative merits of ideas are not discussed and rules are strictly and unthinkingly enforced would most likely retard the development of skill in using this hypothetico-deductive mode of thought.

This view of the development of procedural knowledge suggests that the terms *intuitive* and *reflective thought* are more descriptive of the intellectual changes that take place during adolescence than Piaget's terms *concrete* and *formal thought*. The child-like thinker is not conscious of the hypothetico-deductive nature of his/her thought processes, therefore thinking is dominated by context dependent cues and intuitions. The adult-like thinker, on the other hand, has become conscious of his/her thought patterns and has internalized powerful patterns of argumentation which allow a conscious reflection on the adequacy/inadequacy of ideas prior to action. Reflective thinking is not based upon formal logic as Piaget claimed, but upon alternative ideas, predictions, evidence, and arguments, all mediated by language.

To emphasize the point regarding the key distraction between child-like intuitive thought and adult-like reflective thought, let us reconsider the Mellinark concept formation task. As we saw, formation of the concept of Mellinark involved hypothesis-testing behavior. If this task is given to young children they typically will not be able (by themselves) to identify the defining attributes of Mellinarks. The problem, however, poses little difficulty to the adult (reflective adult that is). Why is this so? The answer we believe is that children have yet to become skilled in use of the necessary hypothetico-deductive pattern which allows hypotheses to be systematically generated and tested. This does not mean that children cannot develop descriptive concepts such as Mellinarks or chairs. Obviously they do. But it does mean that they do not develop the concepts themselves. They need social interaction. Specifically they need other people who have already acquired the concept to provide feedback. A young child learns the word dog and calls the neighbor's cat "doggie" and her father says "No, it's not a dog. It's a cat." Feedback may even be accompanied by additional help such as: "Dogs have floppy ears and cats have pointed ears", or "Mellinarks have a big dot, lots of little dots and a tail." The point is that the hypothesis testing of children is often mediated by exchanges with other children and/or adults.

Another example, given by Gesell (1940) occurred in the dialogue between two children age four and five.

Four: I know that Pontius Pilate is a tree.
Five: No, Pontius Pilate is not a tree at all.
Four: Yes, it was a tree, because it says: "He suffered under Pontius Pilate," so it must have been a tree.
Five: No, I am sure Pontius Pilate was a person and not a tree.
Four: I know he was a tree, because he suffered under a tree, a big tree.
Five: No, he was a person, but he was a very pontius person (p.55).

Here the four-year-old is attempting to form a concept of Pontius Pilate and mistakenly hypothesizes that the words refer to a tree - a big tree. The five-year-old, however, provides contradictory feedback to the hypothesis which will cause the four-year-old to re-think his position and eventually get it right. Here the hypothesis testing takes place through dialogue. The hypothesis testing of the reflective thinking adolescent and adult, on the other hand, can be mediated internally as the reflective thinker generates hypotheses and internally checks them for consistency with other known facts before drawing a conclusion.

How Procedural Knowledge Develops

Notice that we have argued that the reflective thinker has "internalized" important patterns of argumentation that the intuitive thinker has not. This raises the question of just how this "internalization" takes place. According to Piaget (1976) a process called "reflective abstraction" is involved in the development of procedural knowledge. Reflective abstraction involves the progression from the use of spontaneous actions to the use of explicit verbally mediated rules to guide behavior. Reflective abstraction occurs only when the subject is prompted to reflect on his/her actions. The cause of this reflection is contradiction by the physical environment or verbally by other people as was the case of the four-year-old who believed Pontius Pilate was a tree. The result of reflective abstraction is that the person may gain accurate declarative knowledge but also becomes more aware of and skilled in use of the procedures used in gaining that knowledge.

Developing the Procedure of Controlled Experimentation

To obtain a better understanding of how procedural knowledge develops let us consider a specific procedure which is essential for accurately identifying causes of specific events that is central to science and indeed to basic survival in the procedure of controlled experimentation. In this procedure the argument is as follows: If only one independent variable (possible cause) varies and the dependent variable (effect) varies then the possible cause is an actual cause. This form of argumentation is known as the method of differences (cf., Freeley, 1976; Olsen, 1969; Shurter and Pierce, 1966). Thus when one obtains a conscious awareness of this procedure he/she has developed a powerful mode of action and argumentation.

Researchers have found that young children have little difficulty in determining when a test is "fair" or "not fair" when the variables concerned are familiar (Wollman, 1977). However, they lack a general plan of attack or general strategy to use in setting up "fair comparisons" in unfamiliar situations. In other words, after a test has been performed they may be able to state if it is fair or not fair - if the variables are familiar (controlled or not controlled); however, they are unable to use this idea as a general guide to behavior. What is lacking is a general verbal rule to serve as an anticipatory guide to behavior. But we must again stress one important point - students as young as five to six years old have an intuitive feeling for what is fair and not fair.

Ausubel (1964) suggests that it is upon this intuitive feeling that we can base environmental encounters which will transform this intuitive understanding into conscious internally mediated verbal rules to guide behavior. A fair question to ask is where did this intuitive understanding come from? We have assumed that it is derived from situations in which children make comparisons and attempt to evaluate the validity of those comparisons. For example, suppose two children run a race. When the race is over and one child has lost, he blames the loss on the fact that he was wearing street shoes while his friend has on tennis shoes. He claims that the race was not really a fair test of who was the fastest runner. Other familiar examples would not be difficult to imagine. In other words, the intuitions come from argumentation about the truth or falsity of statements (e.g., "I can run faster than you can." "No, you can't, I can run faster than you"). The point is this: from environmental encounters such as this, children develop intuitive understanding of procedures involving the control of variables, probabilities, proportion, etc. What remains is for these intuitions to be transformed into conscious verbal rules so that the child is able to use them as internally mediated problem-solving strategies.

With respect to the strategy of controlling variables, let us examine the manner in which the intuitions about fairness can be transformed to a conscious verbal rule to guide behavior. We will base this discussion on an experiment (Lawson and Wollman, 1976) in which 9- and 13-year-old children who, on the basis of initial testing, were unable to demonstrate the ability to control variables in any general sense. After four half-hour training sessions these same children were clearly able to demonstrate skill in controlling variables systematically and, in most cases, unhesitatingly. Further, as evidence of general skill in using this procedure, their skill transferred to new tasks, both manipulative tasks and pencil and paper tasks.

Session 1. The first session began by giving the child a brief introduction to the intent and format of the training. He/she was told that a number of different kinds of materials would be used to try to teach him/her how to perform "fair tests." This coupled with the initial use of this term in the context of bouncing tennis balls was done to provide an intuitive feel for what the training was all about, in a sense to provide a "ball park" in which to work. The materials used in this session were materials very familiar to children: three tennis balls (two which were relatively bouncy and one which was considerably less bouncy), two square pieces of cardboard, two square pieces of foam rubber and a table. The child was told that the first problem was to find out which of the tennis balls was the bounciest. To do this he/she would instruct the experimenter in how to perform the experiment and the experimenter would carry out the instructions. Although each session varied somewhat, in general the child would begin by telling the experimenter to take two balls and drop them to see which bounced higher (height of bounce then became the dependent variable). The experimenter would then drop the two balls but drop them from different heights (an uncontrolled experiment). The child would then respond by saying: "That isn't fair. Drop them from the same height." On the next trial the height would be equalized, however, one ball would be dropped so that it hit the table top while the other ball hit the floor (again an uncontrolled experiment). This procedure was followed by continually trying to intervene with new uncontrolled variables (spin one ball, push one ball, let one ball hit cardboard or foam rubber). Children were then told that a test was called a "fair test" if all the things (variables) that might make a difference were the same in both balls (except, of course, for the difference in the balls themselves). Each time a test was made in which these variables were not the same was called an "unfair test." Following introduction of those more general statements and terms, several additional examples were given and talked through.

The overall intent of this first session was to allow the students to generate the procedures for testing and then provide contradictions which would force them to reflect on the inadequacies of their chosen procedure. The general verbal rule was also introduced in a context in which it was believed that they could gain initial understanding.

At the onset of the first session virtually all the children insisted that to determine which tennis ball was bouncier the balls must be dropped from the same height and hit the same surface on the floor. In each instance they demonstrated an intuitive feeling that the tests were "not fair" and would respond by saying: drop them from the same height, make them both hit the floor, don't spin one, etc. After the comparisons with the tennis balls were made, they were able to accept or reject them as fair or unfair, but they were unable to state a general rule or procedure for performing fair tests prior to the test itself (i.e., to perform a fair test, keep all the factors equal except that which you are testing). Not even the most articulate children were able to spontaneously respond by telling the experimenter to have "everything the same" for both balls. Even when they were asked to summarize their instructions without mentioning specific factors they were initially at a loss for words.

Students had a feeling for evenness, fairness, and symmetry but not a general rule to act as a guide for behavior – i.e., they lacked skill in using language to structure their thinking. This phenomenon is very much akin to the experience we all have had when we "know" something is true but just cannot seem to find the words to explain it. The extension of this intuitive understanding to the point where this intuition can be expressed clearly through the use of language and applied successfully to internally monitor one's thinking we believe constitutes the essence of "development" of procedural knowledge.

Session 2. The second session began by reminding the child of the intent of the training and by pointing out the new materials. The materials were six metal rods of varying size, shape, and material (Inhelder and Piager, 1958). These were placed on the table and the child was asked to classify them in as many ways as possible. This was done to determine his/her skill in forming the classes of size, shape, and material and to insure that these differences in the rods were noted. The rods were then placed into a stationary block of wood and all the factors (variables) which might affect the amount of bending of the rods (the dependent variable) were discussed. The child was then asked to perform "fair tests" to find out if the variables of length, thickness, shape, and material of the rods, as well of the amount of weight hung on the end of the rods, affects the amount the rods will bend. Whenever he/she performed a test he/she was asked: Is this a fair test? Why is it a fair test? Can you be sure that this rod bends more than that one *only* because it is thinner? Is there any other reason (an uncontrolled variable) why it might be bending more? These questions and others were used to focus the child's attention on all the relevant variables and recognize unambiguous experiments in an attempt to lead them to understand the necessity for a procedure which keeps "all factors the same" except the one being tested to determine causal relationships. A number of examples and counter-examples were discussed at length. The procedures of controlled experimentation involved in this session was of course identical to that of the first, the material (the context), however, was different.

Session 3. At the outset of the third session the child was asked to experiment with an apparatus called a Whirly Bird (Science Curriculum Improvement Study, 1970b). The Whirly Bird consists of a base which holds a post. An arm is attached to the end of the post. When pushed or propelled by a wound rubber band, the arm will spin around like the rotor on a helicopter. Metal weights can be placed at various positions along the arm. The child was briefly shown how the Whirly Bird worked and was given the task of finding out all things (variables) which he/she thought might make a difference in the number of times the arm would spin before it came to rest (the dependent variable). Possible variables included the number of times the rubber band was wound, the number of rubber bands, the number of weights placed on the arm, the position of the weights, how tightly the arm and post were fastened together, the angle of the base, etc. Following these explorations with the apparatus the child was asked to perform "fair tests" to prove that the independent variables mentioned actually did make a difference in the number of times the arm would spin. Again, whenever a test was performed children were asked questions which forced them to reflect back upon their actions such as: Is this a fair test? Why is it a fair test? Does it prove that it makes a difference? Why else might the arm spin more times? (i.e., were all other independent variables held constant?).

The general intent of this session was similar to that of the second session and the fourth and final session. The strategies underlying the questions and materials were identical in all sessions. The symbolic notation (the language used) remained invariant, while transformations in imagery were gained by using materials extending from the familiar to the unfamiliar. Children were given a variety of tasks and were allowed to choose their own procedures for performing those tasks. When mistakes were made the children were forced to reflect back on their procedures and were challenged to correct their procedures.

Session 4. In this session the use of physical materials as the source of activity and discussion was replaced by the use of written problems. Problems posed only in a written fashion were considered to represent an additional step away from the concrete and towards the abstract level. Probing questions relative to children's understanding of the written situations were asked as was done in the previous sessions. In a sense learning by doing was replaced by learning by discussion (language alone). The following two written problems were presented and discussed at length.

<u>Written Problem 1</u>

Fifty pieces of various parts of plants were placed in each of five sealed jars of equal size under different conditions of color of light and temperature. At the start of the experiment each jar contained 250 units of carbon dioxide. The amount of carbon dioxide in each jar at the end of the experiment is shown in the table.

Which two jars would you select to make a fair comparison to find out if temperature makes a difference in the amount of carbon dioxide used?

Table 1. Experimental conditions and results

Jar	Plant Type	Plant Part	Color of Light	Temp (°C)	CO_2*
1	Willow	Leaf	Blue	10	200
2	Maple	Leaf	Purple	23	50
3	Willow	Root	Red	18	300
4	Maple	Stem	Red	23	400
5	Willow	Leaf	Blue	23	150

*This column indicates cm of CO_2 in the jars at the end of the experiment.

Written Problem 2

An experimenter wanted to test the response of mealworms to light and moisture. To do this he set up four boxes as shown in the diagram below. He used lamps for light sources and watered pieces of paper in the boxes for moisture. In the center of each box he placed 20 mealworms. One day later he returned to count the number of mealworms that had crawled to the different ends of the boxes.

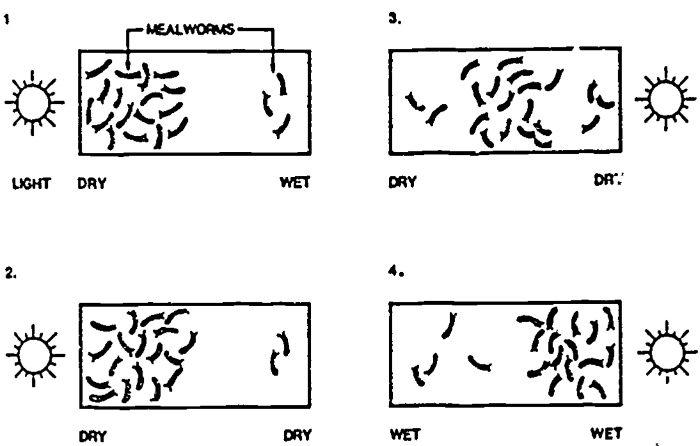

Figure 5. Mealworm responses to experimental conditions.

The diagrams show that mealworms respond (respond means move to or away from) to:

A. light but not moisture
B. moisture but not light
C. both light and moisture
D. neither light nor moisture

The training sessions clearly resulted in students who did indeed have a conscious awareness of the relevant rule. In short, they had internalized the meaning of the argument that to identify a specific cause it alone must be varied while other possible causes must be held constant. Further they appeared capable of using it.

For intuitions to manifest themselves in the form of useful linguistic rules (cognitive strategies/forms of argumentation) we presumed (and the results supported) that children need (1) a variety of problems requiring a specific procedure for solution, (2) contradictions to their proposed solutions which force them to more closely attend to what they are doing or not doing, and (3) useful terms which remain invariant across transformations in images – in this instance the key terms were "fair test" and "unfair test" and additional words used to define these terms. This is essentially the position taken by Bruner and Kenney (1970) studying problem solving procedures in mathematics. They designed instructional strategies to teach eight-year-old children the mathematical concepts of factoring, the distributive and commutative properties of addition and multiplication, and quadratic function. They summarized their instructional procedures in this way:

> *It begins with instrumental activity, a kind of definition of things by doing. Such operations become represented and summarized in the form of particular images. Finally, and with the help of symbolic notation that remains invariant across transformations in imagery, the learner comes to grasp the formal or abstract properties of the things he is dealing with (p. 494).*

In other words, this learning begins with physical experience with objects. This experience provokes children with a task and provides them with a mental record of what has been done and seen. Contradictions by others or by the physical world forces a reflection back on the procedures used to generate the results. By a closer inspection of the procedures, i.e., by noting the differences between the procedures which produced good results and those that produced contradicted results, the child becomes more aware of what he/she should and should not do. The instruction of verbal rules (symbolic notation) also aids in the identification of current procedures in the experiences. Finally, additional experiences that require the same procedure are provided along with the repetition of the invented symbolic notation to allow the student to "reflectively abstract" the procedure from the particular situations.

One further point needs to be made. The older students in the experiment were more successful then the younger students and we got the distinct impression that, although it might be possible to train still younger students (third grade for example), the task would be considerably more difficult. A number of reasons could be suggested for this increased difficulty not the least of which is that many of the children had probably seldom, if ever, engaged in external dialogues in which the relevant pattern of argumentation was used (cf., Seigler, 1976; 1978).

