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The assimilation and accommodation of concepts in astronomy

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THE ASSIMILATION AND ACCOMMODATION OF
CONCEPTS IN ASTRONOMY

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DEDICATION

To my father, Albert, and my mother, Anita, who have loved, supported and inspired me in ways that cannot be described in print.
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ABSTRACT

This study investigates the ways in which knowledge changes were and were not congruent with the conceptual change model of instruction, when astronomy students were taught according to that model.

One leading conceptual change model has been suggested by Posner et al (1982). Their model recommends that instruction create dissatisfaction with students' existing incorrect models, provide alternate models that are intelligible and plausible, and allow students to experience the fruitfulness of their models by explaining and predicting observations.

Students were instructed about the phases of the moon according to this prescription. Tests covering the phases were given before, during, and after instruction. A coding scheme was used to interpret the test responses so as to characterize students' models. The coded data were then used to portray changes that took place during instruction, using definitions of accommodation and assimilation derived from conceptual change theory.

Eight of the nine students starting instruction with alternative models did not sustain those alternative models throughout instruction. These results, consistent with...
expectations of the Posner et al model, suggest that this method has promise, especially in cases where students enter instruction with alternative models.

Students who did not begin instruction with alternative models made significant gains. These results suggest that this method will help such students assimilate correct propositions.

One third of the students in this study developed alternative models as a result of the first phase of instruction, in which students made observations of the moon. Eighty-three percent of these students did not sustain these alternative models throughout instruction, suggesting that the Posner et al method can be used to address misconceptions that arise during instruction.

Finally, the changes described as accommodation were not wholesale changes. They are better described as piecemeal deletions and additions of key propositions that occurred against a base of stable propositions. Those teaching to create accommodation should aim to change the incorrect propositions while building new knowledge upon the pre-existing base of correct knowledge.
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Chapter 1

INTRODUCTION

An emerging line of research in science education is that of conceptual change, which addresses the changes in an individual's knowledge of a given content domain that occur through experience or instruction. A leading theory of conceptual change has been proposed by Posner, Strike, Hewson, and Gertzog (1982). In describing their theory, Posner et al suggest an instructional strategy designed to facilitate accommodation, the strongest form of conceptual change. Posner et al believe this strategy is needed to overcome widespread and strongly held scientific misconceptions.

Significance of this Study

To date, few documented classroom trials of instruction according to the Posner et al prescription for instruction have taken place. Other researchers (e.g., Champagne et al, 1985) have studied conceptual change but have not specifically followed the prescription of Posner et al (1982). Vosniadou and Brewer (1987) have described changes in knowledge in the language of conceptual change theory, yet they have not specifically followed Posner et al either to effect instruction or to describe conceptual change. This study is one of the first documented trials of the Posner et al model and a test of their predictions.
**Statement of Purpose**

The purpose of this study was twofold: 1) to apply the conceptual change instructional method prescribed by Posner et al to an astronomy content domain taught in the planetarium setting, and 2) to determine ways in which students' knowledge changes are and are not congruent with the conceptual change model.

To achieve this end, an instructional domain (the phases of the moon) was delineated in fine detail. Pretests covering this domain were administered prior to instruction, with the goal of inferring the prior knowledge each student maintained. Subsequent instruction was based upon the Posner et al model. Further testing took place during and after instruction, with the aim of charting conceptual change as it occurred and after it was completed.

The conceptual change model, including its instructional strategy and its predictions of knowledge changes, is discussed below. In addition, methods used in this study to employ that strategy and to test those predictions are summarized below.

**Conceptual Change Theory**

Posner et al derive their ideas of conceptual change from the philosophy of science school epitomized by Kuhn (1970). According to this perspective, the progress of
science alternates between states of "normal science"— in which investigations proceed according to a dominant paradigm—and "revolutionary science"— in which scientists are confronted by evidence that challenges the paradigm, and the paradigm changes or "shifts."

From the conceptual change perspective, change in the individual is analogous to the science-wide Kuhnian theory-change process. Wiser and Carey (1983) and McCloskey (1983) provide evidence that this leap from the size, time, and expertise scale of the professional scientific community to that of the individual is appropriate. They cite examples of conceptual change on the individual level that parallels changes that took place over decades or centuries on the science-wide level.¹

The individual equivalent to Kuhn's "normal science" is assimilation, in which the individual acquires new information that is consistent with his or her existing core propositions. Ultimately, however, the individual is confronted with anomalous information that cannot be explained by these core propositions. If the conditions are right, accommodation, the individual's equivalent of a

¹Strike and Posner (1985) caution that this analogy can only go so far; scientists as a group can overcome the limitations of any individual. See Shulman and Carey (1984) for further discussion of the collective rationality synthesized by the group. See Hodson (1988) for more discussion about the relationship between individual learning and scientific theory change.
paradigm shift, will occur. In accommodation, core propositions are replaced by new ones that explain the known observations and allow for the prediction of new ones.

Accommodation is thought to be especially important since we know students often begin with "core concepts" that are erroneous. For example, we know that introductory astronomy students have fundamental misconceptions regarding the explanation of the phases of the moon (Haupt, 1948, 1950). Thus, this study addressed these misconceptions through instruction designed to create the more radical form of conceptual change, accommodation.

Teaching for Accommodation

To facilitate accommodation, Posner et al (1982) propose a prescription for instruction. They suggest that instruction be designed to create dissatisfaction with students' existing incorrect models, to provide alternate models that are intelligible and plausible, and to allow students to experience the fruitfulness of their models by explaining and predicting observations.

Dissatisfaction. A student must feel dissatisfied with existing ideas before he or she will consider replacing them. Strike and Posner (1985) suggest that this dissatisfaction can be generated by illuminating a particular fact (observational or theoretical) as anomalous
with respect to the learner's current conceptions. In addition, certain pre-conditions must be satisfied if a student is to experience dissatisfaction: a student must experience intended anomalies as such, must believe that reconciling the anomaly with his or her current conceptions is important, must accept that inconsistencies need to be reduced, and must not falsely assimilate new information into an incorrect core.

**Intelligibility.** A new theory must be intelligible to the learner before it is accepted. To create intelligibility, Posner et al suggest the use of analogies.

**Plausibility.** Before a new theory is accepted, it must be plausible to the learner. To create plausibility, the new conception must be consistent with the learner's current set of conceptions.

**Fruitfulness.** To be fully accepted by the learner, a new theory must be fruitful to the learner. To create fruitfulness, instruction must include the opportunity for students to explain the observations and make predictions.

**Predictions of the Posner et al Theory**

Given the Posner et al theory, certain predictions can be derived. These predictions are relevant to cases in

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2In this study, Posner's term "conceptions" is replaced by propositions or a set of propositions.
which teaching for accommodation was intended, to cases in
which it was not intended, and to the general nature of
accommodation.

1. Under optimal conditions students with alternative
theories should accommodate when they are taught using
methods consistent with the Posner et al conceptual
change model.

2. Since Posner et al and other conceptual change
theorists recommend teaching for accommodation without
restriction, one might assume that this method will
work for everyone, regardless of their initial state
of knowledge. In addition, because Posner et al view
assimilation and accommodation as different only in
degree, one can predict that teaching for
accommodation should also work for students who need
to assimilate. One might also assume that teaching
for accommodation might work best for those with
alternative models.

3. Posner et al believe that accommodation takes
place against a background of current conceptions;
therefore, one might expect evidence that
accommodation involves additions and deletions of
propositions against a background of stable
propositions.
Instruction and Research Methods

To test the predictions enumerated above, students were instructed in accord with the Posner et al. model. Tests were given before, during, and after instruction. Changes in students' knowledge revealed by these tests were charted and analyzed to see if they were congruent with the predictions of conceptual change theory. The instruction and research methods are described in greater detail below.

Instruction

Instruction for conceptual change focuses upon encouraging accommodation by creating the conditions of dissatisfaction, intelligibility, plausibility, and fruitfulness described earlier.

Dissatisfaction. In this study, dissatisfaction was created by giving students a difficult pretest, by asking students to explain their observations, and by using anomalies to challenge alternative frameworks.3

The pretest given at the beginning of instruction may have created dissatisfaction in two ways. First, the test may have frustrated students who felt they must answer all questions. Second, students may have become dissatisfied with their models when these models could not solve the test problems.

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3Dissatisfaction was not measured although the instructor noted anxiety among some of the students while taking the pretest.
Observations of the moon over the course of a month also created dissatisfaction with students' current models since these models could not explain the observations.

Anomalies were used to challenge alternative frameworks. These anomalies, brought to students' attention during instruction, were inconsistencies between the predictions made by these alternative frameworks and the base of observations as understood by the students.

Intelligibility. Intelligibility was established through the use of models, including the planetarium and a model of the moon.

Plausibility. Plausibility was maintained by using models that were consistent with previous knowledge.

Fruitfulness. Fruitfulness was established by having students use their models to predict the appearance of the moon at different positions and times.

Research Methods

To test the predictions derived from the Posner et al theory of conceptual change, this investigation was guided by two research questions. The first question asks for a detailed description of student knowledge before, during, and after instruction. The second question asks for a description of the changes in knowledge that took place between these three points in time. These questions are stated below.
Question 1. What is the character of the students' pre, mid, and postinstructional knowledge in terms of content, consistency, completeness, and correctness as revealed by the pretest?

Question 2. What changes in the content of students' knowledge can be documented after instruction based on a conceptual change model, and how do those changes compare to the changes predicted by the model?

To answer these research questions, a test designed to cover the content domain of the lunar phases was administered to an introductory astronomy class of 61 students at three points in time: before, during and after instruction.

To answer Question 1, a predetermined coding scheme was used to interpret the test responses so as to characterize students' models. To answer Question 2, the coded data were used to portray the changes that took place during instruction. These changes were evaluated to see if they were consistent with the changes predicted by the Posner et al theory of conceptual change.

Conceptual change theory and its implications for instruction are discussed further in the next chapter. The methods of instruction and analysis used in this study, as well as the results of that analysis, are discussed in subsequent chapters.
Chapter 2

REVIEW OF THE RELATED LITERATURE

The Switch from Piaget to Conceptual Change Theory

Until recently, Piaget's theory of stages and equilibration has been the dominant source for theories concerning cognitive change in science students. Piaget viewed the transformation that takes place during learning as a process of adjusting one's mental structure to achieve equilibrium in the face of new, disequilibrating information (Piaget, 1985; Fuller, Karplus and Lawson, 1977.) Although this aspect of Piaget's theory is fundamental to the theory of conceptual change being considered in this study, other aspects of Piagetian theory have recently come under attack (Carey, 1985; Gelman and Baillargeon, 1983; Mandler, 1983). These authors are critical of Piaget's theory because it assumes cognitive change to be content-independent. Evidence demonstrates that content plays a major role in thinking and learning processes (Johnson-Laird, Legrenzi, and Legrenzi, 1972) and that cognitive change should be viewed as content dependent and domain specific (Carey, 1985; Novak, 1977; Stewart, Finley, and Yarroch, 1982). In fact, recent theorizing about change upon which this study is based (Posner et al; 1982, Rumelhart and Norman, 1978; Carey, 1986; Vosniadou and Brewer, 1987; Hodson, 1988) has concentrated more upon
the change in the concepts than in the underlying logical structures hypothesized by Piaget.

The Sources of Conceptual Change Theory

Current conceptual change thinking has its origin in three separate sources: developmental psychology and biology, information processing, and the philosophy of science.

Developmental Psychology and Biology

Although Piaget's model may no longer be dominant, the impact of his research and theory is still strongly felt among today's theorists of conceptual change. First, his research concerning children's theories can be viewed as the precursor to today's study of misconceptions. Second, his research techniques (including the clinical interview) are widely used. Finally, a close approximation to his assimilation/accommodation theory of cognitive equilibration forms the heart of today's conceptual change theories (Hintzman, 1978).

Information Processing

Rumelhart and Norman (1978) describe three types of cognitive change according to the information processing paradigm. Accretion is the accumulation of facts. Tuning is the modification of categories of interpretation (or schemata) so that they are more refined and precise (e.g., distinguishing between rotation and revolution).
Restructuring occurs when the cognitive structure itself is changed. According to Anderson (1977), accretion is similar to assimilation, since it involves schema use, and tuning and restructuring are both examples of accommodation, since they involve schema change.

**Philosophy of Science**

Some theorists arrived at the notion that conceptual change is a process of assimilation and accommodation from within the information processing paradigm, and others arrived at this notion from the point of view of developmental biology and psychology. Posner et al (1982) agree with this conception, yet they do so from the perspective of the history and philosophy of science (Kuhn 1970; Lakatos 1970; and Toulmin, 1972). According to the perspective of these authors, "current conceptions are a product of a history of conceptual development" (Strike and Posner, 1985). New theories are judged by how well they solve the problems defined by the current conceptions. The current scientific conceptions are either modified slightly (as in Kuhn's "normal" science) or radically (as in Kuhn's "revolutionary" science) as they interact with new information.

The 1982 article by Posner et al suggests both the beginnings of a conceptual change approach to learning and some instructional implications of this developing theory.
Since this study uses conceptual change theory described by Posner et al to examine changes that occur, the perspective of these authors will be described in the following sections.

The Conceptual Change Perspective Described by Posner

The "rational commitment" assumption of conceptual change theory, the types of change in an individual's conceptions, and other assumptions of conceptual change theory, are described below.

The "Rational Commitment" Assumption of Conceptual Change Theory

Posner et al are committed to a rational model for human learning, and believe students have "alternative conceptual frameworks" (Driver and Easley, 1978) rather than what Carey (1986) calls "bags of tricks that they call upon haphazardly" (p. 1128).

This rational assumption is at the heart of Posner et al's conceptual change model (1982). According to these authors, rationality is related to "the conditions under

\[\text{In a sense, Posner and his colleagues contradict themselves by adopting a Kuhnian perspective and then committing themselves to a rational model of human learning. Kuhn (1970) suggested that the grounds for accepting a new scientific theory are fundamentally irrational. Other philosophers, notably Feyerabend (1970), have supported this view on the grounds that science is and should be directed by human values, not on some "rational" process. West and Pines (1983) also suggest that Posner and his colleagues have inappropriately isolated the rational from the underlying irrational elements of learning.}\]
which a person is or should be willing to change his or her mind" (Strike and Posner, 1985, p. 211). If students were not committed to forming consistent, rational models, then what would drive the process of accommodation? What reason would they have for being dissatisfied with their conceptions in the first place? What reason would they have for being satisfied with a new conception?


A significant controversy about this matter remains unsettled (Cohen, 1981; Kyburg, 1983). If it can be shown that the conceptions students hold are significantly inconsistent, this would undermine the conceptual change approach that is the basis of this study. To show this, it would be necessary to document a significant number of

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2One reason that it would take significant inconsistency to undermine the assumptions of Posner et al is that temporary tolerance of anomalies and inconsistencies is not necessarily an irrational behavior. See, for example, the discussion by Lakatos (1978) on what it takes to stop a research program.
cases where students clearly maintain core concepts that are contradictory either to each other or to the domain of observations with which they are familiar.

Types of Conceptual Change Implied by Conceptual Change Theory

The types of change described by theorists of conceptual change include accommodation and assimilation: these changes are determined by examining core and derived concepts.

Accommodation and assimilation. Conceptual change theorists translate the view of science-wide change derived from the Kuhnian philosophy of science to the situation of change in the conceptions of the individual learner:

The important questions are the way learners incorporate new conceptions into current cognitive structures, and the way they replace conceptions which have become disfunctional with new ones. (Strike and Posner, 1985, p. 212)

According to Posner et al, the incorporation of new conceptions into current cognitive structures is assimilation, and the replacing of disfunctional conceptions with new ones is accommodation.