V. TEACHING DECLARATIVE AND PROCEDURAL KNOWLEDGE

Thus far the argument has been made that the hypothetico-deductive constructive process results in the acquisition and/or change of declarative knowledge which resides in conceptual systems of various degrees of complexity and abstractness. Further it has been argued that conscious awareness of the procedures involved in the construction of such knowledge "develops" when arguments with others occur which force one to reflect on the adequacy or inadequacy of one's procedures. Conscious verbal rules to guide behavior develop from such encounters which serve as "anticipatory schemes" to guide behavior in new situations. Thus, development extends the range of effective performance from familiar to novel situations. We now come to the central issue of this book. How can instruction be designed and carried out to help students construct and retain useful declarative knowledge and develop a conscious awareness of effective procedural rules with general applicability?

Essential Elements of Instruction

Our previous discussion suggests that the following elements must be included in lessons designed to improve both declarative and procedural knowledge:

1. Questions should be raised or problems should be posed that require students to act based upon prior beliefs (concepts and conceptual systems) and/or prior procedures.
2. Those actions must lead to results that are ambiguous and/or can be challenged/contradicted. This forces students to reflect back on the prior beliefs and/or procedures used to generate the results.
3. Alternative beliefs and/or more effective procedures should be suggested.
4. Alternative beliefs and/or the more effective procedures should now be utilized to generate new predictions and/or new data to allow either the change of old beliefs and/or the acquisition of a new belief (concept).

Suppose, for example, in a biology class students are asked to use their prior declarative knowledge (beliefs) to predict the salinity that brine shrimp eggs will hatch best in and to design and conduct an experiment to test their prediction. If students work in teams of 2-3 about 10-15 sets of data will be generated. These data can be displayed on the board. Because no specific procedures were given to the groups, the results will vary considerably. This variation in results then allows students to question one another about the procedures used to generate the results. It also provokes in some students the cognitive state of disequilibrium as their results are contradictory to their expectations. A long list of differences in procedures can then be generated. For example:

- *The hatching vials contained different amounts of water.*
- *Some vials were capped, others not capped.*
- *The amounts of eggs varied from vial to vial and group to group.*
- *Some eggs were stirred, others not stirred.*
- *Some groups used distilled water, others tap water, and so on.*

Once this list is generated it becomes clear to the students that these factors should not vary. Thus a better procedure is suggested. All the groups will follow the same procedure (that is variables will be controlled). When this is done, the real effect of various concentrations of salt can be separated from the spurious effects of the other variables. Finally once the new data are obtained, the results are clear and they allow students to see whose predictions were correct and whose were not and they allow the teacher to introduce the terms "optimum range" for the pattern of hatching that was discovered. For some students this will help restore equilibrium, for other students additional activities may be necessary.

The Learning Cycle

The main thesis thus far is that situations that allow students to examine the adequacy of prior beliefs (conceptions) force them to argue about and test those beliefs. This in turn can provoke disequilibrium when these beliefs are contradicted and provide the opportunity to acquire more appropriate concepts and become increasingly skilled in using the procedures used in concept formation (i.e., reasoning patterns/forms of argumentation). The central instructional hypothesis is that correct use of the learning cycle accomplishes this end.

Although there are the three types of learning cycles (not all equally effective at producing disequilibrium, argumentation and improved reasoning), they all follow the general three-phase sequence of exploration, term introduction and concept application introduced earlier.

During exploration, students often explore a new phenomenon with minimal guidance. The new phenomenon should raise questions or complexities they cannot resolve with their present conceptions or accustomed patterns of reasoning. In other words, it provides the opportunity for students to voice potentially conflicting, or at least partially inadequate, ideas. This can spark debate and an analysis of the reasons for their ideas. That analysis can then lead to an explicit discussion of ways of testing alternative ideas through the generation of predictions. The gathering and analysis of results then can lead to a rejection of some ideas and the retention of others. It also allows for a careful examination of the **procedures** used in the process.

A key point is that allowing for initial exploration allows students to begin to interact with the phenomena in a very personal way which can have a very profound effect on not only their observational skills but on their hypothesis generation and testing skills as well. In a series of very interesting studies Wright (1988) examined the effect of intensive instruction on students' skill in making observations of discrepant events and generating and testing alternative hypotheses to explain them. After viewing a discrepant event, students were required to identify 75 potentially relevant details of the event and generate five acceptable hypotheses. This intensive exploration activity proved to be extremely effective, as students became much better at generating alternative hypotheses and at designing experiments to test them. Wright's use of initial exploration and cue attendance hits at precisely the correct place to prompt the use and development of reflective thinking skills.

Three Types of Learning Cycles

Learning cycles can be classified as one of three types - descriptive, empirical-abductive and hypothetical-deductive. The essential difference among the three is the degree to which students either gather data in a purely descriptive fashion (not guided by explicit hypotheses they wish to test) or initially set out to test alternative hypotheses in a controlled fashion.

The three types of learning cycles represent three points along a continuum from descriptive to experimental science. They obviously place differing demands on student initiative, knowledge and reasoning skill. In terms of student reasoning, descriptive learning cycles generally require only descriptive patterns (e.g., seriation, classification, conservation) while hypothetical-deductive learning cycles demand use of higher-order patterns (e.g., controlling variables, correlational reasoning, hypothetico-deductive reasoning). Empirical-abductive learning cycles are intermediate and require descriptive reasoning patterns, but generally involve some higher-order patterns as well.

In descriptive learning cycles students discover and describe an empirical pattern within a specific context (exploration). The teacher gives it a name (term introduction), and the pattern is then identified in additional contexts (concept application). This type of learning cycle is called descriptive because the students and teacher are describing what they observe without attempting to explain their observations. Descriptive learning cycles answer the question "What?", but do not raise the causal question "Why?"

In empirical-abductive learning cycles students again discover and describe an empirical pattern in a specific context (exploration), but go further by generating possible causes of that pattern. This requires the use of analogical reasoning (abduction) to transfer terms/concepts learned in other contexts to this new context (term introduction). The terms may be introduced by students, the teacher, or both. With the teacher's guidance, the students then sift through the data gathered during the exploration phase to see if the hypothesized causes are consistent with those data and other known phenomena (concept application). In other words, observations are made in a descriptive fashion, but this type of learning cycle goes further to generate and initially test a cause(s), hence the name empirical-abductive.

The third type of learning cycle, hypothetical-deductive, is initiated with the statement of a causal question to which the students are asked to generate alternative explanations. Student time is then devoted to deducing the logical consequences of these explanations and explicitly designing and conducting experiments to test them (exploration). The analysis of experimental results allows for some hypotheses to be rejected, some to be retained and for terms to be introduced (term introduction). Finally the relevant concepts and reasoning patterns that are involved and discussed may be applied in other situations at a later time (concept application). The explicit generation and test of alternative hypotheses through a comparison of logical deductions with empirical results is required in this type of learning cycle, hence the name "hypothetical-deductive."

The following steps are utilized in preparing and using the three types of learning cycles:

1. Descriptive learning cycles
   (a) The teacher identifies some concept(s) to be taught.
   (b) The teacher identifies some phenomenon that involves the pattern upon which the concept(s) is based.
   (c) Exploration Phase: the students explore the phenomenon and attempt to discover and describe the pattern.
   (d) Term Introduction Phase: the students report the data they have gathered and they and/or the teacher describe the pattern; the teacher then introduces a term(s) to refer to the pattern.
   (e) Concept Application Phase: additional phenomena are discussed and/or explored that involve the same concept.

2. Empirical-abductive learning cycles
   (a) The teacher identifies some concept(s) to be taught.
   (b) The teacher identifies some phenomenon that involves the pattern upon which the concept(s) is based.
   (c) Exploration Phase: the teacher raises a descriptive and causal question.
   (d) Students gather data to answer the descriptive question.

(e) Data to answer the descriptive question are displayed on the board.
(f) The descriptive question is answered and the causal question is raised.
(g) Alternative hypotheses are advanced to answer the causal question and the already gathered data are examined for their initial test.
(h) Term Introduction Phase: terms are introduced that relate to the explored phenomenon and to the most likely hypothesized explanation.
(i) Concept Application Phase: additional phenomena are discussed or explored that involve the same concept(s).

3. Hypothetical-deductive learning cycles
(a) The teacher identifies some concept(s) to be taught.
(b) The teacher identifies some phenomenon that involves the pattern upon which the concept(s) is based.
(c) Exploration Phase: the students explore a phenomenon that raises the causal question or the teacher raises the casual question.
(d) In a class discussion, hypotheses are advanced and students are told either to work in groups to deduce implications and design experiments or this step is done in class discussion.
(e) The students conduct the experiments.
(f) Term Introduction Phase: data are compared and analyzed, terms are introduced and conclusions are drawn.
(g) Concept Application Phase: additional phenomena are discussed or explored that involve the same concept(s).

Descriptive Learning Cycles

It was stated earlier that the three types of learning cycles are not equally effective at generating disequilibrium, argumentation and the use of reasoning patterns to examine alternative conceptions/misconceptions. Descriptive learning cycles are essentially designed to have students observe a small part of the world, discover a pattern, name it and look for the pattern elsewhere. Little or no disequilibrium may result, as students will most likely not have strong expectations of what will be found. Graphing a frequency distribution of the length of a sample of sea shells will allow you to introduce the term "normal distribution" but will not provide much argumentation among your students. A descriptive learning cycle into skull structure/function (see appendix) allows the teacher to introduce the terms herbivore, omnivore and carnivore. It also allows for some student argumentation as they put forth and compare ideas about skull structure and possible diets. Yet seldom are possible cause-effect relationships hotly debated, and hard evidence is not sought.

Empirical-Abductive Learning Cycles

On the other hand, consider the empirical-abductive (EA) learning cycle called "What Caused the Water to Rise?" described below (also see appendix) which involves the concept of air pressure. It, like other EA learning cycles, requires students to do more than describe a phenomenon. An explanation is required. Explanation opens the door to a multitude of misconceptions. The resulting arguments and analysis of evidence represent a near perfect example of how EA learning cycles can be used to promote disequilibrium and the acquisition of conceptual knowledge and the development of procedural knowledge.

[illegible] students invert a cylinder over a candle burning in a pan of water. They observe that the flame soon goes out and water rises into the cylinder. Two causal questions are posed. Why did the flame go out? Why did the water rise? The typical explanation students generate is that the flame used up the oxygen in the cylinder and left a partial vacuum which "sucked" water in from below. This explanation reveals two misconceptions:

1. flames destroy matter thus produce a partial vacuum, and
2. water rises due to a nonexistent force called suction.

Testing of these ideas requires use of the hypothetico-deductive pattern of reasoning and utilizing the isolation and control of variables (see Figure 6).

Notice that the name given to this intermediate type of learning cycle is empirical-abductive. To clarify our selection of the term *empirical-abductive*, consider an EA learning cycle designed to teach about the process of biological decomposition. During exploration two questions are raised: 1) What factors affect the rate of breakdown of dead organisms? 2) What causes the breakdown? Students are then challenged to design experiments to answer the first question by testing the effects of a variety of variables such as temperature, amount of water, amount of light, and amount of chemicals such as salt, sugar, alcohol and antiseptic. Following student experimentation, results are displayed on the board. The results generally reveal that increased temperatures and increased amounts of water increase the rate of breakdown, while chemicals such as salt, sugar and alcohol retard breakdown.

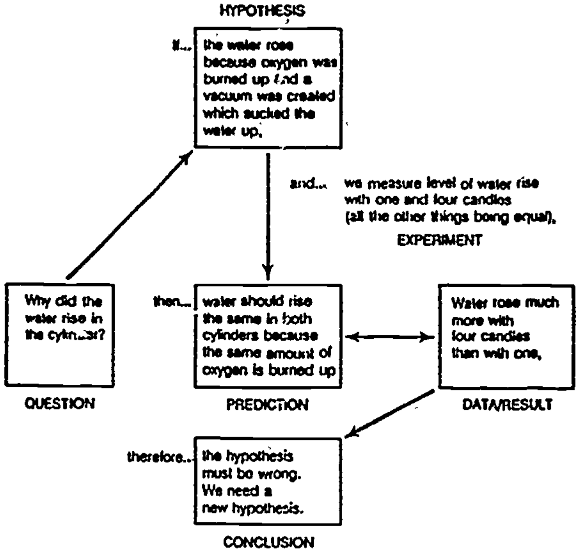

Figure 6. The box on the left represents the key question raised. In this case it is "Why did the water rise?" The subsequent hypotheses, experiments, predictions, results and conclusions follow the hypothetico-deductive if...and...then....therefore... pattern of reasoning and require students to isolate and control independent variables in comparison of water rise with one and four candles. As shown, the initial hypothesis leads to a false prediction, thus must be rejected (reasoning to a contradiction). Students must now generate an alternative hypothesis or hypotheses and start over again until they have a hypothesis that is consistent with the data (i.e., not falsified).

The students are then reminded of the second question: *What causes the breakdown?* In spite of the fact that they have just observed the growth of large quantities and varieties of molds and bacteria, they invariably respond to this question by saying that heat and water caused the breakdown. Only after considerable prodding with questions, such as *What do you suppose caused the terrible odor? What is that fuzzy black stuff all over the bread?* and *What do you suspect the black stuff is doing?* do one or more students generate the idea that perhaps the molds and bacteria are actually causing the breakdown. However, once this idea is generated you can go back to the data to see if the idea "fits". Since molds and bacteria are living things and since all living things presumably require water and a proper temperature for survival, it makes sense that containers with no water, or at freezing temperatures, would show no breakdown since the growth of molds and bacteria would be slowed or stopped. Likewise, containers with excess chemicals such as salt and alcohol might kill the molds and bacteria. Hence, the idea fits the data and the teacher can then introduce the phrase *biological decomposition* to label the process just discussed (term introduction). Other examples of biological decomposition and/or other learning cycles can now be started that allow the idea to be applied in other contexts (concept application).

Let us reflect on this learning cycle to see why we call it empirical-abductive. First, it should be clear that it begins with a look at the empirical world. Further, the students' empirical experiments are not designed with well-stated hypotheses in mind. For example, they may have a hunch that d temperature may speed up breakdown but this idea, more than likely, om past experience (e.g., with refrigeration) rather than from a theory biological decomposition. Second, when asked the second question about the actual causes of the breakdown, they are initially restricted to use of the process of *induction* and they merely induce from their results that water and heat **cause** the breakdown when in fact all the results show is a **correlational relationship**. To go beyond this restricted and incorrect view, students must be given hints and encouraged to think further about the problem until one of them "hits" on the idea the molds and/or bacteria are the actual causal agents. Since we believe that this "hitting" on the right idea involves, not **induction**, but **abduction** (i.e., the use of analogy to borrow ideas from past experience - not direct observation), and since the process is necessary to arrive at the desired theory of biological decomposition, we have chosen the terms *empirical-abduction* to refer to learning cycles of this type. In short, any learning cycle which begins with a "what factors affect....?" question and follows this up by the generation of a hypothetical cause, is an empirical-abductive learning cycle.

Hypothetical-Deductive Learning Cycles

Like EA learning cycles, hypothetical-deductive (HD) learning cycles require explanation of some phenomenon. This opens up the possibility of the generation of alternative conceptions/misconceptions with the resulting argumentation, disequilibrium and analysis of data to resolve conflict. However, unlike EA cycles, HD cycles call for the immediate and explicit statement of alternative hypotheses to explain a phenomenon. In brief, a causal question is raised and students must explicitly generate alternative hypotheses. These in turn must be tested through the deduction of predicted consequences and experimentation. This places a heavy burden on student initiative and thinking skills.

Consider, for example, the question of water rise in plants. Objects are attracted toward the center of the earth by a force called gravity, yet water rises in tall trees to the uppermost leaves to allow photosynthesis to take place. What causes the water to rise in spite of the downward gravitational force? The following alternative hypotheses (alternative conceptions/misconceptions) were generated in a recent biology lab:

1. water evaporates from the leaves to create a vacuum which sucks water up,
2. roots squeeze to push water up through one-way valves in the stem tubes,
3. capillary action of water pulls it up like water soaking up in a paper towel, and
4. osmosis pulls water up.

Of course equipment limitations keep some ideas from being tested, but the "leaf evaporation" hypothesis can be tested by comparing water rise in plants with and without leaves. This requires the reasoning patterns of isolation and control of variables. The "root squeeze" hypothesis can be tested by comparing water rise in plants with and without roots; the "one-way valve" hypothesis can be tested by comparing water rise in right-side-up and upside-down stems. Results allow rejection of some of the hypotheses and not others. The survivors are considered "correct," for the time being at least, just as is the case in doing "real" science, which of course is precisely what the students are doing. Following the experimentation, terms such as transpiration can be introduced and applied elsewhere as is the case for all types of learning cycles (see appendix for more details on this learning cycle).

The water rise in plants question may involve misconceptions, but few students would feel strongly committed to any one point of view as these are not likely to be tied to others which have strong intellectual and/or emotional commitments. But consider the case of evolution and special creation. Here commitments often run deep, thus a hypothetical-deductive learning cycle into the question "Where did present-day life forms come from?" can stir up considerable controversy, argumentation and reflective thought.