Since Posner suggests we look to Kuhn for insight into conceptual change, this would seem to mean that accommodation, which is analogous to scientific revolution,
is a total paradigm shift, and assimilation, which is analogous to normal science, is the addition of new knowledge to a stable core.

We should be aware, however, that Kuhn's early, extreme position (Kuhn, 1962) and even his later version (Kuhn, 1970) of revolutionary vs. normal science became the object of criticism. For example, Kuhn states that:

The normal scientific tradition that emerges from a scientific revolution is not only incompatible but often actually incommensurable with that which has gone before. (Kuhn, 1970, p. 103)

Toulmin (1970, 1972), Keat and Urry (1975) and Kendler (1978) stress that these differences between normal states and revolutionary states, as well as between two successive normal states, have been greatly exaggerated, originally by Kuhn and then by many of his followers. For example, Kuhn (1970) suggests that observations made in two subsequent states can only be evaluated by rules internal to the paradigm and are therefore completely theory-laden and subjective. In essence, one paradigm cannot be evaluated with respect to the other. This raises the question of whether only extreme shifts can be called accommodations. Kuhn has more recently made some concessions, however, by agreeing that there are some permanent standards by which to evaluate theory and observation, and that the evolution
of scientific theories is less punctuated than he had originally thought (Kendler, 1978). Posner and his colleagues may be attempting to overcome this limitation of extreme paradigm to paradigm subjectivism inherent in Kuhn's theory by hypothesizing that inquiry involves

... one additional feature. We believe that inquiry and learning occur against the background of the learner's concepts. Whenever the learner encounters a new phenomenon, he must rely on his current concepts to organize his investigation. Without such concepts it is impossible for the learner to ask a question about the phenomenon, to know what would count as an answer to the question, or to distinguish relevant from irrelevant features of the phenomenon. (Posner et al, 1982, p. 212)

This statement implies that Posner et al believe that a background of conceptions may remain, even after as radical a change as accommodation has taken place.

A recent article by Strike and Posner (1985) also suggests that accommodation need not produce radical change. They note that the differences between assimilation and accommodation may be a matter of degree.
This perspective is in accord with Kuhn's modified position (Kendler, 1978).³

This body of philosophical literature would suggest that when we look for accommodation, we look not for wholesale "conversions," but rather for significant changes in the core content and/or structure of student conceptions. When we look for assimilation, we should look for elaboration of concepts derived from the relatively stable core.

**Core and derived concepts.** To describe changes in the core concepts and additions of derived concepts, it is first necessary to define "core" and "derived" concepts. The conceptual change literature does not give any operational definition of a "core" concept although many authors refer to core concepts when they talk about accommodation. The operational definition assumed in this study is that the core concept relates to the central cause of the phenomenon being described. This definition has no single source as its basis; it is derived from the writings of several authors, notably Meehl, Carey, Lakatos, and Strike and Posner.

³Piaget viewed accommodation and assimilation as two opposite poles of the dynamic of change, both occurring simultaneously, but with each alternating in dominance (Inhelder et al., 1974; Siegler, 1986).
Meehl (1977) talks about causation as being central to a particular disease concept. The causal factor with the greatest and most inclusive predictive power is at the core of the disease concept.

Meehl also writes about the nomological net. Cronbach and Meehl’s (1955) paper about construct validity introduces the concept of the nomological net, which consists of nodes or theoretical constructs that are connected by laws to each other and to observables. The nodes constitute the core of the net, and the connections to the observations constitute the derived concepts. (Meehl [1985, 1986] would describe the theoretical constructs as being the “interpretive text” and the observational language as being the “operational text.”)

Carey (1985, 1986) notes that “strong” theory change, which is defined by a change in the core concepts, includes changes in causal notions. She cites as an example the change in causal notions that occurred as the Aristotelian system was replaced by the Galilean theory.

Lakatos (1978) describes the “hard core” of a theory and suggests that scientific research is usually aimed at

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4 In recent writings, Meehl refers to the nomologicals as stochasticals, implying the frequently probabilistic nature of causal connections.

5 For complete discussions on the different types of language that form the complete nomological net of a theory, see Hempel (1958, 1965) or Scriven (1958).
adjusting the "protective belt" around this core. This protective belt includes auxiliary hypotheses, initial conditions, and observational hypotheses. In the theory of the lunar phases used in this study, the core would be the underlying causal model, and the protective belt would include the observational hypotheses (e.g. that the moon should be a certain phase given a certain angle from the sun).

Strike and Posner (1985) do not specifically define core concepts, but they do give an example of accommodation from the history of psychology. They show how acceptance of Freud's ideas involved accommodating the conception that the mind includes the unconscious as well conscious awareness. The concept of the unconscious is central to Freud's psychoanalytic theory because it explains a wide range of observed and previously unexplained phenomena. Meehl (1985, 1986) would concur, stating that one can be a Freudian without believing in the Oedipus complex but not without believing in the unconscious. Once again, the unconscious is core, whereas other theories that depend upon the unconscious are less central and would be
considered "derived" according to the definitions used in this study.6

Assumptions of Conceptual Change Theory

Assumptions of conceptual change theory relevant to this study are discussed below.

Learning depends upon previous conceptions. Strike and Posner (1985) contrast the underlying philosophy of conceptual change with empiricism. They note that empiricists believe all knowledge comes through the senses in an additive and "bottom up" way and is confirmed or rejected according to logical, content-independent rules.

Conceptual change theorists believe, on the other hand, that:

1. People view sense data within the context of their previous conceptions. Each student will therefore view new information idiosyncratically (although an objective of educational research is to identify patterns of learning). Understanding of new information is both active (Neisser, 1976) and passive (Bransford and Johnson, 1973), but is nevertheless dependent upon the context of the learner's current conception. Solutions to problems that arise within

6Meehl (1977) would also warn that many concepts, even in the physical sciences, are "open" and therefore temporarily unresolved as to the ultimate "cause."
the conception are also judged according to the standards of that conception: they must be consistent with existing conceptions to be acceptable.

2. Knowledge is constructed (Feyerabend, 1980; Kuhn, 1970). Rather than drawing knowledge from memory or directly through experience, each student constructs knowledge using his or her current system of conceptions (Pope and Gilbert, 1983; Osborne and Wittrock, 1983). This notion that learning begins with current conceptions implies that methods such as the learning cycle (Karplus, 1977) must consider the student's prior concepts to be complete. It also implies that problems and anomalies arise from the student's current conceptions, not from experience. A "discrepant event" is an (often) idiosyncratic discrepancy in the student's conceptual system, not a discrepancy in the event itself.

The difficulty of accommodation. Theorists of conceptual change would explain that misconceptions are so resistant to change because of the relative difficulty of accommodating vs. simply wrongly assimilating new information (Carey, 1986; Viennot, 1979; Novick and Nussbaum, 1978, 1981; Nussbaum and Novick, 1982). Students use many tactics to avoid accommodation. Some may compartmentalize new knowledge to prevent it from
contradicting what they believe. They may also attempt to wrongly assimilate new information to their own incorrect models. For example, Posner et al (1982) give examples in which students "Newtonize" relativistic phenomena. In fact, a whole body of experimental evidence from social psychology (Mynatt, Doherty, and Tweney, 1977; Wyer, 1977; Lord, Ross and Lepper, 1979; Snyder, 1984; Glick and Snyder, 1986) supports this notion that it is human nature to assimilate unless the need for accommodation becomes compelling.

Implications for Instruction

The attention of conceptual change literature is focused upon ways of creating accommodation. Instruction designed according to the Posner et al (1982) formula for accommodation meets the criteria described below.

Dissatisfaction

The first condition is dissatisfaction with existing conceptions. This dissatisfaction may arise when enough observations appear anomalous in light of the existing set of central concepts, or when those concepts fail to help solve puzzles and problems.

... The learner will only experience dissatisfaction, however, if four further preconditions are met. (The unlikelihood of a student meeting all four preconditions partially explains why accommodation is rare.)
1. Rather than simply calling a particular finding or observation presented to the learner an anomaly, we must realize that the learner must be the one to see the observation that way. To see it that way, the learner must share or at least understand the theoretical framework in which the observation is anomalous.

2. The learner must believe that understanding the anomaly in terms of his or her existing conceptions is important.

3. The learner must accept the notion that inconsistencies among beliefs must be reduced.

4. The learner must not assimilate anomalous findings when accommodation is called for or the resulting conception may be a misconception.

To create dissatisfaction with students' current conceptions, the instructor must first probe their understanding and reveal these conceptions. Then the instructor should create learning events in which students confront their conceptions and experience anomalies. In addition to presenting or allowing students to uncover anomalies, the instructor must encourage the students to try to reconcile their findings with their existing concepts, and their existing concepts with each other.
For example, this study demonstrated that students use a limited number of models to explain the phases of the moon. In this study, the instructor discussed the alternative models with the entire class, making the models and their implications explicit. Students who believed that the phases are caused by the shadow of the Earth falling upon the moon (referred to in this study as the "eclipse" model) may have experienced an anomaly as they realized that phases occur at times other than when the moon is opposite the sun in the sky, and that the moon is full when it is opposite the sun.

Dissatisfaction was also experienced when students tried to answer questions and solve problems on the pretest. In this study, students reported feeling uneasy with themselves for not being able to answer many of the pretest questions. Although this may not be the same as being dissatisfied with not being able to explain or predict a particular phenomenon, it is dissatisfaction nonetheless.

Intelligibility

Intelligibility of the new conception is the second condition necessary for accommodation. For a new concept or set of concepts to be considered a replacement for the existing one, the learner must be able to make sense of it. To accomplish this, the learner must construct a coherent
model, or representation, of the new concept. This metaphorical representation is similar to Ausubel's (1978) advanced organizer, which serves as an "ideational scaffolding" upon which knowledge is constructed from new information.

For instruction, the use of analogy is important. Models (such as Ping-Pong balls for celestial bodies) were used, as well as audiovisual aids such as overheads and the planetarium.

**Plausibility**

Plausibility of the new conception is the third condition of accommodation. For this condition to be satisfied, the new conception must solve the problem or anomaly that caused dissatisfaction. In this study, the analogies presented had to not only be intelligible, they had to account for the observations and overcome the dissatisfaction. (Students in this study reported a feeling of relief at finally understanding the cause of the lunar phases.)

Furthermore, the new conception must be consistent with any of a number of elements of the learner's thinking, including what Posner and his colleagues refer to as "metaphysical" and "epistemological" commitments, other knowledge, and past experience. In other words, the new conception must account for or explain what is known and
has already been satisfactorily explained by previous theories, while not violating deeply held views about how the universe works or what should count as new knowledge.

For example, so students learn the cause of the lunar phases, the model presented must account for observations already made of the moon's appearance at various places and times. It should include the notion, maintained by many students, that the moon orbits the Earth. At the same time, it must not indicate that the moon's physical shape actually goes through monthly changes due to some spiritual influence. Those who know that the moon is a large rock will not accept this model on the grounds that it violates their metaphysical commitments to the conservation of matter and to causality.

Fruitfulness

The final condition that must be met for accommodation to take place is fruitfulness: a new conception must lead to new ways of experiencing and understanding the world. It must give the learner the power to make predictions and acquire insights that are borne out by later experiments, discoveries, and experience. The learner is further persuaded that the new conception is worth keeping when its fruitfulness is proven by its extension and application to domains and problems not explained (and often not even thought of) by the older theory. For example, the test
used in this study asks what phase the Earth is in as seen from the moon, when the moon is full.

To demonstrate fruitfulness, students need the opportunity to develop rules, the power and validity of which they can test for themselves. Students experienced the fruitfulness of their new model as they made predictions concerning the position and phase of the moon.

**Representation and Description of Cognitive Structure**

Educational and cognitive researchers have developed a number of techniques to represent a scientific discipline and the knowledge of learners (Norman and Rumelhart, 1975; Lindsay and Norman, 1977; Stewart, 1980; Finley and Stewart, 1982; Finley, 1984; West et al, 1985). These techniques are used in this study to represent the content domain to be taught and tested and the knowledge of the students.

**Representation of the Content Domain**

The approach taken to represent the content domain is similar to that of West et al (1985): it is not as extensive as concept mapping often is (Novak, Gowin, and Johansen, 1983; Novak and Gowin, 1984) but not as detailed as associative mapping (Lindsay and Norman, 1977). The concept map used in this study (see Chapter 3) is limited to a description of the phenomenon of the phases, at a
lower "magnification" than an associative map would ordinarily provide.

**Representation of the Students' Knowledge**

For the purposes of this study, knowledge is assumed to be stored in the form of propositions (Stewart, 1980). Finley (1984, 1985) suggests that a promising research technique begins by listing all possible propositions and subsequently checking for their presence (indicated by a 1) or absence (indicated by a 0) in student responses. The overall technique of proposition analysis became the principle technique for comparing responses in this study.

**Model types.** Once the student responses of this study were analyzed for the presence or absence of propositions, the patterns of 1's and 0's were used to classify responses according to a scheme of model types. Other studies (Nussbaum, 1979; Nussbaum and Novak, 1976; Nussbaum and Sharoni-Dagan, 1983; Sneider and Pulos, 1983) have also developed and used classification schemes designed to describe the patterns of student theories existing across the class and across time.

**Descriptions of student models.** The dimensions of completeness, correctness, and consistency appear often in the literature describing student models. A recent article by White (1985), defining a number of dimensions of cognitive structure, mentions completeness (called **extent**
by White), correctness (called accord with reality) and consistency.

Limitations of model classification. When diagnosing student models using the classification scheme mentioned above and described further in Chapter 3, philosophers of science suggest several points of caution about "open concepts" (Carnap, 1936, 1937; Pap, 1962; Meehl, 1977). Meehl describes limitations of open concepts in the diagnosis of underlying theoretical constructs that are not yet fully understood. Two types of open concepts of concern to this study are extendability of the indicator list and the probabilistic link between the indicators and the hypothesized entity.

Extendability of the indicator list refers to the rarity of a single indicator that is definitive of a particular construct. Usually, more than one indicator is called for, and then the list is rarely complete. The implication is that the list of indicators used in the coding scheme to classify models may be incomplete, creating room for error in classification. In this study, however, the diagnostic propositions correspond directly to

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7Meehl (1977) writes about these limitations as they affect medical diagnosis, but the same can be said for their effect on the diagnosis of an individual's underlying mental constructs.
the models, since those propositions were used to define the models in the first place.

In this study, this first form of open concept may also affect the description of a particular model change as being a form of accommodation or assimilation, since the conceptual change literature is unclear about what the precise indicators of each of these types of change would be.

The probabilistic link between the indicators and the hypothesized entity suggests that perfect correspondence between the students' responses and their hypothesized mental models may not exist. Some students may leave out propositions; others may accidentally give propositions that falsely represent their internal models. There is, therefore, an imperfect correspondence between the models portrayed by students on their tests and the models students have in their minds.

Summary

Conceptual change theory suggests both an approach to instruction and a way of representing and interpreting the changes in knowledge experienced by students. The techniques of instruction and representation introduced in this chapter were employed in this study of conceptual change. The specific methods used to teach for accommodation using the phases content domain and to
represent and analyze student knowledge are discussed more fully in chapter 3.
Chapter 3
RESEARCH METHODS

This chapter, which gives a complete discussion of the research methods used in this study, is divided into seven parts:

1) An overview of the methodology is given.
2) The subjects are described.
3) A description of the development and selection of the content domain, as well as the content domain itself, is given.
4) The steps in developing the test instrument, as well as the test itself, are described.
5) The materials and instruments are discussed.
6) The instruction is described in detail.
7) The tabulation and analysis of the data are discussed.