To teach the concept of evolution using a hypothetical-deductive learning cycle once again we start with alternative hypotheses. At least three can be offered:

1. Present-day organisms were all created during a brief period of time by an act of special creation (i.e., by God). Further, organisms were created by God in virtually the same forms as we see today.

2. Present-day organisms have spontaneously arisen from dead material throughout time. For example, dead, rotting meat will produce fly larvae. Old rags in damp places will produce baby rats.
3. Present-day organisms have gradually evolved from very few simple organisms over vast periods of time.

Students may generate other hypotheses but at least these three should be mentioned.

Notice that an interesting thing has happened. What represents the revealed truth for some people, namely special creation, is treated not as truth but simply as one of three alternative hypotheses. The recognition that alternative hypotheses can exist, as opposed to revealed truths, represents a crucial step.

Once the hypotheses have been generated, they must be tested through prediction and data gathering and analysis. The hypothesis of spontaneous generation leads to replication or discussion of the classic experiments of Spallanzani, Needham and Pasteur and to its ultimate rejection. The hypotheses of special creation and evolution lead to consideration of the processes of geologic sedimentation, fossil formation and to the fossil record. Clearly the predicted fossil records for the two hypotheses are quite different, even contradictory, in some respects. Special creation predicts a pattern of fossil remains with no fossils in the deepest, oldest sedimentary layers (before special creation) and all forms of simple and complex life in the layer immediately following creation, with the remaining layers up to the surface showing fewer and fewer life forms as some become extinct. Evolution also predicts no life in the deepest, oldest layers (before evolution began), but the next layers should contain very few and only the simplest life forms (e.g., single-cell bacteria, blue-green algae), with the progressively higher, younger layers showing gradually more complex, larger and more varied life forms.

Students thus have opposing hypotheses with dramatically different predictions. Which is correct? To find out, the students simulate a hike in the Grand Canyon and observe fossils found in six sedimentary layers from the canyon walls. The fossils reveal a pattern like that predicted by the evolution hypothesis and clearly unlike that predicted by the special creation hypothesis. Therefore, evidence and arguments in favor of the evolution hypothesis have been obtained. Subsequent activities allow the concept of evolution to be applied in other contexts. Most certainly one such activity would be a learning cycle into the concept of natural selection.

Learning Cycles as Different Phases of Doing Science

A look back at Figures 4 and 6 will serve to summarize the major differences among the three types of learning cycles described. Descriptive learning cycles start with explorations which tell us what happens under specific circumstances in specific contexts. They represent descriptive science. In the context of the candle burning experiment they allow us to answer questions such as "How high and how fast will the water rise under varying conditions?" But they stop before the question "What causes the water to rise?" is raised. Empirical-abductive learning cycles include the previous, but go further and call for causal hypotheses. Thus, they include both the question and hypotheses boxes of Figures 4 and 6 and may go even further to include some or all of the subsequent boxes. Hypothetical-deductive learning cycles generally start with a statement of the causal question and proceed directly to hypotheses and their test, thus represent the classic view of experimental science.

Clearly there is some overlap among the three types of learning cycles since they represent various phases of the generally continuous and cyclic process of doing science. As is the case with any classification system, some learning cycles will be difficult to classify as they will have characteristics of more than one type of learning cycle. Nevertheless, it is hoped that the system will prove helpful in curriculum design and instruction.

A Note on Creativity

Wallas (1926) described four stages of the creative process. These are:

1. Preparation - the stage during which the problem is investigated in all directions.
2. Incubation - the stage of non-conscious thinking about the problem. During this stage the person dismisses the problem from his/her conscious mind and attends to something else.
3. Illumination - the spontaneous appearance of "the happy idea."
4. Verification - this stage is a conscious and deliberate attempt to test the new idea.

Torrence (1967) defined creativity as the process of becoming sensitive to problems, deficiencies, gaps in knowledge, missing elements, disharmonies, and so on; identifying the difficulty, searching for solutions, making guesses, or formulating hypotheses and possibly modifying and retesting them; and finally communicating the results.

The similarity of Wallas' and Torrence's descriptions of the process of creativity to our description of the constructive process detailed earlier is remarkable. Presumably they are one and the same. If so, creativity can be enhanced by giving students the opportunity to use their own minds in solving problems through use of the learning cycle.

In relation to this idea of fostering creativity in the classroom Torrance (1967) said:

> *Many complain that we do not yet know enough about the factors affecting creative growth. In my opinion, we have known enough about these factors since the time of Socrates and Plato to do a far better job of creative education than is commonly done. Socrates knew that it was important to ask provocative questions and to encourage natural ways of learning. He knew that it was not enough to ask questions that call only for the reproduction of what has been learned. He knew that thinking is a skill that is developed through practice and that it is important to ask questions that require the learner to do something with what he learns–to evaluate it, produce new ideas from it, and recombine it in new ways. (p. 85).*

Thus the acquisition of procedural knowledge, declarative knowledge, and creativity can be fostered within our educational system if students are given the opportunity through learning cycles to use the constructive process to generate and test their own ideas. However, providing the proper climate for this to take place is absolutely crucial. We must become accepting of student ideas. We must become more interested in intellectual invention than in the rightness or wrongness of what is invented. We must cease to form judgments of students' inventions and instead let the evidence itself be the judge. As Rogers (1954) has pointed out:

> *When we cease to form judgments of the other individual from our own locus on evaluation, we are fostering creativity (p. 147).*

A considerable body of literature exists regarding the nature and modifiability of intelligence (e.g., Herrnstein, Jensen, Baron and Sternberg, 1987). The word *intelligence* is typically defined as the capacity for understanding for solving problems and making reasonable decisions and the like. Since these capacities depend upon creative and critical thinking skills and an accurate and organized body of concepts, facts and principles (i.e., both procedural knowledge and declarative knowledge), and since we have just detailed teaching procedures for improving students' procedural and declarative knowledge, we have, therefore, provided procedures for improving students' intelligence. This does not imply that all aspects of intelligence are modifiable and that all student differences in intellectual aptitude can be erased. Nevertheless, there is considerable reason to believe that past methods of schooling can be improved upon considerably and learning cycle instruction can indeed make students more intelligent.

VI. EMPIRICAL STUDIES

Overview

The following review is concerned with research into the learning cycle approach to instruction. The review will be divided into four sections. Most of the original research on the learning cycle was concerned with the Science Curriculum Improvement Study (SCIS) program because this was the first program to explicitly use the learning cycle as an approach to instruction and curriculum development. The first section of the review will discuss this research. After the original development of SCIS, some instructional researchers and curriculum developers saw great promise in using the learning cycle as a general instructional strategy. The second section reviews research on these programs. Since the learning cycle is a global strategy made up of many factors, it has become apparent in recent years that a profitable approach is to research the effect of the various factors within the learning cycle. This research makes up the third section of this review. Finally, two large-scale studies concerning the use of the learning cycle in high school physics and chemistry will be reviewed in the fourth section.

Research on SCIS

A large amount of research has been produced related to the SCIS program. Much of this research evaluated the general effectiveness of the program. Quite a few studies investigated various aspects of intellectual development of students at various ages. Some of the studies focused on the effect of the program on attitudes, and achievement as well. Since the program was designed with the learning cycle as an instructional strategy, the studies are, in effect, *de facto* investigations of the effectiveness of the learning cycle method.

Affective Domain

Brown (1973) studied the effect of six years of exposure to SCIS science. He found the SCIS program superior in developing positive attitudes towards science of middle-class children when compared to non-SCIS textbook-based programs. In a study comparing the SCIS *Systems and Subsystems* unit versus a non-SCIS unit, Allen (1973a) found that slightly better motivation could be attributed to the 87 third-grade students in the SCIS program.

Malcolm (1976) studied the effect of science programs on self-concept. He used subjects from eight elementary classes ranging from grades three through six. After eighteen weeks of exposure he found SCIS produced higher levels of self-concept in the areas of intellect and school status than did a non-SCIS textbook-based atmosphere. Brown, Weber and Renner (1975), Krockover and Malcolm (1976) and Haan (1978) found superior attitudes in students exposed to the SCIS program. Hendricks (1978) also found affective domain gains in SCIS students. When he studied 247 fifth-grade rural disadvantaged students, he found more positive attitudes, a greater preference toward science, and greater curiosity towards science among students after twelve weeks of science in the SCIS program than those in a non-SCIS program. Lowery, Bowyer and Padilla (1980) studied the effect of six years of SCIS on 110 middle-class rural-suburban elementary students. They found that after six years of SCIS, attitudes toward science and experimentation were more positive for the SCIS students than those in a textbook program.

Although an occasional study (i.e., Hofman, 1977) found no relationship between the SCIS program and student attitudes, by far the bulk of the studies comparing SCIS to non-SCIS programs found superior affective domain scores in favor of SCIS.

Achievement in Content and Process Skills

Many of the studies looking at the effect of the instructional methods associated with the SCIS program assessed student achievement content and process learning. One of the stated goals of the SCIS program was the development of scientific literacy where scientific literacy involves both content acquisition and process skills development (i.e., both declarative and procedural knowledge).

Thier (1965) used interview techniques to investigate the effects of the *Material Objects* unit on 60 first graders. He found the SCIS group had superior skill in describing objects by their properties than non-SCIS students. SCIS students also showed superior skill in describing similarities and differences between different forms of the same substance. Finally, SCIS students exhibited greater skill in observing an experiment and describing what happened.

Allen carried out a large scale longitudinal study of the SCIS program and its effect upon elementary school children. In the first of a series of articles, Allen (1967) studied the classification abilities of 190 elementary schools in grades 2-4. Half the subjects were exposed to SCIS while the remaining lacked an SCIS experience. Allen found no difference between SCIS and non-SCIS students in their skill in classifying. He concluded that the middle-class students in his sample received enough experiences with classification in their home environment so that the additional experiences in the SCIS program did little to improve this skill. In looking at 300 first-grade students, Allen (1971) found evidence of the superiority of the SCIS students over non-SCIS students in their skill in describing an object using specific property words. Property works that were used in the SCIS program were applied to new situations giving evidence of specific transfer. A small amount of general transfer was evidenced by the use of non-SCIS property words being utilized. After a second year of SCIS, the same students continued to show evidence of having learned the content associated with the SCIS program (Allen, 1972). Ninety percent of the SCIS students demonstrated understanding the concepts of "interaction." After a third year of the longitudinal study, SCIS students were found to be more skilled in identifying experimental variables and recognizing change than non-SCIS students (Allen, 1973b).

In another large scale evaluation of the SCIS program, Renner and colleagues conducted a number of studies to investigate variables associated with achievement (Renner, Stafford, Coffia, Kellogg and Weber, 1973). The first study researched the relationship between the learning activities of the *Material Objects* unit and conservation skills of first graders. The conservation of number, weight, liquid and solid amount, length and area were assessed. The *Material Objects* students were compared with those who studied science from a textbook and were found to exhibit far more conservation responses. Thus, the data supported the conclusion that the rate of attainment of reasoning skills, as measured by Piaget-type conservation tasks, was significantly enhanced by the experiences provided by the first-grade *Material Objects* unit of the SCIS program.

The second Renner et al. study examined elementary science students who had been exposed to SCIS for at least four years and compared them to students who had been taught science using a textbook for the same length of time. The study used an instrument constructed to measure students' skill in the processes of observing, classifying, measuring, experimenting, interpreting and predicting. The results showed that the SCIS program was superior to the textbook program in leading children to develop and use these process skills in science.

The third Renner et al. study looked at the transfer of process skills developed in the SCIS program to other areas of the curriculum. The Stanford Achievement Test was administered to SCIS and non-SCIS groups during the fifth grade. Scores in mathematics concepts, skills, and applications, as well as word meaning and paragraph meaning were obtained, as were data concerning achievement in social studies skills and content. Forty-six students who had utilized the SCIS program for five years comprised the experimental group. Sixty-nine students who used a textbook-based science curriculum comprised the control group. Analysis of the scores of the two groups on the Stanford Achievement Test showed that the experimental group outscored the control group on every subtest. A statistical comparison of the seven academic areas revealed significant differences between the two groups in mathematics applications, social studies skills, and paragraph meaning. On the other hand, no significant differences were found in mathematical computations and concepts, social studies content, and word meaning.

Of particular interest was Renner et al.'s observation of a thread of commonality in the areas where differences were determined. In the case of mathematics appplications, performance on the instrument was determined by ability to apply mathematical knowledge and to think mathematically in practical situations. The social studies skills test has a stated goal of testing "knowledge in action." The paragraph meaning test was said to measure the students' ability to understand connected discourse involving varying levels of comprehension. The thread of commonality, then, was that each area requires a level of thought that transcends mere recognition and recall. Apparently, children who have had experience with SCIS units tended to utilize the high levels of thinking more effectively than those who have not had this experience.

The fourth Renner et al. study looked at the transfer of the basic skills developed by the SCIS program to those necessary to the learning of reading. First-grade students studying the *Material Objects* unit were used to study the effect of SCIS as a reading readiness program. The experimental group experienced the *Material Objects* unit for several periods a day and did not have any experiences with a reading readiness program. The students in the control group had a learning experience provided by a commercial reading readiness program. The reading readiness of both groups was evaluated with the Metropolitan Reading Readiness Test at the beginning of the school year and six weeks later. Students in the experimental group showed greater gains in five of the six subtest areas. They outperformed the control group in Word Meaning, Listening, Matching, Alphabet, and Numbers. They were outgained by the control group only on the Copying subtest.

Brown, Weber and Renner (1975) compared SCIS students with non-SCIS students and found the SCIS students had superior attainment of scientific processes. Also, using a measure of attitudes towards science and scientists, they found no significant difference between the attitudes of the SCIS students and those of professional scientists. Thus, they concluded that SCIS was successful in its goal of developing scientific literacy with elementary school students.

Linn and Thier (1975) conducted a nationwide survey of the effectiveness of the *Energy Sources* fifth-grade unit in teaching the reasoning involved in compensating variables. In all, 2290 fifth- and eighth-grade students were involved. Forty-seven fifth-grade classes from seven states in which *Energy Sources* had been taught were considered the experimental group. Performance of students in those classes was compared to performance of students in 36 control classes in which *Energy Sources* was not taught. Nine eighth-grade classes that had not had *Energy Sources* were also involved in the study. Posttest performance on tasks requiring the identification and compensation of variables revealed substantial superiority of the experimental group students in both rural and non-rural settings. As expected, the eighth-grade students performed better than either group of fifth-grade students but the experimental group fifth-graders performed more like the eighth-graders than the controls of their own age group.

Bowyer (1976) studied the development of scientific literacy in 521 rural sixth grade students. Sixty-five percent of the students were exposed to the SCIS program for six years. An instrument based on nine Piaget-type tasks was developed. Students showed significant gains in (1) skill in recognizing and describing variables, (2) skill in determining relative position, (3) skill in predicting and explaining the temperatures in energy transfer, and (4) skill in understanding the concept of solution and evaporation. Bowyer used these results as evidence of gains in scientific literacy.

Several researchers investigated the transfer of skills gained in SCIS to other areas of the curriculum. Brown (1973) found that six years of SCIS was superior in producing figural creativity than non-SCIS textbook approaches. Maxwell (1974) studied 102 kindergarten students exposed to eight weeks (20 minutes per day, five days per week) of science. He found that SCIS kindergarten students studying the *Material Objects* unit had significantly greater gains in reading readiness and language facility over non-SCIS students. In a study of the content analysis of textual material, TaFoya (1976) found SCIS materials to have greater potential in developing inquiry skills than textbook approaches. Nussbaum (1979) studied 44 third-grade students in Jerusalem, Israel. He found that the SCIS *Relativity* unit was effective in teaching the concept of "space". Furthermore, he found this learning was lasting and generalizable. He also found some evidence of slight advances in Piagetian developmental level. Horn (1980), in examining eighteen classes of first-grade students, found that the SCIS *Material Objects* unit had no more effect than traditional text materials in contributing to new vocabulary and comprehension of text.

<u>Teacher Variables</u>

As was the case with many of the curriculum projects produced in the 1960's, a massive teacher education program accompanied the development of the SCIS curriculum. As a consequence, much research was done investigating the effectiveness and nature of these teacher training programs. Because some of this research was associated with how teachers utilize the learning cycle approach, some insight into learning cycle variables can be seen in this research.

Moon (1969), Porterfield (1969), and Wilson (1969) found that when teaching, SCIS teachers behaved differently. Their questioning behavior using SCIS focused on higher-order, more open-ended questions rather than fact-oriented questions. Moon (1969) studied 32 elementary school teachers. Sixteen were trained in a three-week SCIS workshop. As a result of either the workshop or the use of the SCIS materials, the SCIS teachers used higher-order questions than the non-SCIS teachers. Porterfield (1969) studied sixteen second- and fourth-grade teachers trained in SCIS and compared their questioning behavior with those of sixteen r. ı-SCIS second- and fourth-grade teachers. It was found that non-SCIS teachers use more recognition and recall questions while the SCIS teachers asked more questions requiring translation, interpretation, analysis, synthesis, and evaluation.

Wilson (1969) analyzed the questions asked of 30 first- through sixth-grade teachers. Half the sample was SCIS trained and showed a greater propensity for asking skill-type questions emphasizing observation, measurement, interpretation, and prediction. The non-SCIS teachers were more prone to ask comprehension questions. Similar results were found by Eaton (1974). This researcher studied the teaching practices of 42 elementary school teachers and 120 of their fourth-, fifth- and sixth-grade students. Twenty-three of these teachers were exposed to a 17-day SCIS workshop and used the SCIS program. It was found that when SCIS teachers were compared with textbook teachers, they were more open-minded, asked higher-level questions, and had pupils with greater science achievement in science processes.

Lawlor (1974) found that students of SCIS trained teachers had better attitudes towards science. Using interaction analysis, Simmons (1974) studied a random sample of 224 teachers and found that SCIS teachers practiced less dominant behaviors and were more student-oriented than non-SCIS teachers. Finally, Kyle (1985) found that SCIS teachers spent a good deal more time teaching science than teachers not trained to teach SCIS.

All of this indicates that SCIS teachers are more likely to have the skills necessary to interact successfully with students as required by the various phases of a learning cycle. This might, in part, explain the success of the SCIS program.

<u>Summary</u>

Although much of the research cited above can be criticized for comparing the SCIS program with an ill-defined "non-SCIS" approach, there still is much evidence to indicate that SCIS was and is an effective elementary science program that has great benefits in promoting students' attitudes and content and process skill achievement. The point should be made, however, that much of this research is not solely an evaluation of the learning cycle approach but rather the evaluation of SCIS, a curriculum project that has many characterisucs including use of the learning cycle. In other words, it may be that some other aspect of the program besides, or in addition to, the learning cycle is responsible for its success. For example, In some cases it may be that the effectiveness of a laboratory versus a non-laboratory approach is being evaluated. That is, the effectiveness of the SCIS program may be due more to the fact that a laboratory, or hands-on, approach is superior to a non-laboratory approach. As a consequence, the research reviewed thus far tells us that the SCIS program is effective, but it does not tell us specifically why.

Learning Cycle Research

As a result of the success of the SCIS program, many science educators saw the learning cycle as a useful model for instruction and curriculum development. Consequently, other groups developed curricula using the learning cycle for science programs at different levels. The research reported in this section is concerned with the investigations of the effectiveness of these individually developed learning cycle curricula.

Attitudes

As it was true of the SCIS program, research groups found that students using the learning cycle often had more positive attitudes toward science and science instruction when using the learning cycle approach than with other approaches usually identified as "traditional". Campbell (1977), for example, found beginning college physics students exposed to a learning cycle approach had better attitudes toward laboratory work than students exposed to a traditional approach. Fifty-five students were exposed to ten laboratory lessons in order to learn physics content. Although there was no significant difference between the groups in learning physics concepts, this research found the learning cycle group had more positive attitudes towards laboratory work, scored somewhat higher on a laboratory final exam, and were not as likely to withdraw from the course.

Davis (1978), using 132 selected fifth- and sixth-grade students exposed to 120 minutes of science for nine weeks, found that learning cycle lessons produced more positive attitudes toward science than either lecture/discussion lessons or verification laboratory approaches. Bishop (1980) found that an eight-lesson planetarium unit taught to three classes of eighth-grade students using the learning cycle developed more positive attitudes than a more traditional planetarium approach. The experimental group enjoyed the unit more and scored better on an achievement test. Although the examples here are not extensive they are parallel and consistent with the results found from the SCIS experience.

Content Achievement

Campbell (1977) compared the effectiveness of the learning cycle approach to conducting physics laboratory activities plus the personalized system of instruction (PSI) to the more traditional lecture-lab-recitation method of college freshman physics teaching. Campbell found the learning cycle and PSI approach to be significantly better than the traditional approach in provoking students to utilize formal reasoning patterns. Students had a more positive attitude (as mentioned previously) and significantly fewer of them dropped out of the learning cycle/PSI course as well. Content achievement was not significantly different between the two approaches.

In the Davis (1978) study cited previously, it was shown that students had a more positive attitude towards science and better understanding of the nature of science using the learning cycle approach. However, this study found no difference in content achievement among three approaches investigated. Bishop (1980) showed that learning cycle students had greater posttest and delayed posttest retention of content than students with traditional planetarium instruction; however, neither group showed mastery of the astronomy concepts being taught. In a five-week unit, Vermont (1985) found no difference between the learning cycle approach and a lecture/laboratory strategy in the learning of the mole concept and the altering of misconceptions related to that concept by 60 college chemistry students.

Schneider and Renner (1980) compared two methods of teaching physical science concepts to 48 ninth-grade students over a one-semester period. One method, labeled *formal instruction*, followed a traditional pattern of lecture, motion pictures, filmstrips, textbook readings, questions and problems, supervised study and demonstrations. The second method, labeled *concrete instruction*, followed the learning cycle approach. Results showed the concrete instruction method was superior to the formal method in content achievement on both immediate and delayed posttests.

Ambiguous results were obtained in a study using 256 college chemistry students by Ward and Herron (1980). In this study learning cycle activities were developed for three experiments in a college chemistry course. Each experiment required approximately three hours to complete. The three experiments (chromatography of a felt tip pen, activity series, and chemical interactions) all required formal schema (propositional, proportional and combinatorial reasoning). Ward and Herron found that the learning cycle approach was clearly superior to the traditional approach in one of the three experiments. In the other two they found no differences. They suggested three possible reasons for these ambiguous results: (1) the limited time spent on the activities of the experiment, (2) flaws in the achievement test used, and (3) suspicion that the teaching assistants who taught the course were not following the guidelines for the learning cycle.

Purser and Renner (1983), using groups of 68 and 67 ninth- and tenth-grade biology students, taught a full eight-month course comparing learning cycle and traditional approaches. They found that for concepts requiring concrete thought, the learning cycle showed definite superiority over the traditional approach. However, for concepts requiring formal thought, the learning cycle approach was no more effective than the traditional approach with their sample of mostly concrete and transitional students.

Saunders and Shepardson (1987) compared what they called "formal" versus "concrete" instructional strategies during a nine-month study of sixth-grade science. The formal approach was characterized by oral and written language activities whereas the concrete approach was defined according to learning cycle parameters. Using groups of 57 and 58 students, Sanders and Shephardson found definite superiority of the learning cycle approach over the formal approach in science achievement.

Thinking Skills

A large amount of research on the learning cycle has investigated the effect that it has on the development of thinking skills. In most cases, *thinking skills* were investigated in the context of Piaget's theory of concrete and formal operational reasoning and were measured using Piagetian-type tasks.

McKinnon and Renner (1971) studied the thinking skills of 131 college freshmen. Approximately one-half of the freshmen were put in an inquiry-oriented science course using the learning cycle approach and the other half served as controls. Significantly greater gains in reasoning were found in the learning cycle group. Similarly, Renner and Lawson (1975) studied 37 college freshmen elementary education majors. Twenty of these were put in an inquiry-oriented learning cycle science class, and the remaining 17 were placed in the traditional physics for elementary education course. The learning cycle class was found to be superior in producing gains in reasoning.

Carlson (1975) studied 133 students enrolled in college introductory physical science. Sixty-six students were trained in formal reasoning using inquiry-oriented instruction that was consistent with the learning cycle approach. The balance of the students served as a control group. This research found the inquiry approach was superior in effecting improvements in formal thinking skills over a non-inquiry approaches.

In a study using 65 high school biology students, Lawson, Blake and Nordland (1975) found that the learning cycle approach was superior to a traditional approach in teaching the skill of controlling variables. However, the skill was not transferable. As a consequence, they concluded that, consistent with Piagetian theory, even the learning cycle used over a short time was not effective in helping students acquire generalizable controlling variables skill. However, Lawson and Wollman (1976), as discussed previously, were successful in teaching 32 fifth- and 32 seventh-grade students to control variables in such a way that the skill transferred to novel tasks. The main difference between the Lawson, Blake and Nordland (1975) approach and the Lawson and Wollman (1976) approach was that the individual training sessions used by Lawson and Wollman allowed for more individual feedback to students' self-generated experimental procedures. This individual feedback was much better at prompting students to reflect on the adequacies and inadequacies of their procedures and to become more aware of those procedures. Lawson and Snitgen (1982) found, during a one-semester college biology class for 72 preservice teachers, that when use of the learning cycle was extended and augmented with special instructional components to directly teach formal reasoning, transferable gains in formal reasoning could be obtained in the classroom setting.

Renner and Paske (1977) compared two forms of one-semester physics instruction for nonscience majors at the University of Oklahoma. The "concrete" mode of instruction followed the learning cycle approach while the "formal" mode followed the traditional lecture-demonstration approach. Students in both groups were pre- and posttested with measures of formal reasoning and the Watson-Glaser Critical Thinking Appraisal. Posttesting also included an attitude survey and a content examination. Three sections were taught by the concrete mode while one section was taught by the formal mode. The concrete instruction sections performed consistently better than the formal section on the content examination and were generally pleased with their instruction, while the formal section was generally dissatisfied with its instruction. Greater gains and fewer losses were made on the Watson-Glaser by the concrete sections. They also showed greater gains on the formal tasks from the low to high concrete levels and from high concrete to low formal levels; however, the formal section showed greater gains from the low to high formal level. This result suggests that inquiry-oriented instruction is more effective at producing reasoning gains for concrete students but for students with some expertise in formal reasoning, further progress is better attained by traditional methods.

Tomlinson-Keasey and Eisert (1977a) reported results of the evaluation of the ADAPT project at the University of Nebraska. ADAPT is an interdisciplinary project based upon Piagetian principles to help college students develop formal reasoning. Instruction in English, history, economics, physics, anthropology, and mathematics was patterned after the learning cycle. A pencil-paper inventory of formal reasoning, administered prior to and following the freshman year, revealed significant differences in favor of the ADAPT group over two control groups. A follow-up study during the sophomore year indicated significant differences in favor of the ADAPT group on the Watson-Glaser Critical Thinking Appraisal (Tomlinson-Keasey and Eisert, 1977b).

Wollman and Lawson (1978) found that 28 seventh-grade students in an "active" group, subjected to 30-40 minute training sessions, which used an inductive learning cycle approach and manipulatives, were superior to those in a "verbal" group which did not use manipulatives, in acquiring skill in using proportional reasoning.

The Schneider and Renner (1980) study cited previously also investigated their ninth-grade physical science course's ability to promote formal reasoning. The learning cycle approach (called concrete instruction) was found to be superior in promoting formal reasoning as assessed by a battery of manipulative tasks. The superiority of the concrete instruction group persisted on the delayed posttests (three months later). One might argue that this superiority does not reflect a real difference in reasoning skill as the concrete instruction students interacted with manipulative materials while the formal group did not. However, this argument is weakened considerably by the finding that the concrete instruction group also evidenced greater gains on a nonmanipulative test of I.Q. (the Short Form of Academic Aptitude). Thus support was obtained for the hypothesis that the learning cycle approach not only improves understanding of science content, but can effect general advances in reasoning skills and academic aptitude as well.

Finally, Saunders and Shepardson (1987) found that sixth-grade students instructed with the learning cycle approach over a semester showed a greater percentage gain from the concrete to the formal stage than students taught using a "formal" instructional methodology.

<u>Summary</u>

Although some of the research reported here is subject to the criticism of comparing the learning cycle approach with a less well-defined instructional strategy (i.e., "non-learning cycle"), many of the studies reported here use comparisons between the learning cycle and more well-defined approaches. When taken in combination with the research reported previously on the SCIS program, several observations can be made. The learning cycle approach appears to have considerable promise in areas of encouraging positive attitudes toward science and science instruction, developing better content achievement by students, and improving general thinking skills. It has showed superiority over other approaches, especially those that involve reading and demonstration-lecture activities. Nevertheless, these studies, like those cited previously, fail to identify precisely what factor or factors associated with the learning cycle are responsible for this superiority.

Research on Aspects of the Learning Cycle

As mentioned, much of the research reported in the previous two sections is subject to the criticism that comparisons of global instructional strategies, such as the learning cycle, even with well-defined "traditional" approaches, do not identify the specific cause or causes of any outcomes of the instructional methods. The approaches are so different, it is agreed, that general studies may not isolate the critical variables that account for the results. Studies are needed of specific aspects of instruction that characterize or define the learning cycle.

To this end, Story and Brown (1979) found more positive attitudes with hands-on materials versus similar, but non-hands-on instruction and Raghubir (1979) found that a laboratory/investigation strategy, where laboratory preceded discussion, had a greater effect on learning and attitudes for twelfth-grade biology students than a laboratory/lecture strategy where the laboratory was used in a verification or deductive mode.

Abraham (1982) conducted a study using college chemistry students designed to identify the differences between "inquiry" laboratories (using the laboratory to introduce concepts, as is done in the learning cycle) and "verification" laboratories (using the laboratory to confirm or verify a concept presented prior to the laboratory). The nature of these two laboratory types was investigated using a Q-sort type instrument consisting of 25 statements describing various characteristics of laboratory activities. Students ranked the 25 statements according to how accurately they characterized the laboratory. Abraham then used these characterizations to distinguish between the laboratory types as perceived by the students exposed to the inquiry, learning cycle and verification formats. Using discriminant analysis, a set of statements used by students to distinguish between the inquiry and verification laboratory types was identified.

The following statements were ranked significantly higher by the verification group.

1. The instructor is concerned with the correctness of data.
2. The instructor lectures to the whole class.
3 During laboratory the students record information requested by the instructor.
4 Laboratory experiments develop skill in the techniques or procedures of chemistry.
5 Students usually know the general outcome of the experiment before doing the experiment.

The following statements were ranked significantly higher by the inquiry, learning cycle laboratory group.

1. Students were asked to design their own experiments.
2 The instructor requires students to explain why certain things happen.

3. Laboratory reports require students to use evidence to back up their conclusions.
4. Students propose their own explanations for observed phenomena.

From this information it can be seen that laboratory activities used in a learning cycle manner are characterized by students as being associated with experimentation, explanation, observation, and the use of evidence. In contrast, laboratory activities used in a verification or traditional mode are usually associated with correctness, lecture, following instruction, and the development of specific laboratory techniques.

In a meta-analysis of 39 studies, Lott (1983) compared inductive and deductive teaching approaches. Although Lott found no main effects between the two approaches, several interactive effects were apparent. First, the inductive approach had a more positive effect on intermediate level students, and was superior when higher levels of thought and outcome demands were required. Second, students in smaller classes, numbering 17 to 26, performed better when experiencing the inductive approach. As the size of the class increased, performance differences, when compared to the deductive approach, decreased. Finally, the inductive approach functioned better when it was part of complete program opposed to isolated units of instruction. These conclusions may explain some of the ambiguous results of the previously cited research.

Lott's analysis suggests that the learning cycle may be especially effective with concrete operational learners in the Piagetian sense. This may be because "formal" learners are better able to compensate for and are, therefore, more tolerant of less-effective instructional approaches. The learning cycle may be more effective with smaller classes because important interactions among students and the teacher during the exploration phase and during discussions, in which data are analyzed, are more difficult to control when class size becomes large. Students may become isolated from the instruction and the instructional materials in larger classes and become confused. Perhaps the learning cycle is more effective as a total program than in isolated instructional units because students need time to become activated to the techniques of inquiry learning. Finally, the learning cycle may be more effective in learning complex and non-intuitive concepts, because self-evident concepts do not require the intense examination of ideas facilitated by the learning cycle. As a consequence, traditional instruction appears to be just as effective as the learning cycle in teaching self-evident concepts.

Finally, Ivins (1986) compared the effect of two instructional sequences involving science laboratory activities. One of these used an inductive approach to instruction and the other used a deductive approach. Here *inductive* means that the laboratory precedes term introduction as is the case in the learning cycle, and *deductive* means the reverse. Using 103 seventh-grade earth science students, Ivins found the inductive approach created greater achievement and retention of content.

Research on Phases of the Learning Cycle in Chemistry and Physics

Instruction designed to teach scientific concepts can generally be thought of as involving three elements: (1) identification of a pattern of regularity in the environment; (2) discussion of the pattern and the introduction of a term to refer to the pattern; and (3) identification of the "concept" in new situations. Thus, instructional strategies can be characterized as a combination of one or more of these elements, taken in a specific sequence, utilizing different formats of presentation. Taking this view, there are three variables which define different instructional strategies designed to teach concepts: (1) the sequence variable, (2) the necessity variable, and (3) the format variable. When judging the effectiveness of different instructional strategies, the research question boils down to how does the order, existence of the three elements of instruction, and format affect concept acquisition?