Part 1: Overview of Methodology to be Employed

The research methods for this study included test development, instruction, data coding, and analysis. Students (N=61) in an introductory college astronomy course were given a pretest designed to elicit their observational, conceptual, and procedural knowledge of the phases of the moon through written explanations and
drawings. This test was designed to cover the discipline-defined domain in detail but was flexible enough to allow for individual expression. Students were then instructed about the phases of the moon in accord with conceptual change theory (Posner et al, 1982). A midtest and a posttest were given during and after instruction so that changes in knowledge occurring during instruction could be compared to the predictions suggested by conceptual change theory.

A predetermined coding scheme was used to characterize students' initial models and compare students' pre, mid, and postinstructional responses to each other and to a discipline-defined model response. The coding scheme was designed to describe and classify student responses according to the underlying central propositions (e.g., the main "cause" of phases) and additional "derived" propositions (e.g., plausible positions for the moon at each phase, as well as explanations of each phase). This coding scheme was also used to compute the completeness and correctness of these propositions. Quantitative evaluations were combined with qualitative assessments of students' pretest, midtest, and posttest responses with the aim of charting, in rich detail, the conceptual change occurring in individuals and groups of individuals as a result of the instruction. These changes were then
evaluated to see if they are consistent with the predictions derived from the Posner et al theory.

Part 2: Subjects

The subjects for the study were 61 students taking an elementary descriptive astronomy course offered at St. Cloud State University during the Spring of 1987. St. Cloud State University is a comprehensive (four-year plus master's degree) institution located in Minnesota, seventy miles northwest of the Twin Cities.

At the beginning of the class, students answered questionnaires asking them to indicate their names, majors, year at St. Cloud State University, and their reasons for taking the course. Other data on these subjects were gathered by checking files at the Records and Registration Office.

The only apparent difference between the students in this course and students in other elementary astronomy courses is that these students were slightly older. In terms of previous experience in science and astronomy, in terms of the subjects in which they majored, and also in terms of their sex and hometown, they are comparable to students taking other introductory astronomy courses at
St. Cloud State University. Their characteristics are described in greater detail in the table on page 37.
Table 1

Characteristics of subjects

<table>
<thead>
<tr>
<th>Average Age</th>
<th>Average Year</th>
<th>Sex</th>
<th>Major</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>2.5</td>
<td>F:  n=37</td>
<td>Science:  n=8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>M:  n=24</td>
<td>Humanities: n=9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Other</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(Business, etc.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>n=44</td>
</tr>
</tbody>
</table>

Participation by these subjects was voluntary in the sense that most of what they learned was not counted as part of their grade. These students were told that pretests and midtests were completely voluntary and that both testing and instruction were part of a study to determine the feasibility and value of incorporating this lunar phase instructional unit in future courses. Questions 4, 5, and 6 (which asked students to make specific predictions about the moon's position, phase, and time) were considered as part of course exam #3, administered near the end of the quarter. Students were told in advance that questions similar in form to these problems would appear on this test. (See the Instrument
and Instruction sections later in this chapter for more details.) Except for questions 4, 5, and 6, the posttests were also voluntary and did not count towards the students' grades.

Part 3: Content Domain

The selection criteria and the selection process of the content domain, as well as the content domain itself, are described in this section.

The Selection Criteria

Six criteria were used in selecting the content area to be used in this study. The first three criteria were defined by the needs of research and the second three by the needs of instruction.

Good Match with the Knowledge Level of the Students

The most dramatic cases of conceptual change occur in students who have definite misconceptions that are changed as a result of instruction. Many topics within astronomy are so advanced that most introductory astronomy students would be unlikely to know anything about these topics, much less have misconceptions. Therefore, careful selection of subject matter is necessary to ensure the best match with the student's knowledge level.

Conceptual Depth

Knowledge gained through instruction should be deep enough that clear cases of assimilation, or proposition
elaboration, will be evident. Concepts so shallow that students can have an all-or-none understanding of them will provide few opportunities for elaboration.

**Originality**

To be interesting as a research effort, the topic must allow fresh insight into students' understanding of a given domain within astronomy.

**Level of difficulty**

Although a good match of difficulty level is important for research purposes, subject matter must also not be too far above or below the students' comprehension level.

**Pedagogical Usefulness**

To be considered useful, the topic must be one taught regularly as part of the standard curriculum at St. Cloud State University and/or similar institutions elsewhere. Ideally, the topic must be the source of at least moderate difficulty for many students who could therefore benefit from alternative forms of presentation.

In addition, a topic that is interesting and useful to the students would provide extra incentive to create conceptual change. If possible, a topic referring to observations with which the students are directly familiar would seem more salient than one referring to more theoretical entities less directly accessible to many students.
Feasibility

Feasibility refers to the availability of equipment, supplies, and facilities on a typical college campus; the availability of the means for constructing any demonstration apparatus that cannot be purchased; and sufficient time to allow for completion of the instruction.

The Selection Process

The criteria mentioned above were applied to the content domains of the celestial sphere, the diurnal and annual motions of the sun, the Earth as a planet in space, the seasons, and the phases of the moon. After developing and testing instruction on these topics as part of the pilot work, the phases of the moon were chosen as the most suitable content area. This topic satisfied all of the criteria mentioned above.

The phases content domain is a close enough match to the students' knowledge level that clear misconceptions exist. Pilot work revealed that students maintained a fascinating spectrum of misconceptions about the lunar phases. In addition, the phases are conceptually and mathematically within reach of students at the introductory science level.

Moreover, the phase content domain is deep enough to allow for clear-cut cases of assimilation. Students can
learn the basic cause of the phases and then go on to elaborate upon that cause by explaining individual phases.

The phases content domain is also feasible. First, the instructional materials can be easily constructed. Second, one month is all that is needed for the observations. Finally, an additional two to three class sessions are needed for the instruction.

Finally, this content domain is pedagogically useful. It is taught in most introductory astronomy courses, and yet experience has shown that it is also the source of confusion for many students. The phases of the moon are also a phenomenon with which most students have some familiarity, and the moon's almost daily appearance makes this phenomenon accessible and useful for students to understand and predict.

**Description of Content**

The types of knowledge considered in this study can be characterized as observational knowledge, knowledge about the explanatory theory, knowledge about related information, knowledge about making predictions using the explanatory theory, and knowledge about extending the explanatory theory into unfamiliar domains.

**Observational Knowledge**

Knowledge of the domain of observations refers to the continuously changing shape of the visible portion of the
moon, as shown in Figure 1 on the following page. Although one might consider knowledge of the concomitantly changing position of the moon as observational in nature, in this study the ability to predict change in position is considered separately, under the heading of predictive knowledge. The decision to consider knowledge about the changing position of the moon as separate from observational knowledge was linked to the way students were asked to observe the moon during the first part of instruction. Since students were asked to make observations only once a day, it would have been difficult for students to develop a powerful, comprehensive model of the phases based upon their observations alone. Instead, the observations were used to help students develop a model that explained the cause of the phases. Students were then shown how the model they developed could be elaborated upon to allow them to make predictions about the moon's position at specific times and phases.
The Explanatory Theory

It is possible to consider related information, predictive knowledge, and even the domain of observations as falling under the rubric of explanatory theory. For the purposes of this study, however, explanatory theory is more narrowly defined as the model that explains the observations; this model must be relied upon to develop predictive mechanisms.

This explanatory model, which draws upon both conceptual and spatial forms of understanding, is commonly found in astronomy textbooks. The two texts referred to for this study were the introductory books, Exploration of the Universe, (Abell, 1982), and Astronomy: From the Earth
to the Universe, (Pasachoff, 1987). Propositions that related to the explanatory model and the domain of observations were culled from each of these texts. (These propositions are listed in the Table of Appendix A.) There were slight differences in the way each author chose to describe the explanatory model; this accounts for slight differences in the propositions from each text. The underlying meanings alluded to by those propositions (described in Figure 2 on the next page) were, however, identical. A concept map constructed using these underlying meanings can be found in Figure 3 on the following page.
DiOrb- The moon orbits the Earth.

DiHaf- The half of the moon facing the sun is illuminated.

DiSee- The part of the half that we see determines the phase.

DiEnts- The relative position determines the part of the half we see.

Figure 2. Propositions from the discipline. The drawings illustrate each proposition.
Figure 3. Concept map of the domain.

Related Information

Some information critical to understanding the concepts involved but not unique to an explanation of the lunar phases was included in the instruction. This
information, which is easy to overlook, includes an understanding of the following concepts: angular measure, the idea that moons and planets can move in orbits, the relationship between the sun's position and the time of day, and the concept that rays from distant objects are essentially parallel.

**Predictive Knowledge**

Predictive knowledge refers to the procedural knowledge necessary for making predictions about the appearance of the moon at various times. Instruction included specific directions for making these predictions.

This procedural knowledge is an algorithm that allows the students to predict: (a) the position of the moon given the phase and the time of day, (b) the phase of the moon given the time and the moon's position, (c) the time given the moon's phase and position, and (d) the change in the moon's appearance after a certain number of days have elapsed since the arbitrary start of the lunar cycle at new moon.
Part 3: The Instrument

This section includes a discussion of the development of the test instrument, as well as a description of the test instrument itself.

Development of the Instrument

The instrument was designed to reveal students' correct, incorrect, and missing information about as much of the domain as possible.

Most of the revisions of the instrument were made as a result of pilot work conducted with a group of teachers taking an in-service physical science course at Marshall, Minnesota, groups and individuals at St. Cloud State University, and students taking a science education course at the University of Minnesota. The modifications could be classified as one of three types: tuning of the specificity of elicited knowledge, refinements to elicit more complete responses, and modifications to avoid "teaching" correct or incorrect knowledge.

Tuning of the Specificity of Elicited Knowledge

The most important task of the test development was to ensure that the instrument was eliciting the knowledge it was intended to elicit in a way that was neither too constraining nor too structured. For example, one question was designed to elicit the students' understanding of the relationship between the moon's angle from the sun and its
phase. Early versions of this question showed the moon in the first quarter position, 90° to the left of the sun. Unfortunately, when the moon is in this position, the moon's phase as seen from the Earth is identical to its phase as seen from space. (The vantage point of the diagram was high above the plane of the Earth-moon system.) The question, asked in this way, would not test the students' ability to picture the moon as if they were viewing it from the vantage point of an observer on the Earth. The moon was subsequently placed at an angle of 45° to the sun, where it would be half illuminated as seen from space high above it, but only a crescent as seen by an observer on the Earth. Other refinements designed to improve specificity included rewording of questions and changes in the accompanying diagrams.

**Refinements to Elicit More Complete Responses**

Several questions redesigned after pilot tests revealed that students tended to give very limited answers. For example, a question which asked students to draw an explanatory diagram was separated from a question that asked them to provide a written explanation. This forced students to both write and draw their explanations. Other modifications of this type included adding more explicit pictorial cues, such as templates in which students were asked to draw phases as part of their response.
Modifications to Avoid "Teaching" Correct or Incorrect Knowledge

Several changes made were designed to reduce the amount of information unintentionally provided to the student. For example, to avoid having the test either "teach" knowledge that the student did not already know, or destabilize any shaky conceptions the student already had, later versions of the pretest did not make any reference to the moon orbiting the Earth or to the relative positions of the Earth, moon, and sun. The deletion of references to the relative positions of these celestial bodies would have posed a special problem for questions 11 and 14, since both questions required diagrams showing the moon in relation to the Earth and sun. For the final version of the pre and posttest, this problem was solved by dividing each test into two parts. After students completed part 1, which made no mention of the relative positions or orbit of the moon, Earth, and sun, each student returned it in exchange for part 2, which included questions 11 and 14.

Other changes of this type included modifications to prevent misconceptions. For example, early versions of this test included a large segment of the sun immediately to the right of the drawing of the moon and Earth. The sun was replaced by an arrow pointing in its direction, with
the words "To Sun" above the arrow to prevent misconceptions about the scale of the solar system.

**The Tests**

The test, which was the result of seven revisions, is shown in Appendix B. The test covered all of the types of knowledge described in the section, "Content Domain." (See Table 2 on the next page.)
Table 2. **Types of Knowledge and the Questions That Refer to Them**

<table>
<thead>
<tr>
<th>Type of Knowledge</th>
<th>Question #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observational Knowledge</td>
<td>1,12a</td>
</tr>
<tr>
<td>Explanatory Theory</td>
<td>2,11,13</td>
</tr>
<tr>
<td>Related Information</td>
<td>7,8,9,14</td>
</tr>
<tr>
<td>Predictive Knowledge</td>
<td>4,5,6,12</td>
</tr>
</tbody>
</table>

This test was used as both the pre and the posttest. The midtest, kept short to reduce student anxiety, was limited to questions 1 and 2, which asked about the domain of observations and the explanatory theory.

**Part 5: Materials and Instruments**

The materials and instruments used during instruction are described below. Except for the planetarium projector, everything was inexpensive, easy to construct, and readily available.

**Cut-Out Moons**

Black and white construction paper was used to construct five-inch diameter discs, each shaped like a
lunar phase. These cut-outs were used to demonstrate the sequence of the changing phases of the moon. Once the cause of the lunar phases had been established, the cut-outs were also used to demonstrate the position of the moon at various times. One complete set of phases was made for each group of four to six students. In addition, each set had a sun, constructed out of yellow construction paper.

Compasses

To determine the direction of the moon, small (1" diameter) compasses were distributed to each student. These compasses were accurate to within approximately five degrees.

Ping-Pong Ball Moon Demonstration

Ping-Pong balls were used to demonstrate the moon's change in appearance as seen from different positions. The balls were glued to golf tees so they could be held in the beam of a light source. Other balls, including golf balls, tennis balls, and Styrofoam balls, were tried. None displayed the phase effect as dramatically as the Ping-Pong balls.

Overhead projectors were used to illuminate the Ping-Pong balls. (Other more commonly available light sources, such as flashlights, were not bright enough to create the effect.) The scarcity of projectors meant that groups of
students had to take turns observing the moon's changing appearance.

Parallel Ray Demonstration

A demonstration device was designed to illustrate the fact that light rays from a distant object are virtually parallel. This apparatus consisted of a large, vertical board, two circular cardboard cut-outs (to represent the Earth and moon), and two spools wrapped in string and attached below the cut-outs. To use the apparatus, the instructor or the student would pull on the string, noting that the two segments of the string became more parallel the farther the string was stretched. (See Figure 4 on the next page.)
The Planetarium Projector

The planetarium projector, a Spitz Model 512, was used to demonstrate the changing position of the moon, with respect to both the moving sun and the earthbound observer.

Below the planetarium projector's star ball was a planet cage. It was equipped with a sun projector that could remain fixed with respect to the rest of the projector, allowing the operator to demonstrate the diurnal (daily) motion of the sun by rotating the entire projector around its polar axis. The projector's automatic horizon shutoff malfunctioned, causing the sun to appear on the lower wall and floor of the planetarium long after it should have "set." This turned out to be a benefit when it came to demonstrating that the sun moves below us and to

Figure 4. The parallel ray demonstrator.
the northern quadrants at night, since it was easy to see the sun moving in that direction after it set.

The sun projector could rotate within the planet cage, allowing the operator to demonstrate, at various speeds, the annual motion of the sun along the ecliptic. This motion could be linked to the daily motion, so that the sun moved less than one degree along the ecliptic over the course of one diurnal rotation of the entire machine.

The planet cage also included a moon projector. As with the sun projector, it could either remain fixed to the rest of the projector, or it could be moved to demonstrate the moon's monthly motion with respect to the sun and background stars. When the moon was set in motion (by linking its motion to either the diurnal rotation or to the annual motion of the sun), a shutter automatically changed its phase.

The planetarium system described above is expensive and usually not available to most educators. Work conducted with other college students before the main study began and since the main study was completed indicated that the planetarium, though helpful and very realistic, was not necessary to demonstrate the changing position of the moon and sun. The cut-out moons and sun (described above) have been used successfully to the same effect and have the
added advantage that they can be used in any setting, including the students' homes.