Two large scale multiexperiment studies were carried out to investigate instruction in terms of these three variables. Specific lessons in high school chemistry and physics were modified in order to do this. Nine experiments in chemistry and eight experiments in physics were carried out over a period of one year. Class observations, case studies, achievement tests and attitude inventories were utilized to assess the effect of varying instructional parameters on the achievement and attitudes of students. A large proportion of the 62 physics students were "formal operational" in the Piagetian sense, while the 159 chemistry students were an even mix of "formal" and "concrete operational." The detailed results of these studies can be found in two reports (Renner, Abraham and Birnie, 1983; Abraham and Renner, 1984) and three research papers (Abraham and Renner, 1986; Renner, Abraham and Birnie, 1985; 1988).

The Sequence Variable

One of the differences between the learning cycle approach and traditional approaches is the sequence of the phases of instruction. In the typical traditional approach, students first are *informed* of what they are expected to learn. The informing is accomplished via a textbook, a lecture, or some other media which discusses the idea to be learned. Next, the idea is *verified* for the student by demonstrating that it is true. In science, the laboratory is often used for this purpose. Finally, the student answers questions, works problems, or engages in some form of *practice* with the new idea. The "inform-verify-practice" sequence of phases corresponds roughly to the three instructional phases of the learning cycle with the sequence of the first two phases reversed (cf., Renner, 1982).

Other instructional approaches could also be simulated by altering the sequence of these phases of instruction. Six sequences of the three phases of the learning cycle are possible. However, noting the specific patterns associated with the three phases allows us to reduce their number somewhat. Going from the exploration phase to the term introduction phase is basically inductive in nature, whereas doing the reverse is basically deductive in nature. In fact, any activity which precedes the term introduction phase would be inductive, and any activity which follows the term introduction phase would be deductive. The exploration and application phases, therefore, function according to their position in the sequence. As a consequence, the sequence question can be refined to a question of the position of the term introduction phase. Therefore, the critical factor to be considered when assessing the effect of the sequence of instructional phases is the position of the term introduction phase. Is it first, second, or third?

The research investigating the sequence of the learning cycle phases was conducted in four separate experiments and the conclusions reached were different for the sample of physics students and the sample of chemistry students. Those conclusions were as follows:

For physics students (Renner, Abraham and Birnie, 1983):

1. The sequence of the phases is unimportant for achievement if all three phases are taught.
2. The students believe that the sequence of the phases is important to how they learn physics and prefer the learning cycle sequence. In particular, the students do not like to discuss a concept until they have gathered their own data from an experiment.

For chemistry students (Abraham and Renner, 1984):

1. "Concrete operational" learners learn review concepts (concepts which were originally taught at an earlier grade) better with sequences which have the term introduction phase last.
2. "Formal operational" learners learn review concepts better with sequences which have the term introduction phase first.
3. All learners learn new concepts better with sequences which have term introduction as the second phase.
4. Students have a more positive attitude towards (preference for) term introduction after the first phase (i.e., either second or third).

The apparent discrepancies between the physics and chemistry samples might be explained by the higher percentage of students who are skilled in formal reasoning in the physics sample. These students might be better able to compensate for the varying sequences of the phases. The above observations can also be seen as consistent with the observations by Lott (1983) concerning inductive versus deductive approaches to instruction. According to Lott, inductive approaches (i.e., learning cycle approaches) are more effective for intermediate level students (like those of the chemistry group). For more accomplished thinkers, the instructional strategy is less important. Also according to Lott, inductive approaches are more effective when greater intellectual demands are placed on students. This would be the case when new concepts are being studied. It would not be as likely to be the case when review concepts are being studied.

The Necessity Variable

Some instructional strategies imply that not all three elements of instruction are necessary. For example, if the exploration phase of a learning cycle were omitted, one would be left with a lesson which began with the introduction of new terms, followed by readings and problems to be solved requiring understanding of the concept(s) implied by the terms introduced. This corresponds to a widely used instructional strategy. Abraham and Renner (1984) and Renner, Abraham, and Birnie (1983) used two strategies to investigate the necessity of the three phases of the learning cycle. The first was to teach lessons that were missing one of the three phases and to compare student attitude and achievement with that of students taught with lessons consisting of all three phases. The second was to vary the sequence of the three phases in lessons taught to different classes and then to test the students after each phase. By comparing the assessment data collected after each phase, Renner, Abraham and Birnie were able to simulate one, two, and three phase lessons. The following conclusions were based on six experiments investigating the necessity variable.

1. In general, all three phases of a learning cycle are necessary for the optimum learning of concepts.
2. Students prefer complete learning cycles, i.e., those with all three phases.
3. Students have negative feelings toward learning cycles which have long and/or complex application phases.
4 The combination of the exploration and term introduction phases is more effective than the term introduction phase alone.
5 The application phase can sometimes substitute for term introduction if this phase includes the use of the term or terms used to refer to the concept.

The Format Variable

Different formats of instruction are commonly used in science lessons. Laboratory, discussion, demonstration, lecture, and reading are probably the most commonly utilized formats at the high school and introductory college levels. The learning cycle typically uses what could be described as a laboratory/discussion format; however, it should be noted that explorations may involve readings and other non-manipulative activities. Seven experiments were conducted which investigated the effect that formats of instruction have on the learning and attitudes of students. The formats investigated were laboratory, discussion, demonstration, lecture, and reading. As was previously the case, the conclusions reached were different for the physics and chemistry students.

For physics students (Renner, Abraham and Birnie, 1983):

1. The format in which the students experienced the phases of the learning cycle did not influence their content knowledge.
2. Students believe they learn more physics content more easily if they first use laboratory apparatus to gather data, discuss the meaning of the data, and have experiences which expand the meaning of the concept.
3. When most of the members of a group have reached the "formal" stage, they can profit from instruction that is not given at an experimental level. However, when students' data from the laboratory are not used as the principle source for building concepts, and reading about or being told about the concepts are substituted for laboratory experience, the students do not like it and become bored quickly.

For chemistry students (Abraham and Renner, 1984):

1. The laboratory format is superior to lecture or reading formats in content achievement for "concrete operational" students.
2. The reading format is effective for "formal operational" students, but ineffective for "concrete operational" students in content achievement.
3. In attitude, the laboratory format is thought of most positively and the reading format is thought of most negatively by students.
4. To be effective, the laboratory format must be used in conjunction with discussions as in the normal learning cycle sequence.
5. The laboratory must provide clear data leading to the concept in order to be effective.

Summary

Research supports the conclusion that instructional strategies utilized to teach science concepts are most effective when they consist of activities which serve three functions. (1) explore and identify a pattern of regularity in the environment, (2) discuss the pattern and introduce a term to refer to that pattern, and (3) discover/apply the concept in new situations. The learning cycle approach is an effective instructional strategy for at least two reasons. First, it utilizes all three of these activities; and second, it uses them in the correct sequence. It should be noted that the sequence, data then concept, is the reverse of the common instructional practice of using the laboratory as a verification of the concept (i.e., concept then data).

The format of each phase of instruction is dictated by the role that the phase plays. The exploration phase is best suited to investigate nature and discover patterns of regularity. The laboratory format has been shown to be most effective in that role, at least for high school students. The term introduction phase is best suited to discuss data, clarify a pattern and give it a name. A class discussion format has been shown to be most effective for this. The application phase is best suited to reinforce, extend, review, or apply the concept. Because of its varying roles, a number of formats can be utilized during this phase (laboratory, demonstration, readings, problem sets, etc.).

In summary, the learning cycle has many advantages over traditional instructional approaches especially when the development of thinking skills is an important goal. Since many studies have shown that a large proportion of the secondary and college population have poorly developed thinking skills, it seems reasonable to conclude that the learning cycle deserves more widespread implementation in science classrooms.

VII. DIRECTIONS FOR FUTURE RESEARCH

Overview

The learning cycle is a very flexible method of instruction which has been shown to be effective at improving students' attitudes toward science, their content knowledge and general thinking skills. For many people, including ourselves, it is not only a good way to teach science, it is **the** way to teach science. Indeed, it is our belief that it is **the** way to teach any subject matter in which concept acquisition is a goal. This, of course, is not to imply that additional research into the learning cycle is not needed. Rather, in the Kuhnian sense, the learning cycle represents a paradigm for instruction (Kuhn, 1970). A considerable amount of "normal science" remains to be done to test its limits of effectiveness and fine tune its use in different disciplines, with different types of students and with different technologies. In that spirit what follows is a brief look at a variety of research areas that deserve attention to insure that the general method of the learning cycle can be most effectively implemented in specific areas.

Conceptions and Misconceptions

A highly productive area of research has emerged in recent years which aims to learn more about the conceptual knowledge students bring to the classroom. Much of this research has centered around identifying what have been termed "misconceptions," where *misconceptions* are defined as conceptions which are inconsistent with, or even contradictory to, modern scientific views (e.g., Arnaudin and Mintzes, 1985; Brumby, 1984; Champagne, Klopfer and Anderson, 1980; Clement, 1982; Driver, 1981; Halloun and Hestenes, 1985; Minstrell, 1982; Piburn, Baker and Treagust, 1988; Simpson and Marek, 1988; Stewart, 1982). Some misconceptions are deeply rooted and quite instructor-resistant. Although the term *misconception* is in fairly wide use, *alternative conception* may be a better label in that all conceptions are merely personal attempts to construct models of external processes; therefore, no two are the same and none is a perfectly adequate representation. Further, the label *alternative conception* does not carry the negative connotation that the term *misconception* does.

In the context of the learning cycle, students' alternative conceptions represent alternative hypotheses to be tested. Thus, they play an integral role in prompting investigations and argumentation. Clearly, they are something to be sought after and discussed rather than avoided. Therefore, a fertile area of research is the identification of alternative conceptions in different areas of science. A careful review of the history of science should prove very helpful in this regard (cf., Wandersee, 1986). Along with their identification, a taxonomy of alternative conceptions is seen as potentially useful. The taxonomy would presumably be based upon the origin of alternative conceptions. For example, the idea of special creation has its origin in religion, whereas the idea that gravity pulls heavy objects down faster than light objects and that we are capable of pulling liquids up through a straw, have their origins in personal experience.

Other alternative conceptions may have their origins in defective classroom instruction while still others may derive from students' lack of thinking skills, or other cognitive deficiencies or differences. A taxonomy of alternative conceptions based upon these criteria, or perhaps other criteria, has potential use because an obvious goal of instruction is to help students acquire more appropriate conceptions, and the way to do this may depend in large part on the nature of the alternative conception and its source (e.g., Anamvah-Mensah, 1987; Smith and Anderson, 1987).

Lawson and Thompson (1987), for example, found that a sample of "concrete operational" seventh graders held more misconceptions about genetics and natural selection than their "formal operational" peers. Lawson and Weser (1989) found the same thing in a sample of college students. Further, they found that the "concrete operational" college students were less likely to give up their misconceptions than their "formal" classmates. Lawson and Weser suggested that this was because the concrete operational students did not have sufficient reflective thinking skills to adequately consider the alternative conceptions, the available evidence, and the arguments in favor of the scientific conceptions; thus, they were less likely to modify prior unsatisfactory beliefs.

Individual student differences, other than thinking skills, are also of potential interest. Cognitive styles, preferences, and a variety of other presumably socially-derived individual difference variables may have profound influence on concept change and concept acquisition (e.g., Okebukola and Jegede, 1988; Staver and Walberg, 1986). Also, it is clear that higher-order concepts are complex and their acquisition requires the coordination of a relatively large number of separate pieces of information. In some cases students may not have sufficient mental capacity to coordinate this information, thus alternative instructional approaches may need to be explored (cf., Niaz, 1988).

Novak's notion of concept mapping (e.g., Lehman, Carter and Kahle, 1985; Novak, Gowin and Johansen, 1983) is potentially a productive one as is Anderson and Smith's (1986) notion of conceptual change teaching and both should be explored in conjunction with these issues. A variety of aptitude-treatment interaction studies are suggested much like those reviewed previously by Renner, Abraham, and Birnie. Finally, methods for carefully evaluating students' concepts and thinking skills, as well as changes in their concepts and skills, will need to be continually refined (cf., Finley, 1986).

In summary, we envision future research designed to answer three general questions: 1) What sorts of alternative conceptions do students bring with them to the classroom? 2) What are the sources of these alternative conceptions, their generality, stability and ease of modification? 3) How should learning cycles be designed to effectively modify and/or replace these conceptions for different types of students?

Motivation and Evaluation

The learning cycle relies on students' intrinsic motivation to fuel their participation in the learning activities. Events occur, data are gathered, and questions are raised, all of which are designed to be mildly disequilibrating, thus arouse student curiosity. The point of learning cycle activities is to find answers to satisfy one's curiosity, rather than obtain an extrinsic reward such as a good grade. Lepper, Greene and Nisbett (1973) found that children who were given an extrinsic reward for performing an initially interesting activity actually lost interest in the activity while non-rewarded children retained their interest. Thus, the learning cycle appears to be designed to properly rely on intrinsic motivation. But the school system generally requires that evaluations of student progress be made and that grades are awarded. How should this be done?

Unfortunately, learning cycle theory offers little help in the area of evaluation. The notion of mastery learning may be a useful one to explore; however, it is not without its problems. Certainly we want students to "master" both declarative and procedural knowledge. Unfortunately the hardest things to master are those that take the most time (e.g., higher-order thinking skills), and if we demand mastery too soon, we may simply frustrate students and ourselves. Too often, the end result is that we give up and resign ourselves to mastery of the trivial. Clearly, both theoretical and empirical work need to be done to resolve these and related issues.

Cooperative Learning

Many of the exploration and application phase activities of the learning cycle are conducted by students working in small groups of two to three students. Students need to communicate with one another and cooperate to design and conduct experiments, gather data and the like; thus the learning cycle includes many elements of cooperative learning as described by Johnson and Johnson (1975). Johnson (1976), found that sixth-grade students in inquiry-oriented science classes perceived those classes to be more cooperative than their textbook classes. Further, they voiced a distinct preference for the cooperative mode. A substantial number of studies have reported various attitude and achievement benefits to cooperative modes but, as is the case for all complex instructional interactions, it is difficult to identify just what factor or factors are responsible for those benefits (e.g., Capie and Tobin, 1981; Humphreys, Johnson and Johnson, 1982; Johnson and Johnson, 1979; Lazarowitz, Hertz, Baird and Bowlden, 1988; Sharan, 1980; Slavin, 1980).

One issue that has been investigated specifically in the context of the learning cycle is optimal ways of establishing laboratory groups. Lawrenz and Munch (1984; 1985) taught a physical science course for pre-service teachers and established lab groups based upon level of reasoning skill in three ways (homogeneously grouped, heterogeneously grouped, student choice). They found the homogeneous grouping to be best in terms of student gains in formal reasoning skills and content achievement. Their results imply that students learn best when they interact with others at or near their level of thinking. This finding appears contradictory to the notion that more able peers can serve as effective classroom teaching assistants. Perhaps, instead of assisting other group members in learning new material and skills, they merely take over and tell others what to do. Clearly, careful research needs to be done to explore the complexities of the group dynamics in learning cycle activities so that appropriate guidelines can be suggested (cf., Tobin and Gallagher, 1987).

Sequencing and Selecting Content

The learning cycle is an approach to lesson planning. Each learning cycle lesson to teach a concept or group of closely related concepts is initiated with an exploration activity into the phenomenon from which the concept(s) either directly or indirectly derive meaning. Because concepts build upon one another to form conceptual systems, some concepts should be taught prior to others. The learning cycle approach does not specifically address these larger curriculum development issues. Thus, key questions remain. In what order should related concepts be taught? How should individual learning cycles be sequenced to produce optimal learning?

Gagné (1970) has long advocated careful task analyses and the construction of learning hierarchies in which subtasks are mastered one at a time, only later to be assembled to allow solution of complex tasks or to comprehend complex concepts. But what motivates students while they learn the subtasks? Should biology students be told, for example, that they must learn concepts of atomic structure because they will need to know them later? Or should the metric system be taught prior to its use? If these ideas and skills are needed later, then why not teach them later?

Much research has been conducted into Ausubel's notion of using advance organizers to precede and help coordinate later instruction. The results of research into advance organizers are mixed and the idea itself is unclear to many (cf., Lott, 1983). What are advance organizers and should they be used with learning cycles? If so, how? Lawson and Lawson (1979) suggested that instruction should proceed from "the whole to its parts." This idea seems similar to Ausubel's but perhaps the opposite of the Gagnéan approach. General ideas such as those need to be made more specific to allow for their satisfactory test and resolution in the context of learning cycles.