The planetarium projector, the cut-out moons, and the Ping-Pong ball moons all have the advantage that they are used to demonstrate the lunar phenomena from the stationary-Earth perspective. This geocentric perspective was chosen because, in contrast to the rotating-Earth perspective of many textbook diagrams, it is the one to which we on Earth are accustomed. Observations made in the classroom and the planetarium are therefore more concrete.

Part 6: Instruction

Instruction was divided into four lessons and delivered according to the timetable in Table 3 on the next page.
Table 3

Timetable of Instruction (all dates are for 1987)

<table>
<thead>
<tr>
<th>Date</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunday, March 29</td>
<td>New Moon</td>
</tr>
<tr>
<td>Wednesday, April 1</td>
<td>Lesson 1</td>
</tr>
<tr>
<td>Tuesday, April 28</td>
<td>New Moon</td>
</tr>
<tr>
<td>Wednesday, April 29</td>
<td>Lesson 2</td>
</tr>
<tr>
<td>Wednesday, May 6</td>
<td>Lesson 3</td>
</tr>
<tr>
<td>Wednesday, May 13</td>
<td>Posttest</td>
</tr>
</tbody>
</table>

The activities for each lesson are described below. (Refer to Appendix C for a complete description of the rationale of each activity, as derived from conceptual change theory.)

**Lesson 1**

In lesson 1, the objectives were to (a) give students a pretest that would reveal their prior knowledge of the lunar phases, and (b) ask students to observe the moon daily for one month.

**The Pretest**

Students were given a pretest before instruction commenced. The purpose of the pretest was to establish students' prior knowledge for purposes of instructional
design and comparison to postinstructional knowledge, and, to some extent, to create dissatisfaction at not being able to answer many of the questions. This pretest can be found in Appendix B, and a complete description of its development can be found in the Development of the Instrument section of this chapter.

The Observing Project

The purpose of the observing project, which began at new moon, was to establish the domain of observations to be explained. Small compasses and blank observation forms were distributed to students at the beginning of instruction. The class adjourned to the roof of the Math and Science Building, where the method of observing the moon was demonstrated.

First the students were given instructions for locating the North and South cardinal points by holding the compass flat and sighting a distant landmark directly over the pointer. The other directions (and landmarks) were found by stretching out the arms at various angles to each other: perpendicular for East and West, and 45° to each other for Northeast, Northwest, Southeast and Southwest.

Students were then given a chance to practice, using a star or planet. (The moon had already set.) They were to indicate the direction of the object as precisely as possible, as well as the approximate altitude, on their
observation forms. (Refer to Figure 5 on the following page.)
Date and time were indicated on the top of these forms. Students were asked to draw a circular template for the moon. They were then directed to shade out the part that was dark. Students were also instructed to indicate whether the sky was cloudy or not.

Each student took home the observation forms and compasses, with directions to observe the moon once a day at the same time each day for a month.

Lesson 2

The objectives of lesson 2 were to (a) give students a midterm designed to show what effect the observing project had on the students' knowledge of the phases, (b) clearly establish the order and changing appearance of the phases,
(c) develop models that might explain the observations, and (d) give students a second midtest to show what those models are. The activities of this lesson were designed to provide data about the conceptual changes that occur in the middle of instruction, to fully establish the domain of observations to be explained, and to enable students to experience dissatisfaction with their models.

Midtest- Part 1

Students were first given part 1 of the midtest, which was identical to question 1 on the pre and posttests. (Refer to Appendix B.)

The Order of the Phases

The class was subsequently divided into ten groups, with six students each. Each group was given a complete stack of cut-out lunar phases and was asked to use its observational data to sort the cut-outs according to the order in which they appeared.

The groups were then brought together again, and a transparency of part 1 of the midtest was shown on an overhead. Using input from the students, the instructor shaded the transparency to indicate the appearance of each phase. In addition, he provided the names of each of the phases.

Next, students were asked to use their data to calculate the number of days elapsed since new moon. Then
they filled out the "Phase Summary Form" (Figure 6 on the following page) using information provided by the instructor, other members of the class, and their own observations.
In the circles below, shade out the parts that are not visible to show the complete sequence of the moon's phases, as seen from here on Earth. Give the names of the phases in the spaces provided (after the word phase), beginning with the new moon. Indicate the number of days that have elapsed since new moon in the spaces provided (after #Days).

**Figure 6.** The phase summary form used to summarize the students' observations.
**Group Discussion of Models**

Once students had the observations in front of them (on the Phase Summary Form), they were asked to split up into their groups again and to try to develop a model explaining these observations.

**Midtest, Part 2**

Following the group discussion of models, the students were given part 2 of the midtest. Part 2, identical to question 2 of the pre and posttests, asked them to provide a model that accounts for the phases. (Refer to question 2, Appendix B.)

**Lesson 3**

The objectives of lesson 3 were to (a) discuss the models developed by the students, demonstrating their strengths and weaknesses with respect to the data, (b) teach students about light rays from distant objects, (c) have students gain an understanding of the cause of the lunar phases, (d) expose students to the types of problems they will be asked to solve, (e) help students develop a more comprehensive, powerful version of the model used to explain the cause of the lunar phases, one which enables students to make predictions, and (f) give students the opportunity to practice solving problems using this more powerful model.
The activities of this lesson were designed to continue to create dissatisfaction with existing models, to provide plausible, intelligible analogies that would be comprehended and accepted by the students, and to provide the opportunity for students to experience the fruitfulness of their models.

Discussion of the Model Types

Lesson 3 began with discussion of the various types of student models revealed by the midtest. Discussion of each model type mentioned how that model could be used to explain the phases, as well as the ways in which the model falls short in its explanation of the observations. For example, students who had the eclipse model were asked to explain how their model could account for the fact that the moon undergoes phases when it is not behind the Earth with respect to the sun.

Demonstration of Parallel Rays

A misconception related to nearly all student models is that the rays of incoming sunlight are portrayed as diverging radially from a hypothetical sun offset immediately to the right of the diagram. The rays should enter in a parallel formation from a sun far off to the right of the diagram. Since this misconception would stand in the way of further understanding of the lunar phases, it was addressed immediately. The parallel ray device
described in the Materials section of this chapter and pictured in Figure 4 on page 55 was used to demonstrate that rays from the distant sun are essentially parallel.

Demonstration of the Cause of Phases

Once the students understood that light rays from distant objects are parallel, instruction about the cause of the phases commenced. Students were taken to a cluster of adjacent lab rooms and were divided into ten groups of six. Each group was given a Ping-Pong ball and light source (described in the Materials section). In addition, everyone was given a booklet showing eight pictures of the Earth and moon as seen from space. Each picture showed the moon at one of eight different angles with respect to the incoming sunlight. (Refer to Figure 7 on the following page.) Before students began instruction, an overhead transparency of a form from this booklet was used to demonstrate the procedures that are described below. In addition to these supplies, students were given a "views of the moon" form upon which they could summarize their results. (See Figure 8 on page 69.)
A. Shade in the moon to show how it looks from space, far above the earth and moon.

View of earth and moon as seen from space, far above North Pole.

B. Shade in the circle below to look like the moon as seen from the Earth.

View of moon as seen from Earth.

Figure 7. Page from workbook on phases.
Students were asked to imagine that the light source was the sun, that the Ping-Pong ball was the moon, and that they were the Earth. This geocentric perspective was chosen because it is immediately intelligible at the concrete level of reasoning. Also, when the diurnal motion of the sun is added later on, the geocentric perspective is more realistic since the celestial motions in both the
planetarium and the real sky appear to be occurring as if the Earth were stationary.

Students used this set-up to simulate the lunar phases. First, the Ping-Pong ball was held out at arm’s length by the person representing the Earth. Next, this student slowly revolved the ball through the eight angles to complete a circle, taking note of its apparent phase and recording it in the booklet described above. While the first student was moving the ball, a second student from the group stood on a chair above the plane of the Earth-moon orbit, noting the appearance of the moon as seen from this perspective. The students then traded positions so that each student could experience the phase phenomenon as seen from both the Earth and space.

After this experiment, the students were brought together to summarize what they had just experienced. To facilitate this discussion, students were asked to contribute their advice on how to shade in a "views of the moon" transparency shown with the overhead projector.

Making Predictions

Students were told that they understood enough of the model that they could explain the phases they had observed. However, without consideration of the rotation of the Earth, they could not make predictions about the moon’s position at a particular time and place.
Sheets were distributed with questions that asked students to make predictions about the phase given the time and moon's position, the position of the moon given the time and lunar phase, and the time given the moon's position and phase. (Refer to Figure 9 on the next page.) Students were asked to examine these sheets and told that they would be asked to solve similar problems on an upcoming test.
Suppose you see a waxing crescent moon in the southwestern sky. What time is it?

Given the position and phase of the moon, predict the time of day.

Suppose you see the moon directly south at sunrise. What is the phase of the moon?

Given the time and position of the moon, predict the phase of the moon.

Suppose it is midnight. Where in the sky would you look to see the waning gibbous moon?

Given the time and phase of the moon, predict the position of the moon in the sky.

*Figure 9.* Moon problems.
Moon facts. Students were subsequently given copies of the "moon facts" sheet. (Refer to Figure 10 on the following page.) The moon facts sheet included a picture of each phase, facts about that phase's various appearances in the sky (e.g., "rises at sunset", "directly South at noon"), and the angle of the moon from the sun at each phase, taken from the "Views of the Moon" form. Next, a transparency of this "Moon Facts" sheet was used in a class discussion about the changing position of the moon in the sky. It was pointed out that it would be difficult to use this collection of seemingly random facts to make predictions. Students were told that some sort of rule, consistent with the model developed so far, was needed for making predictions and solving the problems on their sheets.
<table>
<thead>
<tr>
<th>Observations</th>
<th>Angle from Sun</th>
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<tr>
<td>-southwestern sky after sunset</td>
<td>45°E</td>
</tr>
<tr>
<td>-sets 2-3 hours after sunset</td>
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</tr>
<tr>
<td>-directly south at sunset</td>
<td>90°E</td>
</tr>
<tr>
<td>-southwestern sky after sunset</td>
<td>135°E</td>
</tr>
<tr>
<td>-sets west around midnight</td>
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</tr>
<tr>
<td>-rises east 2-3 hours before sunset</td>
<td></td>
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<td>180°E</td>
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<td>135°W</td>
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<td>-sets west at sunrise</td>
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<td>-rises 2-3 hours after midnight</td>
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<td>-southeastern sky at sunrise</td>
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<tr>
<td>-not visible</td>
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<td>-rises in E at sunrise</td>
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<tr>
<td>-directly S at noon</td>
<td>0°</td>
</tr>
<tr>
<td>-sets in W at sunset</td>
<td></td>
</tr>
</tbody>
</table>

Figure 10. Moon facts sheet.

Rotation of the Earth and time of day. Until this point, the rotation of the Earth and its effect on the
appearance of celestial bodies had been ignored. Instruction focused solely upon the changing appearance of the moon over the course of its revolution around the Earth, and how that appearance is a function of the angle of the moon with respect to the sun and the Earth. In order to make predictions about the moon's location and phase at a particular time, students needed a more complete understanding of the relationship between the position of the sun and the time.

Students were given the opportunity to practice determining time using the position of the sun, as well as predicting where the sun should be at various times. The planetarium sun, placed on the vernal equinox, was used to demonstrate the relationship between the time of day (or night) and the position of the sun. (In the pilot work, a planetarium was not available, so the students held cut-outs of the sun at various angles with respect to South.) Students were then asked to estimate the time, given the position of the sun. The position of the sun was changed from low on the eastern horizon (for sunrise, or approximately 6 a.m.), to halfway between the eastern horizon and the meridian (for mid-morning, or 9 a.m.). It was then moved to due South on the meridian (for 12 p.m.), to halfway between the meridian and the western horizon (for mid-afternoon, or 3 p.m.), and to the western horizon.
(for sunset, or 6 p.m.). Sunset was simulated by turning down the blue sky lights and turning up a twilight projector and the stars. Due to a fortunate malfunction in the automatic horizon shut-off system, the sun continued to shine on the wall and floor as it set below the horizon. This unexpected feature was used to demonstrate that the sun is indeed below us, but in the Northwest at 9 p.m., in the North on the meridian at 12 a.m., and in the Northeast at 3 a.m.

The planetarium moon. Now that students understood the relationship between the time of day and the position of the sun, the moon was brought back into the instruction. In the demonstrations described below, students saw that over the course of a few hours, while both the sun and the moon may move quite far across the sky, the moon’s position with respect to the sun changes slowly. The effect is that of the sun and moon moving across the sky in unison, with the change in angle between the sun and moon noticeable only after a diurnal rotation (one day).

To demonstrate this effect of the moon and sun moving in unison, the sun was placed in the southwestern sky. The planetarium moon was turned on, with the phase initially set at waxing crescent, approximately halfway between the new and first quarter moons. At this point, students were asked to estimate the angle between the sun and the moon.
(about 45°). The projector was then rotated so that the sun was resting on the western horizon. The moon, having moved together with the sun, was now in the southwestern sky, and students were asked to determine the position of the moon, as well as the time of day.

**Predicting time given phase and position.** Students were asked to predict the time the waxing crescent moon would set. To do this, students had to keep in mind that the angle of 45° will change little over the course of the night. They had to visualize the moon setting in the West, as well as the sun 45° to the right (or west) of the moon, below the horizon in the Northwest. Since the sun reaches this position at 9 p.m., the waxing crescent moon could be expected to set at about this time of the evening.

Once students understood how to predict the time the moon would appear at a given phase and position, they were asked to extend their knowledge to other positions. The students were asked to predict what time the moon would rise, and what time it would be due South, transiting across the meridian. These predictions were then tested by demonstrating moonrise and lunar transit with the planetarium.

The annual movement was advanced a few days until the moon was in the first quarter phase, and students were once again asked to predict the time of moonrise, transit, and
moonset. This procedure was repeated for the remaining phases as well.

**Predicting the phase given time and position.** Students were asked to predict the phase, given the time and the position of the moon. (For this exercise, the phase of the moon was set automatically at full and then switched to the correct phase after students had made their predictions.) To predict the phase, students had to measure the angle between the sun and the moon and recall (from lesson 2) which phase corresponded to that angle. If the sun was below the horizon, they had to first use the given time to estimate the position of the sun and then estimate the angle between the sun and the moon to determine the phase. Students were asked to answer questions of this type about several other phases as well.

**Predicting position given phase and time.** Next, students were asked to predict where the moon would be at a given phase and time. At the start the planetarium was set at first quarter phase, with the sun in the Southwest and the moon in the Southeast. Students were initially asked to predict where the moon would be at sunset. To do this, they had to visualize the moon-sun pair, transformed so that the sun rested on the western horizon. The moon would be in the southern sky on the meridian. Students were then asked to predict the position of the first quarter moon at
other times, as well as the positions of other phases at various times.

Finally, students were given the opportunity to answer the questions on the prediction sheets handed out earlier. The planetarium projector was used to demonstrate the answers to those questions.

Part 7: Tabulation and Analysis of Data

Quantitative tabulation and analysis consisted of (a) compiling students' written and drawn responses to form a catalogue, (b) interpreting each student's catalogued response set according to criteria generated by the research questions, (c) assigning numerical values to those interpretations, and (d) answering the research questions by interpreting composite scores computed by combining those numerical values.

The following sections describe the cataloguing of the data, as well as specific analyses performed in response to each research question.

Catalogue of Student Responses

The raw data are in the form of statements and pictures produced by students in response to the test questions. Each student's written responses were copied from the tests verbatim, and listed, phrase-by-phrase, in a catalogue of
the data stored on a computer and later printed for easy reference.