What content should be taught and at what level? Some work has been done to identify intellectually appropriate content for students of various age and intellectual abilities (Shayer and Adey, 1981). The SCIS curriculum is perhaps the best example of articulating student intellectual capabilities with content. The SCIS curriculum begins with a careful descriptive look at objects and their properties, only later to explore theoretical notions such as light, magnetism, energy flow and ecosystem dynamics. This progression from descriptive to theoretical science mirrors children's intellectual development as they progress from the concrete and intuitive skills of the child to the more abstract and reflective skills of the early adolescent. However, many textbook approaches still attempt to teach very young children about theoretical entities such as atoms and energy. Research could be aimed at specifically finding out the consequences of such instruction. If it is found to be largely futile, then it should be modified or eliminated.

Recall that we have classified learning cycles into one of three types: descriptive, empirical-abductive, and hypothetical-deductive. Also the claim was made that the learning cycles require differing types of student thinking skills. The descriptive cycles require descriptive skills, while the hypothetical-deductive cycles require more advanced hypothetico-deductive, reflective skills. The empirical-abductive cycles require intermediate skills. This idea has led researchers such as Kim (1988) to suggest that instruction at the elementary level should be through descriptive and empirical-abductive cycles. The SCIS program, however, does not do this.

Although the SCIS developers did not identify the three types of learning cycles, they clearly exist in the program and a variety of types occur at all levels. The first grade *Organisms* unit, for example, includes a learning cycle into the question "What caused the black stuff on the bottom of the aquarium?" After this causal question is raised, the students assemble to generate possible answers (i.e., alternative hypotheses). Student ideas center on the organisms in the aquarium such as the fish, plants and snails. Students then set out to design and conduct an experiment to test their ideas. To do this, the fish, plants and snails are isolated in new aquariums to see in which aquarium the black stuff appears. Thus, the students are clearly generating and testing alternative hypotheses, as is done in hypothetical-deductive learning cycles. Furthermore, their attempts to do so are generally quite successful. It should be noted, however, that as was the case in the Mellinark concept formation task discussed earlier, the hypotheses were derived from direct observations (i.e., induction) rather than borrowing ideas from other experiences (i.e., abduction). Also, another key element was involved in the lesson – the teacher. Clearly, the teacher is guiding the students as they work in one large group to generate ideas and design their experiments. Perhaps, key variables across age are not the type of learning cycle that should be employed but the extent to which students must rely on induction or abduction and work in a group with much teacher guidance or work individually. Leonard's work on discretionary capacity seems relevant to this last point (Leonard, 1980). Leonard's idea is to design instruction to gradually increase the burden placed on students to carry out their work but only after the teacher has provided sufficient group activities to teach students the skills needed for that work. Some research along these lines has been conducted but additional research would be worthwhile.

The Role of Analogy

The theory of concept acquisition introduced earlier argued that theoretical concepts are formed via use of analogical reasoning (i.e., abduction). This suggests that analogies can play a crucial role in instruction particularly when the concepts under consideration are theoretical and complex. Consider, for instance, the theoretical concept of natural selection. Natural selection is indeed a complex idea as it involves the integration of previously acquired concepts such as biotic potential, limiting factors, heredity, variation, long spans of time and a struggle for survival. Needless to say, it took the keen intellects of a Charles Darwin and an Alfred Wallace, and their considerable efforts, to put these ideas together to explain the evolution of species. Since few, if any, of our students are as intellectually able, experienced, and motivated as Darwin and Wallace, how can they be expected to construct an idea of this complexity? Of course the answer lies in our ability as teachers to guide the students in the appropriate directions. Darwin and Wallace were not so fortunate. But in precisely what directions should students be guided? Learning cycles can be developed and taught to help students acquire the subordinate concepts of biotic potential, limiting factors, heredity, variation and long spans of time. But how can the struggle for survival be taught in the classroom? And how can its integration with prior concepts be facilitated? The answer may lie in the use of the appropriate analogy. Recall that Darwin claimed that a key moment in his thinking occurred when he saw the similarity between his own experiences with artificial selection of domestic animals and the natural world — when he "saw" that the same selective process could take place in both places he presumably had the necessary framework to assimilate the subordinate concepts and "invent" the concept of natural selection.

Unfortunately, most of our students will not have personal experiences with artificial selection so it may not be an effective analogy. Therefore, another analogy must be found. In this case one has been found and it appears to work quite well (Stebbins and Allen, 1975). The analogy is, in fact, a simulation activity in which the students play the role of predatory birds capturing and eating mice (paper discs of various colors). Over three generations of this selection process the color of the mice population changes to "fit" the environment in which they live (a patterned piece of fabric). Thus students actually simulate the process of selection in the classroom and can, like Darwin, borrow this pattern and apply it to nature to understand the process of natural selection.

Our theory of the role of analogy in the concept formation and the success of this type of lesson suggests that a considerable amount of research could be conducted to identify other useful analogies and devise learning cycles in which they are used to teach complex theoretical ideas. Clearly a careful examination of the history of science could be helpful in this endeavor. Gabel and Samuel (1986), for example, investigated the role of analogies in solving molarity problems in chemistry and Clement (1986) investigated their role in understanding Newtonian mechanics.

Retention and Transfer of Thinking Skills

Most studies of the effectiveness of the learning cycle have been of a relatively short duration. The notable exceptions (e.g., Renner et al., 1973) have been conducted with SCIS students who have studied science through learning cycles for as many as six to seven years. These studies have shown transfer of performance gains in thinking to academic areas as diverse as mathematics, social studies, and reading. However, the ultimate goal of instructional approaches such as the learning cycle is to improve thinking skills that will transfer to tasks outside of the school environment. Do more able reasoners make more informed decisions about political issues? Do they influence their children more in the direction of rational thought? Do they become more personally involved in social issues? Do they reject pseudoscientific positions in favor of more empirically supported positions?

The retention and transfer issue is indeed a complex one and difficult one to research. In general it can be attacked in steps. First, one would like to know if the learning cycle is better than other approaches at teaching thinking skills that were the explicit focus of instruction. Research strongly suggests that this is so. Second, one would like to know if the learning cycle is better than other approaches at teaching thinking skills that were not the explicit focus of instruction. Research suggests that this is so. Third, do the improved thinking skills transfer to other academic subjects? The answer to this question appears to be "yes". Fourth, are the improvements in thinking skills lasting? A clear answer to this question is more difficult to obtain because it requires longitudinal data. Clearly studies are needed of this sort. Fifth, do lasting improvements (if they exist) translate into improved academic performance and improved performance in "real" life? It should be noted that improvements in academic performance would be expected to occur only when that academic performance requires thinking skills. Certainly many "advanced" courses are not really advanced at all as they simply require the memorization of huge amounts of facts and place very little, if any, demand on higher-order thinking skills. One might well predict that the more able thinkers would be "turned off" by such courses and do poorly. All of this is not to say that research can not be carried out to investigate these issues. It merely says that such research will indeed be difficult, particularly because appropriate dependent measures of success will be difficult to identify.

Prior research into some of these issues has been suggestive of future trends. Lawson (1985) reviewed programs designed to teach formal reasoning skills and concluded that, in general, more diverse and longer duration instruction was slower to achieve *specific* gains (e.g., Fuller's ADAPT program at Nebraska) than were short-term efforts to teach *specific* thinking skills (e.g., Seigler, Liebert and Liebert, 1973) but that the slowly acquired gains were of a more general nature as they involved a greater variety of skills that were applicable in a greater variety of contexts. This result seems reasonable because more diverse and longer term instruction more closely approximates the out-of-school experiences which contribute to intellectual development. The suggested research study is one in which students are raised on a diet of learning cycles in all disciplines, in say grades K-12, and are compared to those raised by more traditional means.

Teaching Content Versus Process

Virtually everyone who first hears about the learning cycle method wonders if it allows for a sufficient number of concepts to be taught. Clearly, the notions that students bring their own conceptual baggage to the classroom and that they are active agents in constructing their own knowledge imply that the teacher can not simply "cover" topic after topic in rapid fire succession via the lecture method and achieve much student understanding. Consequently, the number of concepts/facts "covered" must be reduced. Another implication, however, is that this reduced coverage should be more than compensated for by increased understanding and retention. The key issue then is one of deciding just what content, from among the vast available supply, teachers should attempt to teach. Clearly, textbooks are of little help here because most textbook authors and publishers are primarily in the business of making money and the way to do this is to satisfy as many people as possible by loading up the text with as many topics as possible. Consequently we now have textbooks that not only cause headaches, they cause backaches as well.

Lewis (1988) has a suggestion that may provide a solution to this problem. Recall earlier we stated that concepts reside in conceptual systems. In the sciences these are known as *theories.* A finite set of embedded (scientifically accepted) theories exist in each science and each theory consists of a finite set of postulates. Therefore, much of what exists in textbooks can be ignored as unimportant provided we identify and teach the embedded theories of each science and their key postulates. Since the postulates define the concepts, learning cycles would be designed to teach those key concepts in the appropriate areas. We would like to see these ideas implemented and researched in the future.

Textbooks

Which role should the textbook play in the learning cycle? Previously we have suggested that the textbook should be used only during the concept application phase, although little research has explicitly investigated this issue. In one study Abraham and Renner (1984) substituted reading material in chemistry for the exploration phase and found that this adversely affected poor reasoners but not more able reasoners. However, neither group of students preferred reading as a substitute for the laboratory in the exploration phase.

In the previous section we suggested the development and research of a new type of text that deals only with specific theories and their postulates. We can also suggest that text material be written according to learning cycle phases. In other words, the author would first raise questions, describe observations, and present data. Then he/she would discuss patterns and introduce terms. Then applications of the concepts in other contexts would be discussed. Such an approach of phenomenon first, idea second is clearly different from the common practice of using key terms as section headings as proceeding to define them after their introduction. Use of the learning cycle in text passages may prompt better understanding and retention and may better engage students' use of "metacognitive" skills (cf., Holliday, 1988).

New Technologies

There presently exists a considerable interest in the science education literature regarding new technologies such as microcomputers and videodiscs (e.g., Berger, Pintrich and Stemmer, 1987; Brasell, 1987; diSessa, 1987; Ellis and Kuerbis, 1988; Good, 1987; Hawkins and Pea, 1987; Heath, White, Berlin and Park, 1987; Mokros and Tinker, 1987; Nachmias and Linn, 1987; Reif, 1987; Rivers and Vockell, 1987; Sherwood, Kinzer, Bransford and Franks, 1987; Ulerick, Bybee and Ellis, 1988). In our view, there must be contact with nature or one simply is not doing science. Therefore, we do not see these new technologies as ever replacing the "hands-on" activities of learning cycles. On the other hand, new technologies can, in theory at least, provide useful additions to the learning cycle. The learning cycle itself can be used as a guide to help develop effective use of these technologies. We view one appropriate use of the technologies to be in the concept application phase of the cycle where simulations and the like could be used to greatly extend and refine the usefulness of concepts previously introduced. For example, the simulation of genetic crosses over numerous generations or the simulation of ecological trends over many years, even centuries, can be easily accomplished with computers. Simulations could also be used in the exploration phase when the phenomena of interest can not be directly experienced given the normal classroom constraints. Of course many other uses are sure to be found (e.g., to help plot data gathered during explorations or to present other data bases for analysis). These issues can easily serve as settings for future research.

Teacher Education

Hurd, Bybee, Kahle and Yeager (1980) reported the results of a nationwide survey that indicated that the percentage of science teachers in this country that teach using learning cycles or similar "inquiry" methods to be less than 25%. Given the clear and convincing evidence in favor of the learning cycle method, the obvious question is why do so few teachers use the learning cycle? Costenson and Lawson (1986) asked this question to a sample of high school science teachers who offered ten reasons. Among the most frequently cited reasons were that too much time must be devoted to developing good materials and that the approach is too slow to "cover" the district curriculum.

While acknowledging that these may be real problems that must be solved in specific instances, none of the teachers' ten reasons taken alone or in combination need prevent the learning cycle from being implemented. To do so on a wider scale, however, will require curriculum development and major pre-service and in-service teacher education efforts. Obviously for teachers of K-6 the SCIS and ESS materials exist which can be immediately implemented. The availability of high quality learning cycle materials, appropriate curriculum guides and comprehensive tests at other grade levels is more problematic. Various science educators, such as ourselves, have developed materials appropriate at the high school level and some programs, as mentioned earlier, have been developed at the college level. However, publication and distribution of such materials has been a problem due to their nontraditional nature. Clearly, teachers need to be made aware of their existence and the advantages of using such materials. They must also be educated to use the materials properly. Given the fact that teachers generally teach as they have been taught, and given the fact that they are typically taught science with the very traditional lecture method, discovering and implementing ways of doing this is a very researchable issue. Here we might do well to consider teacher education and dissemination efforts in other countries. In Japan, for example, a much more centralized, systematic and extensive in-service teacher education program exists which appears in many ways to be more effective than our generally disjointed and haphazard methods.

Other Currently Popular Methods

There never has, nor is there likely to be, a shortage of Brand X versus Brand Y teaching method studies. A few currently popular Brand X methods are mastery learning/outcome-based education and Hunter's essential elements of instruction (Hunter, 1982). The basic naive notion behind the mastery learning approach is that all students are capable of acquiring the key ideas/skills and they should do so (i.e., master them) before going on to the next topic. Hunter's approach appears even more simplistic and misguided. She argues correctly that good instruction includes a few essential elements but she incorrectly concludes that these elements are things such as teaching one objective at a time and telling the students beforehand precisely what they are supposed to learn.

The most regrettable result of these naive conceptions of the teaching/learning process is that they quickly degenerate into teaching of only the simpl most useless facts. This happens because students are unable to "master" higher-order thinking skills or acquire complex concepts in a short time, so attempts to have students do so are dropped. The Hunter approach is even more problematic than the mastery approach as it immediately denies the dualistic goal of every learning cycle lesson which is to teach concepts and improve thinking skills. Further, telling students precisely what they are supposed to learn robs the lesson of its inquiry nature and, therefore, eliminates curiosity, the most powerful source of motivation in science that we know. The Hunter approach also appears to directly contradict the notion that the child actively constructs his/her knowledge which is a basic tenet of the learning cycle method. Nevertheless, some educators (e.g., Granger, 1988) have attempted a synthesis of the Hunter and learning cycle approaches. Perhaps a closer look is in order as it may be possible to go beyond these apparent contradictions to find some common ground to strengthen both approaches.

Testing

Most methods of standardized aptitude and achievement tests, such as the Scholastic Aptitude Test, the Iowa Tests of Educational Development, and the American College Testing Program test, attempt to assess general knowledge and thinking skills. The American College Testing Program, for example, is developing a new test of critical thinking which includes items in four main categories: recognition of the elements of an argument, analyzing the structure of an argument, evaluation of an argument, and extension of an argument (American College Testing Program, 1988). The Science Research Associates (1970), makers of the Iowa Tests, had this to say about the skills required for success on their tests:

> ... the student must interpret and analyze material that is new to him, and apply broad concepts and generalized skills to situations not previously encountered in the classroom, ... (pps. 1-2).

In other words, most standardized tests at the national level correctly attempt to assess broad concepts and general thinking skills. Regrettably, many local districts have set up committees to develop district level tests in specific disciplines that are far less imaginative. In some cases they test exclusively for the rote recall of isolated facts. Clearly such tests are counterproductive to efforts to develop and teach with the learning cycle method. Whether or not this is simply a policy issue or one open to research, we are not certain. One learning cycle teacher did, however, report to us that her students outperformed those of traditional teachers in her school on a fact-oriented district developed biology test. Her students even did better on topics that she did not teach! Perhaps improved thinking skills generalize to previously unsuspected areas.

Theoretical Issues

Theoretical issues that will no doubt continue to impact on instruction and help us refine our own view of the learning cycle include: a) a better description of general thinking skills (e.g., Yap and Yeany, 1988); b) the role played by specific content in their use (e.g., Griggs, 1983; Lehmann, Lempert and Nisbett, 1988; Linn, Pulos and Gans, 1981; Staver, 1986); c) principles of neural modeling, information processing, and memory (e.g., Grossberg, 1982; Lawson, 1986); and d) the nature of intelligence and its potential modifiability (e.g., Sternberg, 1985; Herrnstein, Jensen, Baron and Sternberg, 1987). Space does not permit a detailed discussion of these issues. Rather it suffices to say that we view these theoretical issues as extremely interesting and important. They will surely add precision to our ability to design effective instruction in the future.