Diagrams and pictures drawn by the students were redrawn and inserted into the computerized catalogue. These included pictures of the lunar phases, diagrams illustrating the phase or position of the moon, and diagrams illustrating the rays of sunlight. Other diagrams, such as those used to illustrate the model that explains the lunar phases, were xeroxed and inserted in the catalogue book.

Each line of text and every diagram or picture in the catalogue was numbered. (See Appendix D for a sample page from this catalogue.) This numbering system made it possible to provide specific catalogue numbers of student statements and drawings as references to support conclusions made during coding of the data.

The Codebook and Analysis of Data

A codebook listing the specific criteria by which to judge student responses was compiled prior to the analysis. (Refer to Appendix E.)

An accounting file was set up on the computer for each student. (Refer to Figure 11 on page 82 for a sample file.) Each file was divided into columns that refer to the criteria of the codebook. When a proposition was found in the student's catalogue of statements that met the
requirement of a diagnostic criterion in the codebook, a "1" was registered in the appropriate column of that student's file. A "0" was registered if a student made no reference to the criterion proposition.
The following sections describe in greater detail how this handbook was used to perform the coding and what analysis was done of the students' files in answer to each of the research questions.

**Question 1. What is the character of the students' a) preinstructional, b) midinstructional, c) postinstructional knowledge in terms of content, consistency, completeness, and correctness as revealed by the pretest?**

This question addresses four separate but not completely independent dimensions along which the student models can be described: content, consistency, completeness, and correctness.

---

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<td></td>
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</tbody>
</table>

**Figure 1.1.** Part of a students' computer file.
Content refers to the initial model type. A model, as the term is used in this study, refers to any group of clearly meaningful propositions intended to explain the lunar phases. Analysis of pilot study results indicated that students believe in a variety of model types, and a typology was developed for this study to allow for easy classification of models.

Two students may have fundamentally identical model types, and yet their knowledge of those models may differ on the dimensions of consistency, completeness, and correctness. A way of further describing their models according to these dimensions was therefore developed.

Content

Pilot work revealed that students usually came to instruction with one of the following model types: (a) the correct model, (b) pieces of the correct model, (c) an alternative model, or (d) no model. Before characterizing the extent to which a particular student model is complete, consistent, or correct, it was first necessary to establish which type of model the student maintained. To do this, each pretest response was compared to the diagnostic criteria of the codebook, as described in the following sections.
The correct model. The first model used for comparison was the “correct” model. To be classified as “correct”, a response had to contain the following diagnostic elements:

1. Some reference must be made to the fact that the moon revolves around the Earth. Although this point is basic to many different models, it is essential for a correct understanding of the cause of the lunar phases. Students indicating that the moon orbited the Earth received a "1" in the "DiOrb" column of their file in the coding of the data.

2. The notion that the half of the moon facing the sun is always illuminated is also important in understanding the phases. If a student indicated this somewhere in the test response, a "1" was registered in the "DiHaf" column.

3. When we see different phases, it is because we are seeing different portions of the illuminated half of the moon. If some reference was made to seeing a portion of the illuminated half, then a "1" was registered in the "DiSee" column.

4. The part of the moon that we see is determined by the relative positions of the Earth, moon, and sun. If someone indicated understanding of this relationship, a "1" was registered in the "DiEMS" column.
5. A score of at least "1" had to be registered in the "DiExp" column. The "DiExp" category refers to the extent to which the phases are explained. The explanation must refer to the fact that half of the moon is illuminated, to the fact that we see a portion of that half, and to the fact that the portion of that half we see is determined by the relative positions of the Earth, moon, and sun. One point was given for each phase explained, with a maximum total of eight points if all of the phases were explained. (Usually, at least either the new or full phase was explained, qualifying that student to be categorized as having the correct model.)

Alternative models. Student models that were clearly "alternative frameworks" were compared to sets of propositions (developed for this study) that provided complete, plausible, alternative explanations for the lunar phases. For example, one such alternative framework was unofficially labeled the eclipse model. According to this model, the phases of the moon are caused by the shadow of the Earth. To qualify for the eclipse model, some mention must have been made of the Earth's shadow as the cause of the lunar phases. In this case a "1" would have been registered in the "EcHaf" column.
Some students combined elements of the correct and the eclipse model to form a composite eclipse/correct model. To be classified as having this model, the student's response had to satisfy the criteria of both the correct and the eclipse model.

A few students reported they believed the phases were caused by the moon orbiting the Earth and the sun. In this model, unofficially labeled the heliocentric model, the moon would regularly disappear as it was either occulted or lost in the glare of the sun. To qualify for this model, a student's response had to refer to the moon moving to the side of the sun opposite the Earth. A "1" was indicated in the "EcHaf" column for students satisfying this criterion of the heliocentric model. (The "EcHaf" column is a register of any cause of phases other than the correct one, whether it be the Earth's shadow or the sun's glare.)

Students with the double moon alternative model believe that there are two moons. One moon passes in front of the second, causing its changing appearance. (Refer to Figure 12 on the next page.) As with other alternative models, a "1" was registered in the "EcHaf" column for students holding this model.
A model seen often in the pilot work was the Earth rotation model. Students with this model attribute the phases to the rotating Earth. No plausible explanation is given as to what the Earth's rotation has to do with the phases of the moon. A "1" was registered in the "EcHaf" column for students holding this model.

Fragments. Students whose knowledge does not meet the key criteria for any specific group, but nevertheless includes some correct facts about the phases of the moon, were classified as having "fragments." The facts that these students know are not complete and coherently organized enough to provide a plausible explanation of the phases. Students in this group usually had a "1" registered in only a few of the columns in their file. Their knowledge of the phases was limited and qualified.
them for neither the "correct" group nor for any alternative model group.

**No model.** Students who appear to have no knowledge whatsoever were placed in the "no model" group. These students often had a "0" in virtually all columns, except those relating to the domain of observations.

**Missing.** Student who did not hand in their test, for whatever reason, were classified as "missing."

Once the students were classified by model type, a pie chart was used to show the distribution of model types for the class.

**Consistency**

Consistency, as the term is used here, refers to the agreement between the student's theory and his or her knowledge of the observations, as well as the internal agreement between various parts of the student's theory. This measure is independent of the correctness of the theory.

Statements and groups of statements about the student's model were compared to each other and to statements and drawings that describe the domain of phenomena with which the student is familiar. When contradictions were found (among core, not derived propositions), an attempt was first made to see if there is some imaginable alternative
framework in which the apparently contradictory statements could be reconciled.

As an example, consider someone who has elements of both the correct and the eclipse model. In many cases, this may be considered inconsistent since the two mechanisms are at odds, especially during new and full moon. (At new moon, the moon should be between the Earth and sun in the correct theory, and on the opposite side of the sun in the eclipse theory.) In one case, however, a student participating in the pilot study had the correct explanation for the quarter moon, but she had the Earth's shadow causing the new and crescent moons. (See Figure 13 on the next page.) These two propositions are reconcilable, and therefore consistent, if you neglect the fact that they imply a sudden shift in the phases when one mechanism is replaced by another as the phase changes from quarter to full.
Once pairs or groups of irreconcilable statements were found, these were noted in the "comments" section of each
student's file. The prevalence of inconsistency within the student's answers was then evaluated by reviewing the comments sections and estimating the proportion of cases (among the students overall) with contradictory models.

**Completeness**

Completeness refers to the fraction of total propositions possible according to either the discipline or an alternative model that was represented by the student.

Before analysis for completeness can be further explained, the terms *core proposition* and *derived proposition* must be defined. Propositions were considered *core* if they related to the *cause* of the lunar phases. Propositions were considered *derived* if they related to the further *explanation* of specific phases in terms of the model defined by the core propositions. The core propositions specified by the discipline can be found in some form in virtually all astronomy texts. (Refer to Figure 2 on page 45.) Examples of some derived propositions as specified by the discipline (and also mentioned in astronomy texts) can be found in Table 4 on page 93.

Alternative core propositions for the eclipse model, developed for use in this study, are listed in Figure 14 on the next page. Examples of alternative derived propositions can be found in Table 5 on page 94.
<table>
<thead>
<tr>
<th>Propositions</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>DiOrb—The moon orbits the Earth</td>
<td>![Diagram of moon orbiting Earth]</td>
</tr>
<tr>
<td>EcHaf—The part of the moon in the shadow of the Earth is dark.</td>
<td>![Diagram of moon in shadow]</td>
</tr>
<tr>
<td>EcSee—Extent of moon in shadow determines phases.</td>
<td>![Diagram of moon phases]</td>
</tr>
<tr>
<td>EcEMS—Extent is determined by relative positions.</td>
<td>![Diagram of moon phases]</td>
</tr>
</tbody>
</table>

**Figure 14.** Core propositions for the eclipse alternative model.
Table 4

Propositions Derived from the Discipline

"During new moon we can't see the dark side because it is turned away from us."

"At crescent we see a little bit of the lit part."

"When the moon is between us and the sun, the side that is bright is facing away from us, so we can't see the moon. This is new moon."
Table 5

Propositions derived from eclipse model

"At new moon the Earth blocks the sun's light from getting to the moon."

"Full moon is when the Earth comes fully out from the shadow of the moon."

"Crescent moon is when we see a little bit of the moon that is not covered by the Earth's shadow."

The term "completeness" as used here refers to the fraction of both the total possible core and total possible derived propositions, as defined either by the discipline or by a plausible alternative model represented by the student. A 100% complete set of propositions would fully explain the cause of phases and provide an additional explanation for each individual phase.

Discipline-defined completeness. Four core propositions (those discussed above and listed in Figure 2 on page 45), as well as sixteen possible additional derived
propositions (similar to those in Table 4 on page 93) comprise the complete discipline model.

Each of the phases explained by a student was evaluated against two criterion categories: DiAll and DiExp.

1. "DiAll"- This category indicates the presence or absence of an explanation (right or wrong) for a given phase. It indicates completeness of the student's explanation with respect to the inclusion of each phase of the lunar cycle. A number was placed in the student's column under the "DiAll" heading to indicate the number of phases accounted for by any sort of explanation. For example, a student who showed just the full and new moons, whether the explanation was right or wrong, got a "2" under the "DiAll" heading.

2. "DiExp"- This indicates the completeness of the explanation about each phase. A student who drew moons to indicate knowledge about where all eight phases are located along the lunar orbit received points under the category "DiAll" but received points under "DiExp" only for phases explained. (Refer to Figure 15 on the next page for an example of one student response that rated an "8" under DiAll and a "0" under DiExp.)
It was necessary to define the derived proposition set in this twofold way because some students gave complete explanations for only a few phases, while other students gave almost no explanation although almost all of the phases were portrayed in their drawings.

Alternative-model defined completeness. Complete sets of core and derived propositions were developed for each
alternative framework. For these alternative frameworks, the complete sets of core and derived propositions, described below, had the same number of propositions and were similar in form to those of the correct, discipline-defined model described above.

1. "EcHaf" - Students who received a "1" in this category included in their responses a proposition indicating an alternative cause for the lunar phases. Students who held the "eclipse" theory received a "1" for writing that the phases are due to the shadow of the Earth. Students who believed in the heliocentric theory received a "1" in this category for saying, for example, that the new phase is caused by the sun blocking our view of the moon.

2. "EcSee" - This category, referring to the change in the phases, was determined by the extent of the particular causal notion's influence as explained by the student. This category was developed because pilot work indicated that some people in the "eclipse" group would write only that the phases were caused by the Earth's shadow. Others gave a more complete account of the changing phases, describing each phase as caused by a different degree of covering by the Earth's shadow. For students with the eclipse model, a score of "1" on "EcSee" indicated the student presented a developed
account of how the phases change as the degree to which the Earth's shadow is covering the moon changes. For students with a heliocentric model, a score of "1" indicates that the student gave a developed account of how the phases change as the degree to which the sun covers the moon changes.

3. "EcEMS" - This category, meant as an alternative framework version of the "DiEMS" category, gave one point to students who referred to the relative change in positions of the celestial bodies as part of the cause of the phases. The correct theory says that a given phase is determined by the relative positions of the Earth, moon, and sun. Most plausible alternative frameworks also involve such a change in the relative positions of at least two celestial bodies. For example, in the eclipse model, the change in the extent of covering of the moon by the Earth's shadow is dependent upon the change in the relative positions of the Earth, moon, and sun. In the heliocentric theory, change in the degree of the sun's blockage of the moon is due to change in the position of the moon with respect to the sun. One point was given to students who referred to the relative positions of celestial bodies as part of their explanation of the cause of the phases.
4. "EcExp" - This category was developed as an alternative framework analogue of the "DiExp" category. One point was given for each phase explained in a way consistent with the alternative model. For example, someone holding the eclipse model got one point for a picture showing the Earth directly between the moon and the sun at new moon. A second point was given if the student's picture also showed the moon extending from the shadow of the Earth during a crescent phase.

5. "EcAll" - This category was meant as an alternative framework parallel to the "DiAll" category. One point was given for each phase included, whether it was portrayed correctly (according to the alternative model) or not.

Completeness of the domain of observations. Pilot work revealed that many students had only partial knowledge of the visual appearance of the lunar phases. Some students seemed to be aware of only the first half of the cycle (from new to full), completely leaving out the waning phases from their drawings. Others drew only the new, first quarter, full, and third quarter phases, leaving out the gibbous moons entirely.

To estimate the completeness of students' knowledge of the changing forms of the moon, the "DiCom" category was devised. One point was given for each of the eight phases...
drawn. Completeness was somewhat dependent upon the correctness of the phases shown. For example, at one extreme, some students portrayed all eight phases but with drawings that had terminators that were only slightly off from their correct forms. On the other extreme, some students drew upon all eight circles in the template, but the phases drawn bore no relation to the true phases. If the student seemed to have the correct idea, but simply drew the terminator with a slightly wrong curve, then one point was given for that phase.

Computation of completeness. Once test responses were interpreted and their values recorded in each student's file, the next step was calculating the percent completeness. At first, it was thought that completeness could be represented by one number. This number would be the ratio of all of the propositions included by the student to the total number of possible propositions. Later, completeness was separated into two numbers, one representing model completeness and the other representing completeness of the domain of observations. Finally, completeness scores were further resolved into core and derived completeness since it would be difficult to compare categories as different from each other as those of the core and derived propositions.
Students' response patterns were scored according to the following categories: discipline-defined core propositions (referred to in this study as DiCoreCom), discipline-defined derived propositions (DiElabCom), alternative model core propositions (AltCoreCom), alternative model derived propositions (AltElabCom), and completeness of the domain of observations (ObCom). In each case the per-cent completeness score was calculated by taking the total number of propositions in each of these categories and dividing that number by the total number of propositions that would be possible in a complete response set. The following formulae were used in the computations of completeness:

\[
\begin{align*}
\text{DiCoreCom} & = (\text{DiHaf}+\text{DiSee}+\text{DiEMS}+\text{DiOrb})/4 \\
\text{DiElabCom} & = (\text{DiExp}+\text{DiAll})/16 \\
\text{AltCoreCom} & = (\text{EcHaf}+\text{EcSee}+\text{EcEMS}+\text{DiOrb})/4 \\
\text{AltElabCom} & = (\text{EcExp}+\text{EcAll})/16 \\
\text{ObCom} & = (\text{DiCom})/8
\end{align*}
\]

These calculations were done for each student, as well as for particular subgroups of interest within the sample. For example, the average completeness of the domain of observations was calculated for the group of students maintaining the "eclipse" model. Once the computations
were done, the results were displayed graphically, using bar graphs to illustrate completeness in each of the categories.

**Correctness**

Correctness refers to the proportion of students' statements that are correct according to the discipline. The total number of propositions that are correct (compared to statements found in an astronomy textbook) was divided by the total number of propositions put forward by the student. This ratio is a measure of correctness. (For Venn diagrams illustrating the difference between completeness and correctness, refer to Figure 16 on the next page.)
Figure 16. Venn diagrams showing differences between completeness (top) and correctness (bottom).
The correctness score was separated into three scores:
(a) discipline core correctness (referred to in the
analysis as DiCoreCor%), (b) discipline derived correctness
(referred to as DiElabCor%) and (c) correctness of the
domain of observations (referred to as ObCor%).

**Core Correctness.** Discipline-defined core correctness
(DiCoreCor%) was calculated by dividing the number of core
propositions that were correct (according to the
discipline) by the total number of core propositions
offered by the student. The correct propositions would
include DiHaf, DiSee, DiEMS, and DiOrb, as defined
previously. The core correctness was calculated by taking
the number of correct propositions included by the student
and dividing that by a sum equaling that number plus the
number of propositions included from the following
categories: EcHaf, EcSee, EcEMS, Ot1, Ot2, and Ot3. As an
example, a student with an eclipse model would have extra
incorrect alternative model propositions (such as EcHaf) in
the denominator that would deflate that student's
correctness score. The formula used for calculating
DiCoreCor% was:

\[
\text{DiCoreCor%} = \frac{(\text{DiHaf+DiSee+DiEMS+DiOrb})}{(.00000001+} \\
\text{DiHaf+DiSee+DiEMS+DiOrb+EcHaf+EcSee+EcEMS+Ot1+Ot2+Ot3)}
\]
The .000000001 was added to prevent computing errors that would arise were the other variables in the denominator zero.

**Derived Proposition Correctness.** Derived proposition correctness (DiElabCor%) was calculated by dividing the number of derived propositions by that number plus the number of other, alternative derived propositions. The formula used was:

\[
\text{DiElabCor\%} = \frac{\text{DiExp}}{0.00000001+\text{DiExp}+\text{EcExp}}
\]

The .00000001 was added, once again, to prevent computational errors.

**Observational Correctness.** Observational correctness (ObCor%) was calculated using two variables, "DiSha" and "DiDir." The formula for observational correctness is:

\[
\text{ObCor} = \frac{(\text{DiSha} + 2 \times \text{DiDir})}{10}
\]

DiSha is the correctness of the shapes of the phases as drawn by the students. This category was included because pilot work revealed some students included all of the phases, in terms of the rough percent shown to be in darkness, but drew wrong curves for the terminator, including curves that resembled "bites" and curves that
were not curved at all. One point was given for each phase shown correctly.

DiDir refers to the direction the terminator is shown moving as it passes across the moon. (The terminator moves from right to left as we see it.) A "1" was registered for students who showed the direction correctly, and a "0" was registered for students who showed the moon's phases in reverse order, or who did not give any clear order to the phases at all.

**Question 2. What changes in the content of students' knowledge can be documented after instruction based on a conceptual change model, and how do those changes compare to the changes predicted by the model?**

To answer this question, analysis was performed at two levels of magnification. At high magnification, the changes occurring within students were examined on a case-by-case basis. At low magnification, changes occurring in the class as a whole were examined. The methods of analysis are described in the following sections.

**Analysis of Individual Cases**

For each student, the pretest, midtest, and posttest values for each proposition column in their file were subtracted from each other to yield change values for each type of proposition. For example, if a student added the DiOrb proposition between the pretest and the midtest, the
DiOrbl2 score would be +1. If that student deleted two EcAll propositions between the midtest and the posttest, the EcAll23 score would be -2.

The proposition change values described above were combined to form composite scores for core and derived proposition sets for both the discipline and alternative models. This system allowed easy analysis in terms of the definitions of conceptual change used in this study: it was easy to see if core or derived propositions were deleted, remained the same, or were increased.

Once proposition change values were calculated, each student was classified as to whether they experienced accommodation, incomplete accommodation, assimilation, or no model change. These types of change are described below.

**Accommodation.** Accommodation occurred when the cause of the phases had clearly changed (e.g., from eclipse to the correct model). The new propositions are inconsistent with the old ones. Core proposition change values for alternative models were negative, and for the discipline were positive.

**Incomplete accommodation.** Incomplete accommodation occurred when a student deleted his or her core, but did not add core propositions from the new model. Core proposition change values for alternative models were
negative, but the values for the discipline were zero or positive.

**Assimilation.** Assimilation appeared in cases where new knowledge had been added that was consistent with the core. Core proposition change values were usually zero, but proposition change values in either the alternative or discipline-defined derived proposition sets were positive.

In this study, a significant number of students began instruction with "no model" so that it was difficult to evaluate the type of change that occurred as they added propositions. Conceptual change theory does not account for students beginning with no apparent knowledge. In fact, conceptual change theory assumes that these students must have some knowledge upon which new information can be built, but that this knowledge was not tapped by the tests. Piagetian psychologists would suggest that students starting with no knowledge must "bootstrap" new knowledge through a dynamic combination of accommodation and assimilation (Jacobvitz, 1988). In this study, it is assumed that most of the students who showed "no model" actually had some notion that the moon orbits the Earth. Given this assumption, most cases involving the addition of correct propositions would be instances in which assimilation is the dominant form of change, although accommodation may be occurring as well.
No Change. No change occurred when there were no changes in the propositions. Proposition change values were zero.

Analysis of Class Data

Analysis took the form of charts designed to display the changes undergone by the students. (Refer to Figure 17 on the next page for an example.) Charts of this type were constructed to represent the pretest to posttest changes. Pie charts were used to show the proportions of students undergoing each type of change (accommodation, assimilation, etc.)
Figure 17. Model change diagram for entire class.
These results were then evaluated to see if they are consistent with the following predictions derived from the Posner et al theory:

1. Under optimal conditions students with alternative theories should accommodate when they are taught in a way that is consistent with the Posner et al conceptual change model. The optimal conditions are that a student must experience intended anomalies as such, a student must believe that reconciling the anomaly with his or her current conceptions is important, the student must accept that inconsistencies need to be reduced, and the student must not falsely assimilate new information into an incorrect core.

To judge whether or not the changes are consistent with the Posner et al model, the cases in which students begin instruction with alternative frameworks and are therefore expected to accommodate will be examined. If a high proportion of these cases accommodate by the end of instruction, this will be consistent with the Posner et al model.

2. Since Posner et al and other conceptual change theorists recommend teaching for accommodation without restriction, one might assume that this method will work for everyone, regardless of their initial state of knowledge. Because Posner et al view assimilation (the
other type of possible change) and accommodation as different only in degree, one can predict that teaching for accommodation should also work for those who need to assimilate. In addition, this suggests that this method might work best for those with alternative models.

To decide whether teaching for accommodation helps students who need to assimilate, those cases without alternative frameworks will be analyzed for gains in correct propositions.

3. Posner et al state that accommodation takes place against a background of current conceptions; therefore, we should see evidence that accommodation involves additions and deletions of propositions against a background of stable propositions.

To find evidence that accommodation involves additions and deletions of propositions against such a background, the individual cases of accommodation will be examined closely. If a stable base of propositions remains from one stage of instruction to the next, that will be evidence that change takes place in a way that is consistent with the Posner et al theory.

The results of the instruction and analysis described above are detailed in the next chapter.
Chapter 4
RESULTS

The research questions of this study focused on the changing content of the students' knowledge. The first question concerned the state of students' knowledge at three points in time: prior to instruction, during instruction, and after instruction. The second question focused on the changes that took place between these three states. The research questions are restated below, followed by the corresponding results and the interpretation of these results in light of conceptual change theory.

Question 1a. What is the character of the students' preinstructional knowledge in terms of content, consistency, completeness, and correctness as revealed by the pretest?

Content of Student Models

As seen in Figure 1 on page 115,1 aside from one student who had the correct model and a small number who

---

1The distribution of model types and subgroups on all three tests can be found in Appendix F.
had alternative models (eclipse: n=8, eclipse/correct: n=1, earth rotation: n=1), most students began instruction with either fragmentary knowledge (n=13), or no knowledge whatsoever (n=37), about the cause of the phases of the moon. The content of these student models is described below.
The Correct Model

Only one student, #12, had the correct model, the core of which by definition was complete. A stylized version of his model can be found in Figure 2 on the next page. In addition to this diagram, he wrote a response, shown in Table 1 on page 117, that included most of the key propositions. The discipline propositions that he refers to are shown in the right column.
Figure 2. Stylized version of #12's diagram. This diagram, along with the accompanying written response (see text in Table 1) indicated that #12 had the correct model.
Table 1

Statements extracted from response of student with correct model and corresponding discipline propositions.

<table>
<thead>
<tr>
<th>Student's statements</th>
<th>Discipline propositions</th>
</tr>
</thead>
<tbody>
<tr>
<td>The moon is orbiting around the Earth.</td>
<td>The moon orbits the Earth.</td>
</tr>
<tr>
<td>So if the moon is basically between the earth and the sun, the far side of the moon will be its lit side...</td>
<td>(DiOrb). The half of the moon facing the sun is lit. (DiHaf.)</td>
</tr>
<tr>
<td>and to earthlings the moon will be in phase 1.</td>
<td>The part of that half we see determines the phase. (DiSee.)</td>
</tr>
<tr>
<td>As the moon moves to the side of the earth opposite that of the sun...</td>
<td>The part of the half we see depends upon the relative configuration of the Earth, Moon, and Sun. (EMS.)</td>
</tr>
<tr>
<td>We see the lit side of the moon.</td>
<td>(DiSEE)</td>
</tr>
</tbody>
</table>
The Eclipse Model

Of the students who had pretest models that were capable of explaining the phase phenomena (though in some cases in a rudimentary way), most (8 out of 10) had the eclipse model. (The other two were correct and eclipse/correct.)

Responses using the eclipse model ranged from the nearly complete model (#53) to only a brief mention that the cause of the phases is the Earth's shadow (#17). The proposition matrix, which shows the presence or absence of propositions given by each student without the supporting references, is shown for students of this group in Figure 3 on the following page. Students with the eclipse model either showed the Earth-moon system as seen from above the plane of the ecliptic, showed the Earth-moon system as seen from the sun, or described the eclipse model in their written response only. The models of students in each of these subgroups are described below.
<table>
<thead>
<tr>
<th>119</th>
</tr>
</thead>
</table>

## Key to proposition names:

- **DiOrb**: The moon orbits the Earth.
- **DiHaf**: Half of the moon is illuminated by the sun.
- **DiSee**: We see part of the illuminated half.
- **DiEMS**: The relative positions of the Earth, Moon, and Sun determine the portion of the half we see.
- **DiExp**: One point for each phase correctly explained.
- **DiAll**: One point for each phase represented in some way.
- **EcHaf**: Alternate framework cause of phases.
- **EcSee**: Alternate explanation given for different phases.
- **EcEMS**: Alternate explanation depends upon relative position of Earth, Moon, and Sun.
- **EcExp**: One point for each phase explained according to alternate theory.
- **EcAll**: One point for each phase represented in some way.

**Figure 3.** Matrix of propositions for students with the eclipse model.
Eclipse model as viewed from above. Five of the eight students holding the eclipse model described their models as viewed from above. These five students (#17, #53, #15, #14 and #60) represented the phenomenon of the phases as seen from above the plane of the Earth-moon system. They drew diagrams that showed the sun, Earth, and moon, and the shadow the Earth projects on the moon. A stylized version of one such student diagram (#53's) is shown in Figure 4 on the next page. Another student (#14) also portrayed the Earth-moon system as seen from above, although she did not specifically draw the shadow of the Earth. In addition, she made no reference to her model in the question that asked for a model (question 2). She did, however, mention her model in answer to question 11. She stated, "The Earth's shadow blocks out the right hand portion of the moon."
The phases of the moon are caused by the alignment of the earth, sun and moon and the shading of the sun's rays by the earth and the moon... Note: 6-8 may actually be describing a solar eclipse. Note also: for diagrammatical simplicity I drew the Earth circling the sun... This usually does not happen in 1 month.

Figure 4. #53's diagram and additional text describing an eclipse model.
This student also drew the eclipse model picture (as seen from above) directly on the accompanying diagram. A stylized version of her diagram is shown in Figure 5 on the next page. What is interesting about this response is that the test diagram already included a large, bold arrow pointing to the right, with the words "To Sun" in bold letters. This student added her own sun, however, to the lower left, apparently so that the Earth could now cast a shadow on the moon. She may have felt strongly enough about the eclipse model that she failed to attend to the sun already provided.
Figure 5. #14’s drawn response to question 11 of the pretest. She apparently added her own sun to keep her commitment to the eclipse model.

In response to question 5, #15 stated that "the earth would shade the light from the sun so only part of the moon would reflect the sun's rays." The accompanying diagram showed the moon being blocked by the Earth.

Eclipse model as viewed from the Sun. Two students (#26 and #32) showed the phase phenomena as seen from the vantage point of the sun. The Earth was shown occulting the moon, where the extent of the occultation determined
the phase. A stylized version of #26's diagram is shown in Figure 6, which follows.
Figure 6. #26's diagram, illustrating eclipse model viewed from vantage point the sun.

**Written eclipse responses.** One student, (#50) drew no diagrams, but her statements indicated that she also believed in the eclipse model:

The moon also travelling in orbit move [sic] about the earth when the earth is between the sun and the moon, we have a new moon phase with no sunlight reflecting off the moon... when the moon is between the earth and sun it's full moon with the sun reflecting off or lighting the moon.

This student sounds as if she is saying that the moonlight comes from reflected earthshine, which was a common statement found in the pilot work. Possibly the earthshine
model is related to the eclipse model; someone believing
the eclipse model would have to explain why we don't have
two new moons: one at the full position, and one at the new
position. Earthshine solves this difficulty by
illuminating the moon when it is between the Earth and sun.

Eclipse/Correct

Only one student (#11) had the Eclipse/Correct model:
that is, he seemed to switch back and forth between the
correct and the eclipse model. His diagram shows the
positions of the moon according to the correct model. His
statement in response to question 1, however, was
consistent with the eclipse model:

It's hard to tell by the diagram, but each portion of
the moon that is shadowed in on the previous page is
caused by the earth blocking the light from the sun--
we are seeing our own shadow.

Later, in response to question 11, he drew the moon
correctly (a crescent) and finally supported this correct
drawing with a correct explanation, saying that "... 1/2 of
the moon facing the sun is lit up... from our perspective
we would see a sliver of it."

Earth Rotation Model

The Earth Rotation model, a confusion of the concepts
of the diurnal rotation of the Earth and the orbital motion
of the moon, does not seem to be powerful in terms of being
either explanatory or predictive. It may also result from confusing the terms "rotation" and "revolution." (Other students also seem to confuse these terms. See, for example, #19's drawn response in Figure 23, page 162.)

The one student who had this model, #48, gave the following written response, as well as the drawn response shown in Figure 7 on the next page:

Cause earth is rotating itself and earth is also revolving... that's why moon starting shade and takes 15 days to become full moon [sic].
It is possible that his confusion arose due to the fact that he is from Japan, and English is his second language. However, his drawing of the earth rotating while it orbits the sun seems to point to a genuine misconception.

**Fragments**

Most students who knew anything at all about the moon's phases knew only fragments of the correct model ($n = 13$). These students ranged from knowing next to nothing about the cause of phases to knowing all but one of the essential concepts needed for a complete discipline-defined model. Students in this "fragments" group most commonly failed to mention that the half of the moon facing the sun is illuminated (Dihaf), and that the portion we see depends upon the relative position of the Earth, moon, and sun (EMS). More students indicated that the phases are caused
by the part of the lit side we can see (DiSee). Most students stated the fact that the moon is going around the Earth (DiOrb). The thirteen students in the fragments group had eight different combinations of the core propositions. The proposition matrix for this group is displayed in Figure 8 on the next page. To make some sense out of this diversity, these eight models are divided into two groups: those that made reference to the orbit of the moon (the DiOrb subgroup, n = 6), and those that did not (the non-DiOrb subgroup, n = 7.)
Figure 8. Matrix of propositions for students with fragments on the pretest.