VIII. KEY POSTULATES AND CONCLUDING REMARKS

We believe that the educational system should help students (1) acquire sets of meaningful and useful concepts and conceptual systems, (2) develop skill in using the thinking patterns essential for independent, creative and critical thought, and (3) gain confidence in their ability to apply their knowledge to learn, to solve problems, and to make carefully reasoned decisions. The preceding pages have presented an instructional theory. That theory which argues that the most appropriate way, perhaps the only way, to accomplish these objectives, is to teach in a way that allows students to reveal their prior conceptions and test them in an atmosphere in which ideas are openly generated, debated and tested, with the means of testing becoming an explicit focus of classroom attention. Correct use of the learning cycle method allows this to happen. The entire theory can be summarized by the following 12 postulates:

1. Children and adolescents personally construct beliefs about natural phenomena, some of which differ from currently accepted scientific theory.
2. These alternative beliefs (misconceptions) may be instruction resistant impediments to the acquisition of scientifically valid beliefs (conceptions).
3. The replacement of alternative beliefs requires students to move through a phase in which a mismatch exists between the alternative belief and the scientific conception and provokes a "cognitive conflict" or state of mental "disequilibrium."
4. The improvement of thinking skills (procedural knowledge) arises from situations in which students state alternative beliefs and engage in verbal exchanges where arguments are advanced and evidence is sought to resolve the contradiction. Such exchanges provoke students to examine the reasons for their beliefs.
5. Argumentation provides experiences from which particular forms of argumentation (i.e., patterns of thinking) may be internalized.
6. The learning cycle is a method of instruction that consists of three phases called exploration, term introduction and concept application.
7. Use of the learning cycle provides the opportunity for students to reveal alternative beliefs and the opportunity to argue and test them, thus become "disequilibrated" and develop more adequate conceptions and thinking patterns.
8. There are three types of learning cycles (descriptive, empirical-abductive, hypothetical-deductive) that are not equally effective at producing disequilibrium and improved thinking skills.
9. The essential difference among the three types of learning cycles is the degree to which students either gather data in a purely descriptive fashion or initially set out to explicitly test alternative beliefs (hypotheses).

10. Descriptive learning cycles are designed to have students observe a small part of the world, discover a pattern, name it and seek the pattern elsewhere. Normally only descriptive thinking skills are required.
11. Empirical-abductive learning cycles require students to describe and explain a phenomenon and thus allow for alternative conceptions, argumentation, disequilibrium and the development of higher-order thinking skills.
12. Hypothetical-deductive learning cycles require the immediate and explicit statement of alternative conceptions/hypotheses to explain a phenomenon and require higher-order thinking skills in the test of the alternatives.

A considerable amount of research has been conducted and reviewed which supports the notion that correct use of the learning cycle in the science classroom is effective in helping students obtain the stated objectives. In our view, more research remains to be done to explore various facets of the learning cycle and to extend and test its effectiveness in new areas and for longer periods of time. Also, we expect that future theoretical work in the field of neuroscience and new technologies will aid our understanding and ability to teach effectively. Although we predict that these improvements will help fine tune the learning cycle method (e.g., Hestenes, 1987), we believe that they will not alter its fundamental role and importance. We believe this to be the case because learning cycle instruction follows the way in which humans spontaneously construct knowledge. This pattern of learning may be made more explicit by educational theorists and researchers in the future, but it will not be changed unless the human mind evolves a different means of acquiring knowledge.

APPENDIX

Example Learning Cycles

1. Exploring Rotoplanes – Physical Science[1]
2. What can be learned from skulls? – Biology[2]
3. What caused the water to rise? – Chemistry[3]
4. What causes water to rise in plants? – Biology[2]
5. How do lenses work? – Physics[3]

[1]From Science Curriculum Improvement Study (1978) reproduced with permission from Delta Education, Inc., Nashua, NH.
[2]From Lawson (1989).
[3]From Renner, Nickel, Westbrook and Renner (1985).

1. EXPLORING ROTOPLANES

Teaching Suggestions

This is an exploratory chapter on Propeller-Rubber Band-Stick (PRS) systems and rotoplanes that sets the stage for the invention of energy sources and energy receivers. It also reviews controlled experimentation. This is a descriptive learning cycle.

Exploring the PRS Systems

Distribute a tray to each team and invite your pupils to assemble the parts so the wound-up rubber band can spin the propeller. Observe the children while they investigate the PRS systems, encouraging them to operate the systems in a variety of ways. Some may expect the systems to fly, while others may attach the tray or a piece of paper to serve as "wings" Still others will be content to use the PRS systems as fans. Allow enough time for the children to try out these idea, watch one another, and discuss their observations informally. If children have a great deal of trouble, show them how to set up the PRS system.

Exploring the Rotoplanes

As teams exhaust the possibilities of their PRS systems, point out the rotoplane you have assembled and indicate where they may pick up the necessary items. Invite them to assemble these objects, together with their PRS systems, so the platform turns. After a few minutes, show any teams that are having trouble how to attach PRS systems to the platform. Also show them how to attach the colored dots and to use these as reference points in counting rotations. Allow further time for exploration.

Discussion

At the beginning of the next session, arrange for a brief discussion of the children's experiments and observations. Invite several pupils to report the number of rotations they counted.

Then construct a class histogram by drawing a vertical number line extending from 0 rotations on the bottom to 21 at the top, and tally an X next to each number for each team reporting that particular number of rotations.

Finally, ask your pupils to name some of the variables that might affect the number of rotations of the platform. List these on the chart paper under a suitable title suggested by the children.

Controlled experiments

To introduce the next activity, explain that the class will investigate how winding up the rubber band affects the rotation of the platform, while the other variables, such as the placement of the PRS systems, remain the same. Invite the children to name possible variables that will not change.

Remind the pupils that when they try to keep all variables but one constant and observe the effect of allowing that one to change, they are carrying out a controlled experiment. Emphasize that controlled experiments help you to find out the effect on the system of the variable you let change.

Carrying out the controlled experiments. Using student manual page 7

Ask the children to turn to page 7 and read the descriptions of the four experiments. Point out that they should repeat each experiment at least once as a check and do it a third time if their previous data differ greatly. Answer any questions the children may have.

After the teams pick up their equipment, explain the procedure individually to children who need help while the others go ahead with their experiments. Do not be overly concerned about numerical accuracy of the children's counts, since this is less important than the trend of the results.

Discussion

Ask your pupils to compare their observations for the four experiments recorded on page 8. Invite them to comment on the reproducibility of the data – were their two results similar when they repeated an experiment without purposely changing any variable? Use discrepancies to stimulate a search for additional variables that might be added to the list prepared in the first discussion. If necessary, again post the chart of possible variables prepared previously.

Analysis of the data

Post the grid chart and label. Explain that the numbers along the bottom of the chart represent windings of the rubber bands, while the numbers along the left edge represent rotations of the platform. Point out that the class will mark the data for each of the four experiments on page 7 as follows: the numbers of rotations found in *E* are marked along the vertical line for 40 windings and those found in *F* along the vertical line for 60 windings.

If none of the children mention the trend in the data from experiments *E* to *H*, ask them to explain why the platform made more rotations in the last experiment than in the earlier ones. Most of the children will relate their observations to the greater energy or increased winding of the rubber bands. Listen to the ideas and terminology and then during Chapter 5 refer to their explanations while "inventing" the energy source concept.

The data recorded on this chart and the trends that become visible will serve as stimuli for fruitful discussion.

"INVENTING" ENERGY SOURCES AND RECEIVERS

The chapter includes the invention phase of the learning cycle for the energy source, energy receive, and energy transfer concepts. A definition of energy itself is implied, but no attempt is made to formally define it for the children for the reasons given on pages 21-22.

Survey

To survey your pupils' understanding of energy, write *energy* on the chalkboard and ask whether they have seen that word. Then invite them to explain how the word is used and/or what it means to them, and list their ideas on the chalkboard. Most of their ideas will probably be related to food, human activity, fuels, or machinery. Keep the survey brief, and at its conclusion tell the children that you will show them a few experiments that have to do with energy.

Introducing energy source, transfer, and receiver

Display a rotoplane with one PRS system attached. Wind up the rubber band, release the system, and let the platform turn. Then ask the children to identify the objects in the system. Wind up the propeller again, pointing out that your hand is transferring energy to the propeller, which passes the energy to the rubber band. Explain further that after you release the propeller, the energy from the rubber band is transferred again through the propeller to the platform and the air.

Tell the children the band is called an *energy source* while it winds up the rubber band, and the rubber band is called an *energy receiver* while it is being wound up. Write *energy source* and *energy receiver* next to each other on the chalkboard. Also point out that the knots or twists of the rubber band are evidence of *energy transfer.* Write *energy transfer* above the other two terms and draw an arrow leading from energy source to energy receiver. Tell the children that the arrow is the symbol for energy transfer.

Feedback

To gather feedback about the children's understanding, demonstrate with several of the items you have prepared, each time asking the children to identify the energy source, energy receiver, and evidence of energy transfer. You might also write the names of each energy source and receiver on the board, with an arrow from one to the other to represent the energy transfer. Here are a few examples for your consideration:

1. Crumple up and throw a piece of paper across the room.
2. Light a match and hold it under a candle so that some of the wax melts. (Do not light the candle.)
3. Wedge a file card into a groove of the rotoplane platform and blow at the card in order to rotate the platform.
4. Turn on a battery-operated toy, radio, or flashlight and allow it to operate during the discussion of energy transfer.
5. Play a musical instrument, if one is available, or, ask one of your pupils to play one.
6. Wind up a spring-driven toy and allow it to operate on the demonstration table.

If necessary, repeat your explanation of the concept of energy transfer from source to receiver a second or third time. Also point out, with reference to the examples, some of the evidence of interaction that takes place in the energy source and receiver during the energy transfer. For instance, the spring unwinds and the toy moves, the match is consumed and the candle wax melts, or the flashlight shines. All these changes are observable evidence of interaction and energy transfer.

Energy Transfer chart

To help your pupils relate to the ideas of energy source, transfer, and receiver to experiences outside the classroom, make a chart as shown in Figure 5-3 You and your pupils can now suggest and discuss other interesting events to be added to the chart. If you use impersonal events (a candle burning, water boiling on the stove, a hammer hitting a nail), it will be easier to avoid some of the complexities of energy transfer to or from animals and/or persons.

If your class is interested, encourage them to consider conditions involving plants and animals. Their attempts to explain these more complex situations will help you assess their understanding of energy transfer and will also challenge them to use language effectively to express their ideas. Observe whether they relate the concept of energy transfer to their experiences with the concept of food transfer in the SCIIS *Communities* unit. This can be a most valuable experience for them.

2. WHAT CAN BE LEARNED FROM SKULLS?

Synopsis

Students observe a variety of vertebrate skulls and attempt to identify the animal and what it eats. Through class discussion the relationships between skull characteristics and implied functions are explored and the terms herbivore, omnivore, carnivore, nocturnal, diurnal and niche are introduced. This is a descriptive learning cycle.

Suggested time

Two class periods

Background Information

Vertebrate skulls reveal adaptations for specific functions. Large eye sockets, for example, accommodate large eyes needed for nocturnal activity. Eye sockets located on the sides of the head imply a similar positioning of the eyes for the good peripheral vision needed by prey animals, whereas a more frontal location implies good depth perception needed by predatory animals. Teeth also reveal adaptations. The teeth of herbivores are relatively flat for the grinding of plant material while the teeth of carnivores are more pointed and sharp for the grasping and tearing of flesh.

The purpose of this learning cycle is to provide students with an opportunity to observe skull characteristics and attempt to infer facts about the animal's food source and habitat (i.e., place where it lives) and to improve their ability to support or refute ideas through use of evidence and logical argumentation. It also provides you an opportunity to introduce the terms *herbivore*, *omnivore*, *carnivore* and *niche*, where niche is defined as an organism's role or function within a biological community.

Teaching Tips

Advance Preparation

1. Place a different skull at each of the 10 numbered stations.

Exploration

2. To introduce the lesson you may want to remind students of the work of paleontologists who are able to infer many things about the lifestyle and habitat of ancient animals from only a very few fossil bones. Ask them for any examples of this sort of work that they may know of and what might be some of the clues paleontologists use to draw their inferences. Tell students that the lesson today will challenge them to draw inferences about the lifestyle and habitat of a variety of vertebrates by observing their skulls located throughout the room. Specific questions they should consider are:

What type of food does this animal eat (e.g. plants, animals or both) and what evidence exists for that inference (e.g., number, shape, size, location of teeth)? Is this animal active during the day, night, both? What is the evidence (e.g., size, location of eye sockets)? Is the animal a predator or prey? Why (e.g., eyes front for depth perception: predator, eyes to side for peripheral vision: prey)? Make sure to raise the questions only during the introduction. Do *not* mention specific characteristics and inferences such as sharp teeth mean meat eater or eyes front means predator. Let the students discover these on their own. If they are not discovered, you may mention them later during the term introduction discussion.

Term Introduction

3. After students have gathered data on each skull, have them describe the differences they observed. Start the discussion by holding up skull 1. Ask for ideas and evidence. Go on to skull 2, etc.

4. As the discussion begins to center on teeth, put on the board the words the students use to describe them (tearing, crushing, grinding).

5. These teeth types will suggest function. Discuss this relationship. At the appropriate time introduce the terms herbivore, carnivore, omnivore and niche. Introduce them by stating the definitions first. Then state the term. For example, say, "This animal has sharp teeth for tearing and no flat teeth for grinding. This implies that it eats only animals. An animal that eats other animals is called a *carnivore*." "An animal that eats only plants is called a *herbivore*," etc.

6. Student attention to eye sockets will allow you to introduce the terms *nocturnal* and *diurnal* (e.g., "This animal has large eye sockets which implies that it has large eyes for night vision. An animal that is active during the night is called *nocturnal*.").

Concept Application

7. For concept application, provide opportunities for students to examine a variety of bones in addition to skulls and make inferences from their structure about their functions. For example, bird bones, fish bones, etc.

Biological Concepts	Thinking Skills
nocturnal	observation
herbivore	isolation of variables
carnivore	inference
omnivore	seeking and stating evidence
niche	
diurnal	

STUDENT MATERIAL

WHAT CAN BE LEARNED FROM SKULLS?

Introduction

Do we need to see an entire animal to determine where it lives or what it eats? Sometimes we can use bones as clues to provide insight into possible answers to these questions. Observation is a key to understanding. What can be inferred by looking at skulls?

Objectives

1. To infer function and animal behavior from observation of skull characteristics.

2. To improve your ability to support or refute hypotheses through use of evidence and logical argumentation.

Materials

10 skulls of 10 different species of vertebrates.

Procedure

1. In your group go to a station and take about 5 minutes to carefully examine the skull.

2. Observe the size and shape of the overall skull as well as other characteristics of the teeth, eye sockets, brain case, etc. Record interesting observations on the data sheet. Make a sketch if you want.

3. Try to decide what kind of animal the skull came from and what type of food it eats and where it might have lived. What characteristics of this skull allow organisms of this type to be successful? What evidence do you have for your guesses?

4. Move to the next station when you are ready. (No more than two groups may work at one station simultaneously.)

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3. WHAT CAUSED THE WATER TO RISE?

Synopsis

Students invert a cylinder over a candle burning in a pan of water. They observe that the flame soon goes out and water rises into the cylinder. They then attempt to explain their observations. Testing these explanations leads to new explanations and increased understanding of combustion, air pressure and the nature of scientific inquiry. This is an empirical-abductive learning cycle.

Suggested Time

Two class periods

Background Information

The primary purpose of this learning cycle is to personally involve students in the use of science in an attempt to answer two questions which arise from first-hand observation.

A burning candle is held upright in a pan of water using a small piece of clay. Shortly after a cylinder is inverted over the candle and placed in the water, the candle flame goes out and water rises in the cylinder. These observations raise two major questions: Why did the flame go out? Why did the water rise?

The generally accepted answer to the first question is that the flame "consumed" oxygen in the cylinder to a level at which too little remained to sustain combustion, thus causing the flame to die. The generally accepted answer to the second question is that the flame heated the air in the cylinder causing it to expand and causing some to escape out the bottom. When the flame went out, the remaining air then cooled and contracted creating a partial vacuum. This partial vacuum is then replaced by water rising into the cylinder until the air pressure pushing on the surface of water inside is equal to the air pressure pushing on the water surface outside.

This investigation is a particularly good way to introduce students to science as a hypothesis generating and testing enterprise as the hypotheses they invariably generate to answer the second question can be experimentally shown to be inadequate, and therefore must be modified through the use of both creative and rational thought processes and data gathering and analysis.

Students' initial misconceptions generally center around a theory which states that oxygen is "used up", creating a partial vacuum which "sucks" water into the cylinder. They fail to realize that when oxygen is "burned" it combines with carbon producing CO_2 rather than being destroyed (hence no partial vacuum can be created in this way). They also fail to understand that a vacuum cannot "suck" anything. Rather, the force which causes the water to rise is a push from the relatively greater number of air molecules hitting the water surface outside the cylinder.