The DiOrb fragments subgroup. Students in the DiOrb subgroup ranged from almost having the correct model (one student, #3) to simply knowing that the phases are somehow related to the moon orbiting the sun (three students; #4, #33, and #38.) Refer to the stylized diagrams of the models of these students, shown in Figure 9, which illustrates the basic structure of the models of students in this subgroup.
Only one student (#27) in this group referred to the DiHaf proposition, and only one (#3) referred to the DiSee proposition. These two propositions are essential to a
complete understanding of the phase phenomena. It seems that the students in this group concentrated on the larger picture, that of the moon orbiting the Earth, while paying little attention to the details of why we see a particular phase.

The non-DiOrb fragments subgroup. All of the students in the non-DiOrb subgroup focused on the cause of one or more phase but neglected the larger picture, that of the moon orbiting the Earth. Students in this group knew that the phase is determined by the portion of the illuminated half that we see from Earth (DiSee). Yet they rarely extended that knowledge to include other phases, and they left out references to the orbit of the moon. (Refer to the stylized models of these students in Figure 10 on the next page.)
"The moon can only get so much light from the sun and we can only see a certain portion of that light, depending on the position of the sun, the position of the moon, and our location on Earth." (From #59)

In addition to leaving out references to the orbit of the moon, students in this subgroup drew diagrams that revealed some misconceptions. For example, in response to question 11, four students (#29, #16, #24, and #45) drew
the terminator slanted, as if they believed that sunrays propagated radially from a sun immediately to the right of the diagram (refer to Figure 11 on the next page). Their responses to questions 14 and 15 (which asked about the paths of sunlight) indicated these students did indeed have this misconception about the sun's rays. Their response makes interpretation difficult, because with the terminator in this new slanted position, the moon would appear in the first quarter phase as seen from the Earth. Since the terminator appears as a straight line from both above the moon and from the Earth, it is hard to be certain that the student has really drawn the moon from the Earth's perspective, as asked by the question.
Some students drew the terminator slanted, as if the sun were to the immediate lower right.

Two students (#52 and #13) were also confused about the phase mechanism. (See Figure 10 on page 133 for stylized versions of these students' diagrams.) #52 drew lines of sight from the Earth to the moon, but incorrectly concluded from his diagram that we would only be able to see the dark part of the moon. #13 was the only one in this subgroup who left out the DiHaf proposition. He showed light rays coming from the sun and then bouncing off
the moon. Although moonlight is indeed reflected sunlight, his model does not explain why only certain portions of the moon are visible at any one time.

No Model

Most students (n=38) began with no model. These students showed no written or drawn propositions indicative of any model explaining the lunar phases. For the most part, these students had blank test forms.

Consistency

Most student responses were very consistent. This may be due, in part, to the fact that most models were not complete enough to allow for inconsistencies.

Completeness

Students varied in the degree of completeness of their core and derived concepts. The single student with the correct model had the most complete core (100%) and derived (88%) propositional sets. Even those students who began instruction with the eclipse model (n=8) or fragmentary knowledge (n=13) had some proportion of propositions (16% for eclipse, 44% for fragments) from the core of the correct model that could be built upon in future instruction. Most eclipse model holders knew that the moon orbits the Earth (DiOrb) and hence the 16% figure for discipline-defined core completeness. Students in the
fragments group had a variety of propositions from the
discipline. (See section 1a above.)

As can be seen in Table 2 on the following page,
students with the eclipse model had alternative model core
proposition sets that were fairly complete but alternative
derived proposition sets that were less so: it is somewhat
more difficult for someone holding the eclipse model to
develop a complete set of explanations for each phase.
Table 2

Completeness of Pretest Responses as a Function of Model Type

<table>
<thead>
<tr>
<th>Model</th>
<th>n</th>
<th>DiCore</th>
<th>DiElab</th>
<th>AltCore</th>
<th>AltElab</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>1</td>
<td>1.00</td>
<td>0.88</td>
<td>0.25</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Earth Rot.</td>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.25</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Eclipse</td>
<td>8</td>
<td>0.16</td>
<td>0.02</td>
<td>0.59</td>
<td>0.30</td>
<td>0.70</td>
</tr>
<tr>
<td>Eclipse/Correct</td>
<td>1</td>
<td>1.00</td>
<td>0.63</td>
<td>0.50</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Fragments</td>
<td>13</td>
<td>0.44</td>
<td>0.08</td>
<td>0.13</td>
<td>0.00</td>
<td>0.54</td>
</tr>
<tr>
<td>No Model</td>
<td>37</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.42</td>
</tr>
</tbody>
</table>

DiCore = discipline-defined core propositions  
DiElab = discipline-defined derived propositions  
AltCore = alternative core propositions  
AltElab = alternative derived propositions  
Obs = domain of observations

As seen in Figure 12 on page 140, students varied in the completeness of their prior knowledge of the phase phenomena. There is a relationship between the predictive power of the students' model and how much they knew about
the observations. Students with a model powerful enough to account for the observations knew the most (100% for correct and eclipse/correct, 70% for eclipse) about the observations. Those whose knowledge was incomplete or missing knew the least (54% for those with fragments, 42% for those with no model).
Figure 12. Completeness and correctness of knowledge of observations as a function of model type.

Correctness

Except for those who subscribed to the eclipse model, most students stated core propositions that were correct. Even if their models were incomplete (as with those who had fragments), those core propositions they did state were stated correctly. The incorrect core propositions were primarily related to the eclipse model, as can be seen by the depressed correctness mean score of the eclipse subscribers and the slightly depressed mean score of the correct/eclipse model subscriber. (See Table 3 on the next page.)
Table 3

Correctness of pretest responses as a function of model type

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Core Correctness</th>
<th>Observational Correctness</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>1.00</td>
<td>0.80</td>
<td>1</td>
</tr>
<tr>
<td>Earth Rotation</td>
<td>0.00</td>
<td>0.30</td>
<td>1</td>
</tr>
<tr>
<td>Eclipse</td>
<td>0.23</td>
<td>0.56</td>
<td>8</td>
</tr>
<tr>
<td>Eclipse/Correct</td>
<td>0.80</td>
<td>0.80</td>
<td>1</td>
</tr>
<tr>
<td>Fragments</td>
<td>0.97</td>
<td>0.42</td>
<td>13</td>
</tr>
<tr>
<td>No Model</td>
<td>0.00</td>
<td>0.32</td>
<td>37</td>
</tr>
</tbody>
</table>

The relationship between having a model that is defined enough to account for the phases and being familiar with the domain of observations existed for observational correctness as well. (See Figure 12 on page 140.) Those that did have fairly complete, explanatory models (correct, eclipse, and correct/eclipse) had largely correct responses for the domain of observations (.80, .56, and .80, respectively). On the other hand, those students from the fragments and no model...
group drew fewer of the phases correctly (.42 and .32, respectively).

Summary of Results for Question 1a

One student began instruction with the correct explanatory model. By definition, his core propositions were complete. His derived propositions were mostly complete (88%). His propositions were entirely correct. Learning for this student consisted of assimilating other derived aspects of the model to his already correct core of understanding.

Of the 24 remaining students who knew something about the cause of the phases, about half (13) knew various combinations of fragments of the correct model. The students with fragments had somewhat incomplete sets of core propositions (44%) and extremely incomplete sets of derived propositions (8%). These students were unable to account for the individual phases, even though they were able to state several propositions related to the cause of the phases. The most common propositions represented by people in this "fragments" group were that the phases are due to the part of the moon we can see (DiSee), and that the phases are somehow caused by the moon orbiting the Earth (DiOrb). These propositions are knowledge upon which future learning could be based.
Most of the remaining 10 students had models that could account for the phases fairly well, but were nevertheless incorrect. Eight of these students had the eclipse model, one student had the earth rotation model, and one student had a mixed model with correct and eclipse core propositions. Presumably, students in these circumstances needed to accommodate to learn the correct model.

Responses of students with the eclipse model were not as complete (59% for core completeness, 30% for derived completeness, relative to the eclipse model itself) as the responses of the student with the correct model (100% for core and 88% for derived completeness relative to the discipline propositions). In part, this incompleteness may be due to the fact that alternative models are usually not as good as the correct model in accounting for the observations. Someone using such a model would find it harder to account for the complete set of phases.

The student with the eclipse/correct model gave mostly complete responses in terms of both his core and derived propositions. The student with the earth rotation model gave a very incomplete response.

Most students (37 out of 61) began instruction with no knowledge of the phases of the moon. In addition, student knowledge prior to instruction was characterized by being mostly consistent and correct, but largely incomplete.
The results also indicated a relationship between completeness and correctness of the observational knowledge and the completeness of the explanatory model. Students who were more able to describe the phenomena of the lunar phases adequately may have also been better able to learn and remember their underlying causes.

Knowledge Claims for Question 1a.

1. One student entered instruction with the correct model, 13 with fragments of the correct model, 10 with alternative models, and 37 with no model. The most common alternative model (8 out of 10) was the eclipse model.

2. The knowledge of students entering instruction was mostly correct and consistent, but very incomplete. Most incorrect propositions were associated with the "eclipse" alternative model.
Question 1b. What is the character of the students' midinstructional knowledge in terms of content, consistency, completeness, and correctness as revealed by the midtest?

Content of the Student Models

The midtest responses were very different from the original, pretest responses.² (Refer to Figure 13 on the next page.) Whereas on the pretest most students had no model, by the midtest, all except one student had some explanatory knowledge, right or wrong, of the moon's phases. Two students had the correct model. The majority of students had either fragments (n = 21) or eclipse models (n = 21). Students also had a greater variety of models, with the addition of alternative models other than the eclipse model, including the "double moon," (n = 1), "earth rotation," (n = 1), and "heliocentric" (n = 2). The knowledge students demonstrated on the midtest is described further below.

²Twelve out of the original sixty-one students did not return for the midtest, either because they had dropped the course or because they missed class that day. Of these twelve students, ten had no model and two had fragments on the pretest.
The Correct Model

Two students, #12 and #50, had the correct model. #12 was the one student who began instruction with the correct model. #50 gave the correct model, but included additional incorrect knowledge as well. She wrote:

As the moon orbits the earth the side that faces the sun is illuminated...as it moves in its orbit our view of it changes and rotates...when we face the back side of the moon we are probably in the new moon phase... which direction is first and third quarter is unclear. The student's incorrect knowledge is shown by the statement "when we face the back side"; incorrect knowledge is also shown by the student's diagram, appearing in Figure 14 on page 148, which shows the moon's far side as always dark.

Figure 13. Distribution of model types on the midtest.
The students' statements and diagram may result from a common confusion between the moon's "far" side and "dark" side. This confusion would not interfere with the correct prediction of the phases, although it indicates a somewhat weak understanding of the correct model.
Figure 14. #50’s midtest diagram, showing the far side of the moon always dark. Note: the shading may have also been meant to represent the part we cannot see.

Fragments

One third of the students \((n = 21)\) had fragments of the correct model. The proposition most frequently given by members of this group was that the phases are related to the moon orbiting the Earth \(\text{DiOrb}\). In fact, unlike the pretest, when only six out of thirteen students provided this proposition, all members of the midtest fragments
group stated this proposition. Next to DiOrb, the second most frequently given propositions described the positions of the moon at its various phases. In other words, most students made some reference to the moon orbiting the Earth and gave the positions along that orbit for the various phases. The propositions stating that half the moon is illuminated by the sun (DiHaf), that the portion of the half we see (DiSee) depends upon the relative position of the Earth, moon, and sun (DiEMS), each were less commonly given than the DiOrb and DiAll propositions. It was also rare to find any particular phase satisfactorily explained (DiExp).

The twenty-one students in the fragments group had seven different combinations of the core propositions. The proposition matrix for this group is displayed in Figure 15 on the following page. For ease of discussion, this group has been divided into two subgroups: those indicating that half the moon is illuminated by the sun (the DiHaf subgroup, n = 6) and those that did not (the non-DiHaf subgroup, n = 15).
Figure 15. Proposition matrix for students having fragments on the midtest.

The DiHaf fragments subgroup. Students in this group typically included many of the important propositions in their responses. They would fall short, however, of giving a complete explanation of any particular phase. Sometimes they were very close to being classified as having the correct model. #57, for example, eloquently stated the key propositions of the correct model:

The phases are caused by rays (approximately parallel) coming in from the sun. These rays reflect off the moon and reach the earth. The portion of the moon
that is visible depends on where the moon is in its orbit with respect to the earth. This student also drew pictures of the moon at the appropriate positions for each phase and showed that the half of the moon facing the sun would always be illuminated (see Figure 16 on the next page). However, she never took the additional step of applying this (correct) knowledge to explain a particular phase. (#27 and #35 had similar models.)
Responses by the other three students in this subgroup were similar: they fell short of explaining a particular
phase, but gave somewhat less complete responses than those described above.

Non DiHaf fragments subgroup. Students in this subgroup fell into three sets: 1) those stating all but the fact that the half of the moon facing the sun is illuminated (DiHaf); 2) those stating only that the moon orbits the Earth and giving its location at the various phases; and 3) those stating nothing but the fact that the moon orbits the Earth (DiOrb).

The first set of students, those that stated all but DiHaf, gave responses that, like those of the DiHaf subgroup, bordered on the correct model. The missing DiHaf proposition prevented these students from explaining more than the new and full moons. For example, #52 wrote:

1) Moon is between the earth and the sun so we can see none of the sun's light on the moon.
2) the moon has moved and is now at a different angle in reference to the earth and sun. We can see a little light.
3) moon has moved through the quarter of orbit so we can see half the light.
4) we now see about 3/4 of the sun's light reflecting off the moon
5) moon is straight across so we see all the light.
Yet #52's drawn response, shown in Figure 17 on the next page, includes the missing reference to DiHaf, which makes his model difficult to interpret. Specifically it is difficult to know why we see "half the light" or "3/4" the light at quarter and gibbous phases, although it is clear why at new moon we would see "none of the sun's light on the moon." The written and drawn responses of #40 and #26 were similar to #52's.
Figure 17. #52's midtest model diagram.

The second set of students, those that had the next most complete set within the non-DiHaf subgroup, showed the positions of the moon at the different phases but gave no other explanation of the phases. #1's diagram, Figure 18 on the next page, is typical. Students with this type of response represented the largest number within the Fragments group.
The third set of students had the DiOrb proposition only. They showed the moon orbiting the Earth, as in #23's diagram, Figure 19 on the next page. In some cases, people in this set may be similar to some of the subjects of the pilot study, who believed that the physical motion of the moon around the Earth was somehow responsible for the phases. In other cases, we may simply be seeing very incomplete knowledge.
The Eclipse Model

Students with the eclipse model were equal in size (n = 21) to the fragments group. (The proposition matrix for this group is shown in Figure 20 on the next page.) A much larger proportion of midtest responses than pretest responses (about half compared to one quarter) were fairly complete eclipse models. In other words, more students taking the midtest gave responses extensive enough to explain at least several phases.
One of these responses was that of #53. As Figure 21 on the next page illustrates, she apparently tried on the midtest to overcome the confusions of her previous pretest model of Figure 4 (refer to page 121) by removing the sun from the center of the diagram and redrawing it for each phase. On the midtest she managed to explain several phases; however there are some inconsistencies, including the fact that she showed the first quarter moon in its position according to the correct model.
Several other students gave responses similar to #53's, yet these responses were less complete in explaining each phase. For example, #54's diagram (see Figure 22 on the next page), showed the moon orbiting the Earth (DiOrb), the moon in the Earth's shadow (EcHaf), the moon moving through the Earth's shadow (EcSee), and the moon changing its position with respect to the Earth and sun to give rise to different phases (EcEMS). Her diagram accounted for three phases, however: new, waxing crescent, and waning crescent.