The experiments and discussions provide you with an opportunity to attempt to modify these misconceptions by introducing more satisfactory models of combustion and air pressure. More importantly, it allows you to introduce science as an intellectually stimulating and challenging way of trying to describe and explain nature.

Teaching Tips
Exploration

1. You may wish to initiate this lesson with a demonstration or simply let the students obtain the materials and get started on their own.

2. If you decide to demonstrate the phenomenon, procedure steps 4 and 5 can be done during the class discussion. If you let the students start on their own you will probably have to stop them after about 15 to 30 minutes for a discussion of their observations and ideas.

3. During the discussion, observations and ideas should be listed on the board. The most obvious questions are: Why did the flame go out? Why did the water rise? The most likely explanation to the second question is that since the oxygen was "burned up" the water rose to replace the oxygen which was lost.

   Lead the students to realize that this explanation (hypothesis) predicts that varying the number of burning candles will *not* affect the level of water rise. Four candles, for instance, would burn up the available oxygen faster and go out sooner than one candle, but they would not burn up more oxygen hence the water should rise to the same level.

4. Have the students do this experiment and report results. The results, of course, will show that the water level is affected by the number of candles (the more candles, the higher the water level). Their hypothesis, therefore, has been contradicted. At this point you should emphasize the need for an alternative explanation and ask students to propose one. This may be an excellent time for the bell to ring as no one may have a good alternative and you can

challenge them to think up a new explanation as their homework assignment.

5. If someone does propose the "correct" explanation (i.e., the heated air escaped out the bottom, etc.) do not immediately tell the class it is correct. Rather treat it as just another hypothesis to be tested. Ask students to try to think of a way to test the hypothesis. They should realize that the hypothesis leads to the prediction that bubbles should be seen escaping out the bottom of the cylinder. (Note that it also leads to the prediction that the number of candles will affect the level of water rise because more candles will heat more air; therefore, more will escape and in turn will be replaced by more water.) Have the students repeat the experiment to see if bubbles can be seen. If no one proposes the correct explanation you will have to propose it yourself. But again, make sure that you do not give the students the impression that this is the correct explanation. Rather, it is simply an idea you had that should be tested along with any other ideas that are generated. The conclusion that it is correct should come only after data have been gathered which are consistent with its predictions (e.g., bubbles, more candles: higher water rise, water rise *after* flame goes out while air cools).

Term Introduction

6. After such data have been gathered, you should carefully repeat your explanation of the phenomenon introducing the term *air pressure* and a molecular model of gases which assumes air to be composed of moving particles that have weight and can bounce into objects (such as water) and push them out of the way. You may wish to discuss the common misconception of "suction" in this context. The molecular model implies that suction (as a force that can suck up water) does not exist (i.e., the water is being pushed into the cylinder by moving particles of air rather than being sucked by some nonexistent force).

Concept Application

7. To allow students to apply the molecular model of gases and the concept of air pressure to new situations, provide each group a piece of rubber tubing, a syringe, a beaker and a pan of water. Instruct them to invert the beaker in the pan of water and fill it with water in that position with the mouth of the beaker

submerged. *Hint*. Students will probably make futile efforts to force water through the tube into the beaker before discovering that they must extract the air through the tube.

8. As a homework assignment, challenge the students to find a way to insert a peeled, hard boiled egg into a bottle with an opening which is smaller in diameter than the egg. They must not touch the egg after it has been placed on the opening. *Hint*. After a small amount of water in the bottle has been heated, it is only necessary to place the smaller end of the egg over the opening of the bottle to form a seal. The egg will be forced into the bottle by the greater air pressure outside as the air inside cools.

9. Unobserved by the students, place water in a ditto fluid can to a depth of about one centimeter and boil the water vigorously. Then screw the cap on tightly to form a seal. Place the can on your desk in full view of the students and allow them to witness the can being crushed. Challenge the students to explain their observations using the molecular model of gases and the concept of air pressure.

Chemical Concepts	Thinking Skills
air pressure	observation
molecular model of gases	hypothesis testing
combustion	control of variables
energy transfer	analogical reasoning
	identification of variables
	hypothetico-deductive reasoning

STUDENT MATERIAL

WHAT CAUSED THE WATER TO RISE?

Introduction

Often things seem simpler at first glance than they really are. Upon closer examination the complexity and mystery become more apparent. Discovering and solving these mysteries can be enjoyable and more satisfying than looking for answers in books or asking people who claim to know better than you. There is a way to search for your own answers. It is called science and it can be fun. We are going to do some now.

Objectives

1. To stimulate curiosity about natural phenomena.

2. To become aware that science is an activity that involves generating hypotheses and predictions to arrive at explanations.

Materials

aluminum pie tins	cylinders (open at one end)
birthday candles	jars (of various shapes, sizes)
matches	beakers and/or test tubes
modeling clay	syringes
	rubber tubing

Procedure

1. Select a partner and obtain the materials.

2. Pour some water into the pan. Stand a candle in the pan using the clay for support.

3. Light the candle and put a cylinder, jar or beaker over the candle so that it covers the candle and sits in the water.

4. What happened?

5. What questions are raised?

6. What possible reasons can you suggest for what happened?

7. Repeat your experiment in a variety of ways to see if you obtain similar or different results. Do your results support or contradict your ideas in #6? Explain.

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4. WHAT CAUSES WATER TO RISE IN PLANTS?

Synopsis

Students design and conduct experiments to test hypotheses about causes of water rise in plants by removal of plant parts, by coating surfaces with petroleum jelly, etc. This is a hypothetical-deductive learning cycle.

Suggested Time

Two to three class periods.

Background Information

The stems of vascular plants contain xylem vessels that conduct water which rises up from the roots to the leaves where it is used for photosynthesis and other vital cell processes. But what causes water to rise against the physical force of gravity? Apparently a number of factors are involved.

One force results from the osmotic movement of water into root from the soil. This osmotic force, called *root pressure*, is generated at the bottom of the xylem and tends to push water upward. Evidence of this root pressure comes from cut stems which will "bleed" fluid for some time after the stems are cut.

Root pressure is also presumably responsible for the occasional appearance of drops of water on the tips of leaves at the leaf vein endings when water loss due to evaporation (called transpiration) is low and the soil contains a lot of water. This "bleeding" is called *guttation*.

Root pressure alone, however, is not strong enough to account for the movement of water up a tall tree. Another force or set of forces must be involved. One of these forces appears to be the cohesion of water molecules. The polarity of water molecules provides a very strong attraction among water molecules, thus, a column of molecules will stick together so that any "pull" on the top molecules will result in the rise of the entire column.

But what sort of a pull can exist at the top of the column? A number of popular textbooks suggest (even state) that the transpiration of water from the leaves will cause a partial vacuum that can "suck" the water up like sucking a milkshake through a straw. Clearly, however, this cannot be the case because "suction" as a force is nonexistent. The force which moves the milkshake up the straw is a push from below due to greater air pressure on the surface of the milkshake outside the straw than on the surface inside the straw. A number of your students will most likely hold this "suction" misconception.

What, then, provides the pull? The best guess at this point appears to involve osmosis and goes as follows: Transpiration of water in leaf cells increases their concentration of solutes and therefore increases osmotic "pull" of extracellular water into the cells such as that in nearby xylem tubes. Because the column of water sticks together (due to cohesive forces of water molecules) the osmotic pull at the top will cause the entire column to rise. This theory is commonly referred to as the *cohesion theory*.

Although the cohesion theory has gained wide acceptance among plant physiologists, it leaves a few problems unresolved. The theory requires the maintenance of the column of water in the xylem, yet breaks frequently occur. How the theory can accommodate this contradictory finding is not clear. Another puzzle is how the column of water is established in the first place. Perhaps it "grows" there as the plant grows.

The fact that no single theory solves all the problems should be viewed as a positive aspect of this learning cycle. In a very real sense this learning cycle allows students to move quickly to the "cutting edge" of this area of research.

Expect a variety of hypotheses from your students at the outset. For example, the following alternative hypotheses were generated by students in a previous class:

a.) water evaporates from the leaves to create a vacuum which sucks water up,

b.) roots squeeze to push water up through one-way valves in the stem tubes,

c.) capillary action of water pulls it up like water soaking up into a paper towel, and

d.) osmosis pulls water up.

Of course equipment limitations keep some ideas from being tested, but the "leaf evaporation" hypothesis can be tested by comparing water rise in plants with and without leaves, requiring the isolation and control of variables. The "root squeeze" hypothesis can be tested by comparing water rise in plants with and without roots; the "one-way valve" hypothesis can be tested by comparing water rise in right-side-up and up-side-down stems. Results allow rejection of some of the hypotheses but not others. The survivors are considered "correct," for the time being at least, just as is the case in doing "real" science – which of course is precisely what the students will be doing.

Teaching Tips

Exploration

1. Start by posing the problem and calling for alternative hypotheses. These should be listed on the board followed by a discussion of how students might try to test them. Point out that the strategy they should attempt to follow is to falsify hypotheses rather than attempt to "prove" them. For instance, the "one-way valve" hypothesis predicts that water will rise in a right-side-up stem but not in an up-side-down stem. If water rises equally well in both stems, the hypothesis must be false. Tell students to test as many hypotheses as they can in the time provided.

2. Advise students to cut stems under water, and keep the stem in water for a minute before performing other manipulations. This prevents air bubble blockage of the xylem.

Term Introduction

3. At an appropriate time have students report their experimental designs and results to the class. This can be done in a variety of ways. Select the way that best suits your needs and the amount of time available. One successful approach is to have each group select a spokesperson to present a brief oral report (e.g., three to five minutes) and allow questions to be asked at the conclusion of

each report. At the conclusion of all the reports you can summarize the major findings and introduce or reintroduce terms such as osmosis, transpiration, cohesion and xylem. Be prepared to deal with the notion of suction. You may wish not to tell students that there is no such thing as suction but have them try to imagine what goes on at the molecular level when evaporation occurs. Ask them to try to imagine how a molecule escaping from the water surface could possibly pull those left behind.

Concept Application

4. As this concludes the set of learning cycles on plant physiology in our course, no specific activities have been included to allow the direct application of these specific biological concepts. However, the thinking skills involved here will be applied in a number of the remaining learning cycles.

Biological Concepts	Thinking Skills
transpiration	analyzing data
xylem	organizing and communicating results
osmosis	observation
cohesion	control of variables
root pressure	analogical reasoning
guttation	hypothesis testing
	hypothetico-deductive reasoning

STUDENT MATERIAL

WHAT CAUSES WATER TO RISE IN PLANTS?

Introduction

If you place a plant such as a stalk of celery (with leaves) in a beaker with colored water, you will soon notice that the colored water somehow moves up through the celery stalk into the leaves. Observations such as this suggest that the general pattern of water movement in plants is from the roots, through the stem, to the leaves. But what causes the water to move upward? Clearly this movement is against the force of gravity which pulls things down. Do you have any ideas?

Objectives

1. To determine the cause or causes of water rise in plants.

2. To identify some of the structures through which water travels in plant stems.

Materials

food coloring
toluidine blue stain
slides and coverslips
compound microscope
colored pencils or markers
petroleum jelly
test tubes
test tube rack
single edge razor blade
a variety of plants and stems (e.g., celery, coleus, bean, onion, sunflower, pyrocantha, palo verde, orange, corn, *Impatiens*)

Procedure

1. List any hypotheses you and others in the lab may have concerning the cause of the upward movement of water through plants.

2. Select one partner to work with. Use the materials provided to design experiments to test these hypotheses. In general you will have to place plants or plant parts into containers partially filled with colored water and wait several minutes to observe the movement or lack of movement of the colored water through the plant. Your plan of attack should be to try to disprove (or support) each of the hypotheses advanced by comparing predicted results with actual results. Use Table 1 to summarize your work for each experiment. Should you include some sort of control? If so, what and why?

3. Were you able to tell precisely where in the plant stem the water was moving? If not, you may want to make some cross sections of stems that have had colored water and/or stain passing through them. Perhaps the colored water will have stained the water conducting portion of the stem that will be visible under the microscope in cross section.

4. Be prepared to report your observations, experimental results, and tentative conclusions to the class near the end of the lab period.

5. HOW DO LENSES WORK?

Synopsis

Students explore the images formed by convex lenses and discover that when the distance between an object and a lens becomes great, the distance between the lens and its upside-down image becomes constant. This is a descriptive learning cycle.

Suggested Time

Teaching Tips

Exploration

1. The students are given one convex lens and a white card at the start of the learning cycle and instructed to find out everything they can about the lens and to make and record any measurements they believe to be important. The students generally measure the diameter and sometimes the thickness, and find that the middle of the lens is its thickest portion. Using the card the students also find that the lens projects an image onto the card.

2. The students also usually find that the distance between the lens and the image on the card is variable because they are using an object – usually a light bulb – relatively close to the lens.

3. Students typically ask questions relative to what would happen if an object were moved a greater distance from (or moved closer to) the lens. They have probably already found that for every distance between the object and the lens there is only one distance at which the image will focus clearly on the card and as the object is moved closer to the lens, eventually the image on the card disappears and the image of the bulb when viewed through the lens becomes larger. That effect provides the teacher the opportunity to introduce the term *magnification*.

4. After a time the students will find that no matter how far they move the object from the lens, the distance between the lens and the object's image becomes relatively constant.

Term Introduction

1. At this point in the investigation the numerical data that came from the measurements need to be examined. The students should be required to put their data on the chalkboard. Those data will

consist of the measurements taken of the image distances and the object distances and if not done so earlier, this is an opportune time to introduce those ideas. Eventually – and not too much time will pass – the students will agree that as the *object distance* gets larger the *image distance* remains relatively constant. In fact, the students will probably insist that the image distance is constant. The data the class has collected should be clear on that point before the central terms coming from the learning cycle are introduced.

2. Those terms are the *focal length* of a convex lens, which can be generally stated like this: When the distance between the object and the lens becomes great, the distance between the lens and its upside down image becomes constant. That distance is known as the *focal length* of the lens.

   Physicists usually refer to the object being at an "infinitely great" distance from the lens but that phrase is generally not meaningful to students – even though it is later – if the teacher introduces it now. Probably the phrase is not meaningful because during the investigation distances were called "great" and "greater" and not infinite; besides, "infinite" is a rather indefinite term.

Concept Application

1. The students are now ready to apply the idea of focal length and that phrase – *focal length* – should be used as frequently as possible during the application phase. We have found that there are at least two fruitful directions to follow in this phase of the learning cycle and you might think of others to use instead of or in addition to the ideas which follow. We have found that it is not generally a good practice to allow the initial application phase of the learning cycle to go on for too long a time. The two applications of the concept being referred to can be expressed as questions.

   a. How closely can an object be brought to the lens before its image distance begins to change?

      When the image distance begins to change it is no longer the focal length. At this point the term *infinity* can – and probably should – be introduced and the importance of what that infinite distance is being compared to should be explored. All the discussion should *follow* a period when measurements are taken and observations made.

Data can be collected to answer the first question by moving an object closer to and farther away from a convex lens and measuring the distance between the lens and the image projected on the card. Keep in mind that when the object is far away that distance is the focal length of the lens. So what is really being researched is the relative size of infinity. Our experience has shown that the size of infinity depends upon the thickness of the lens.

One of the purposes of the application phase needs to be reviewed at this point. When new ideas are introduced they are understood well by some, tentatively by most and not at all by a few. One of the principle purposes of the application phase is to increase the number of teachers available. Those who understand the concept well can now begin to function in a teaching role and begin to teach those who have achieved a tentative understanding and those who have no understanding. This new influx of teachers allows for several small classes to begin and the results are encouraging. The data collected to answer the first question are numerical and that type of data is generally easy to explain because of the definiteness of the numbers. Furthermore, supporting conclusions with data is more important than the conclusions themselves. So when evaluating the contributions of students toward the application of a newly-introduced idea, the discussion of the data and the nature of the argument are more important than the conclusions reached.

b. How do the focal lengths of a thick lens and a thin lens compare?

To collect data to answer the second question, two lenses – or more – can be held together at their edges with tape. That technique allows the students to begin with one lens and add others as they wish. The technique is sometimes not approved by physicists because of the air that is present between the faces of the convex lenses. But the results usually demonstrate that as the lens combination increases in thickness, its focal length becomes shorter. The entire process of securing lenses together is not necessary if a supply of lenses of varying thicknesses is available.

2. Note that this learning cycle as described has been classified as a descriptive learning cycle primarily because as presented, students attempt to describe the numerical relationships among objects, the lenses, and the images. Clearly, however, the learning cycle can and should go beyond this descriptive phase. If and when students generate models of light rays to explain their observations, the learning cycle becomes empirical-abductive.

Physics Concepts	Thinking Skills
magnification	analyzing data
focal length	observing
infinity	measuring
	organizing and communicating results

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Appendix 16

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