Figure 21. #53's midtest model diagram.
Figure 22. #54’s midtest diagrams, showing the positions of the moon, as well as specific diagrams for phases 1 and 2.

A much less complete eclipse model, given by #19, is shown in Figure 23 on page 162. Mention of the Earth moving in front of the sun indicates she has an eclipse model. Yet her choice of words creates problems of interpretation. The word “rotation” appears instead of “revolution.” If she meant to write “revolution” instead of “rotation,” then her diagram would have shown the changing phases as apparently due to the revolution of the
Earth around the sun, an interesting variant of the eclipse model. Her true intention is unclear.
Other less complete eclipse responses ranged from showing all but the moon's orbit around the Earth to mentioning briefly that the phases are caused by the moon's light being blocked by the Earth.

Several eclipse models were inconsistent. Two of these (#8 and #60) gave the Earth's shadow as the cause of the phases, but showed the positions of the phases as if the

"Earth slowly moving in front of sun with sun slowly revolving."

Figure 23. #19's midtest model diagram.
students had the correct model. (See the stylized diagram of #60, Figure 24 on the next page, for an example.)
The Double Moon Model

Only one student (#45) used the "double moon" alternative theory, which says that the phases are caused by two moons, one passing in front of the other. (Refer to the stylized drawing of her diagram in Figure 25 on page 166.) This theory is similar in structure to the eclipse theory, shown in Figure 6, if the word "Earth" is substituted for "new moon." In fact, the student's written response to question 2b is, "the new and full moons are constantly going around each other as they are orbiting the sun." Yet she leaves the Earth out of both her written and
drawn responses, possibly due to difficulty in imagining the view of the Earth and moon as seen from space.
Table 25. #45's diagram showing the double moon theory. Note the difficulty she has reconciling her theory with her (correct) knowledge that the moon's terminator is straight during phases #3 and #7. In phase #3 she combines her theory with the correct terminator shape, yielding a strange composite of correct and incorrect knowledge. In phase #7 she ignores her theory and draws the moon as she knows it appears.
The double moon theory, though incorrect, can account for the phases at least as well as its structural equivalent, the eclipse model of Figure 6 on page 125. Therefore, the double moon theory's attractiveness to #45 may be partly due to this success in explaining all of the phases. (It is also interesting to note that she does in fact give an eclipse model in her posttest.)

**Earth Rotation Model**

#48 continued to be the sole student to have the Earth rotation model. He gave the following written response, as well as the drawn response shown in Figure 26 on the following page:

Earth rotates itself (once for 24 hours) then viewpoint move as earth move then first you are directly sun 12 hour later sun is behind you [sic].

Although #48 is Japanese, and his difficulty with English may have interfered with his explanation, he still seems to confuse the Earth's diurnal rotation with the moon's orbital motion. The difference is that he has now added to his diagram the moon's orbit, showing its position at each phase.
The Heliocentric Model

Two students used the "heliocentric" model. According to this model, the moon orbits the sun and the Earth. (Refer to §59's diagram, Figure 27 on page 170, for an example of the heliocentric model.) At new moon, the sun blocks our view of the moon entirely. The other phases are caused by various degrees of blocking, with the full moon occurring when the moon is opposite the sun (in the correct "full" position.) The students who used this model
ignored the fact that the other phases can be seen at night, when the moon is far from the sun.
Figure 27. #59's diagram showing the "heliocentric" model.

"Sun is blocking the moon"

(H, V stand for Mercury and Venus)
Consistency

Student responses on the midtest were less consistent than they were on the pretest. The inconsistencies appeared primarily in the group of students holding the eclipse model. Perhaps these inconsistencies occurred because the eclipse model is not completely consistent with the observations. In addition, the eclipse model is not consistent with the notion, reinforced by class discussion of the observations, that the phases occur at equipartitioned angles along the moon's orbit.

Completeness

As with the pretest, students with the most complete responses were those in the "correct" category. These students had discipline-defined core knowledge that was (by definition) 100% complete, and elaborated (or derived) knowledge that was 56% complete.

In contrast, students holding the eclipse model had alternative framework cores that were fairly complete (76%), but alternative framework derived propositions that were much less complete (20%). Students in the fragments group had discipline-defined cores that were 48% complete and derived proposition sets that were 42% complete. These results represent an improvement over the pretest, where the cores were 44% and derived proposition sets were only 8% complete. This difference could be due to greater
familiarity with the observations, which would help define the ways in which the explanatory model could be applied and elaborated. The summary of completeness scores can be found in Table 4 on the next page.
Table 4

Completeness of midtest responses as a function of model type

<table>
<thead>
<tr>
<th>Model</th>
<th>n</th>
<th>DiCore</th>
<th>DiElab</th>
<th>AltCore</th>
<th>AltElab</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
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<td>1.00</td>
<td>0.56</td>
<td>0.25</td>
<td>0.00</td>
<td>0.81</td>
</tr>
<tr>
<td>Dble Moon</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>1.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Earth Rot.</td>
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<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Eclipse</td>
<td>21</td>
<td>0.20</td>
<td>0.08</td>
<td>0.76</td>
<td>0.22</td>
<td>0.58</td>
</tr>
<tr>
<td>Fragments</td>
<td>21</td>
<td>0.48</td>
<td>0.42</td>
<td>0.25</td>
<td>0.01</td>
<td>0.69</td>
</tr>
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<td>Heliocent.</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.75</td>
<td>0.44</td>
</tr>
<tr>
<td>No Model</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The relationship between having a well-defined model and being familiar with the observations was not as strong as it was with the pretest. This may have been the result of the instruction about observations that immediately preceded the midtest, which would have brought students from different model groups up to an equally high level of completeness with respect to the observations. (Refer to Figure 28 on the next page for a graph of observational completeness and correctness versus model type.)
Figure 28. Completeness and correctness of observations as a function of model type.

Correctness

As on the pretest, student responses on the midtest were mostly correct. Once again, most incorrect propositions were stated by students with alternative models. The few core propositions given by students with fragments were mostly correct.

Figure 28 above shows that the correlation between correctness of the observations and having a well-defined model that was found on the pretest was not as strong on
the midtest. Once again, we may be seeing the effect of the instruction, whereby students from different model groups are brought up to an equally high level with respect to their knowledge of observations, thus minimizing the variance among model groups.

Summary of Results for Question 1b.

Once students were exposed to the observations to be explained, more students had knowledge of the phases (48 out of 49), and there was a greater variety of models among those students. Most students either adopted the incorrect eclipse model of the lunar phases or acquired fragments of the correct model. Some students presented other misconceptions: these include the notion that the phases are caused by the moon going to the other side of the sun, the notion that the far side of the moon is also the "dark side," and the notion that there are two moons, one light and one dark, that create the phases by occulting each other. Although these misconceptions first presented themselves on the midtest, it is hard to pinpoint their origin. Some may have been pre-existing misconceptions that were only elicited once a more thorough discussion of the phases took place. Other misconceptions may have been evoked by the observations themselves. Still others may have resulted from some aspect of the instruction or the group discussions.
Knowledge Claims for Question 1b.

1. At an intermediate point in the instruction (after observations and discussions) most students (48 out of the 49 present for the midtest) had some knowledge of the lunar phases.

2. At an intermediate point in the instruction (after observations and discussions) there was a greater variety of alternative models, including the heliocentric \((n=2)\) and double moon \((n=1)\), as well as the eclipse \((n=21)\) and earth rotation models \((n=1)\).

3. Midtest responses were less correct (because of the large number of alternative propositions) but more complete (due to the added number of correct propositions resulting from the instruction) than the pretest responses.

4. Many responses were inconsistent, due to difficulty in reconciling the eclipse model with the fact that the phases occur at equally spaced intervals along the moon's orbit.
Question 1c. What is the character of the students' postinstructional knowledge in terms of content, consistency, completeness, and correctness as revealed by the posttest?

Content of the Student Models

Important differences occurred between the distribution of model types on the midtest and the distribution on the posttest (see Figure 29 on the next page). First, no alternative models other than the eclipse model appeared on the posttest. Second, there were more correct models on the posttest (n = 11, or 20%, as opposed to n = 2, or 4% for the midtest), as well as more students with fragments (n = 35, or 65%, versus n = 21, or 43% on the midtest). Third, fewer eclipse models appeared (n = 5, or 9% as opposed to n = 21, or 43% on the midtest). Finally, three students had no model. The knowledge students had as represented on the posttest is described below.

---

3 Seven of the original 61 students did not return for the posttest, and two of those seven had also not been present for the pretest.
Figure 29. Pie chart illustrating distribution of model types on posttest.

The Correct Model

Eleven students had the correct model on the posttest. Of those 11, both of the students who used the correct model on the midtest continued to use the correct model on the posttest. In addition, #50, who on the midtest had the correct model plus additional incorrect propositions, deleted those incorrect propositions on the posttest. The other eight students developed the correct model between taking the midtest and taking the posttest.

Fragments

The majority of students had fragments of the correct model (n = 35) on the posttest. Within this group, the
most commonly given proposition was the DiOrb proposition:
all 35 students stated the fact that the moon orbits the Earth. (Refer to the proposition matrix for this group, Figure 30.) The next most commonly given propositions, given by 32 of the 35 students in this group, were all eight DiAll propositions, the correct positions of the moon at each of the eight phases. In other words, most students in this group knew that the moon orbited the Earth and that the moon's phases are associated with certain positions along its orbit. Less than half of this group (15 out of 35) stated at least one of the other propositions necessary for the correct explanation, such as DiHaf, DiEMS, or DiSee.
The largest subgroup within the Fragments group (16 of the 35) represented only DiOrb and DiAll. They were able to say where the moon would be in its orbit for each phase but were unable to explain why we would see any particular
phase. For example, when asked to explain the cause of the phases, #46 simply states, "the moon going around the Earth." His diagram, seen in Figure 31 on the following page, shows the moon at each of eight positions, corresponding to the eight phases. Other response patterns within the Fragments group were similar to those described in the discussions of the pre and midtest results.
Five students had eclipse models. In some cases, these students grafted some correct propositions onto their incorrect eclipse cores. For example, #28's written statement shows that she has the eclipse model:

We only see the part of the moon that the sun shines on when the moon revolves around the earth, the earth blocks some of the light in certain positions causing shadows to occur.

She also uses the eclipse model in her diagram, shown in Figure 32 on page 184. Note that she shows the correct positions of the moon for each phase, but that she has...
drawn the shape of the terminator in a way that is consistent with her eclipse model.
Figure 32. #28's posttest model diagram, showing the moon in the correct positions, but the terminator shaped according to the eclipse model.

#14's response was very similar to that of #28 in that she added correct propositions while maintaining her incorrect "eclipse" core. As seen in Figure 33 on page 186, she showed the correct positions of the moon along its orbit (as well as the correct appearances of the terminator). Her written statement, however, clearly indicated that she maintained the eclipse model:

As the moon moves around the Earth, different shadows are thrown by the earth onto the moon's visible surface. This gives the different phases.
A clue to what may have allowed #14 to simultaneously maintain her correct and eclipse propositions can be found in the annotation of her diagram. She writes the phrases "total blockage," "partial blockage," and "no blockage" near the new, crescent, and full moons, respectively. The word "blockage" used in this correct context may refer to the fact that the moon itself blocks our view of its lit side. The same word, however, would have been even more appropriately used in the eclipse context, where it was used by many students to refer to the blockage of sunlight by the Earth.
Other students adapted concepts learned in the instruction to fit their prior knowledge. For example, #16 continued with the eclipse model that he first used on the midtest (refer to his diagram in Figure 34 on the next page), but he elaborated upon it by showing the moon orbiting the Earth, with a different phase at each of eight positions along the orbit. (Refer to Figure 35 on page 188.) His diagram looks similar to the diagram drawn by students with the correct model, only he has rotated the moon's orbit 180° so that phase 1 (new moon) occurs when the moon is opposite the sun.
Figure 34. #16's midtest diagram, showing (a) new moon and (b) waxing crescent, according to the eclipse model.
Three students had no model on the posttest. One of these students, #58, also had no model on the pretest and was absent for the midtest. #61 had no model on the pretest and showed very incomplete fragments on the midtest. #23 knew only that the moon orbits the Earth on the midtest, and she dropped that proposition by the posttest, leaving only a diagram showing a celestial body orbiting the sun. Since it was unclear that this body was the moon, she was classified as having no model instead of the heliocentric model. Previous statements by her,
however, indicated that she had the elements of a heliocentric model. In her midtest, she states "...because the moon revolves around the sun, and the sun takes the place of the moon." This statement reveals a link between the common misconception that the moon substitutes for the sun at night and a version of the heliocentric model, since if the moon revolves around the sun, it can replace the sun every time it is between it and the Earth.

**Consistency**

Overall, student responses were fairly consistent. Once again, most inconsistencies were apparent in the eclipse models. This was especially evident for those students who learned enough of the correct model to alter but not to eliminate their eclipse notions.

**Completeness**

The models of students in the "correct" group had complete discipline-defined cores (by definition) and fairly complete (72%) derived proposition sets, as shown in Table 5 on the next page.
Table 5

Completeness of posttest responses as a function of model type

<table>
<thead>
<tr>
<th>Model</th>
<th>n</th>
<th>DiCore</th>
<th>DiElab</th>
<th>AltCore</th>
<th>AltElab</th>
<th>Obs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>11</td>
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<td>0.72</td>
<td>0.25</td>
<td>0.00</td>
<td>0.94</td>
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<tr>
<td>Eclipse</td>
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<td>0.30</td>
<td>0.23</td>
<td>0.50</td>
<td>0.31</td>
<td>0.78</td>
</tr>
<tr>
<td>Fragments</td>
<td>35</td>
<td>0.39</td>
<td>0.44</td>
<td>0.24</td>
<td>0.00</td>
<td>0.97</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Students with the eclipse model seemed to have alternative cores that were somewhat incomplete (50%), but had somewhat more complete than expected discipline core (30%) and derived propositional sets (23%). The added completeness of correct propositions may result from students incorporating correct knowledge into their eclipse models.

Students with fragments had incomplete cores. This is perhaps because the fragments group was larger on the posttest and included students who only knew the fact that the moon orbits the Earth.

As Table 5 shows, by the time of the posttest, most students had very complete knowledge of the domain of observations.
Correctness

Once again, student responses were mostly correct, with the few incorrect propositions coming mostly from students with alternative models.

Summary of Results for Question 1c.

By the end of instruction, the students' knowledge was more complete and correct than it was before and during instruction. Their familiarity with the domain of the observations was nearly complete and very accurate. Most were able to apply the model of the phases to make predictions about the moon's position at different times and phases. The majority of students (n = 35) had fragments of the correct model. Many of that majority (21 out of the 35) said that the phases were caused by the moon going around the Earth, in most cases also showing the moon's position at various phases. Others in the fragments group had models that were nearly complete, but were missing a key proposition.

As of the posttest, eleven students met the requirements for the correct model. Five students were persistent enough to have eclipse models. Since these students had been exposed to instruction about the correct model, they often did assimilate some correct propositions to their models. This was done either by inconsistently stating these correct propositions along with their eclipse
propositions, or by changing the propositions to conform to their pre-existing notion.

Knowledge Claims for Question 1c.

1. The majority (35 out of 54) of the students taking both the pre and posttests finished instruction with fragments of the correct model. 11 out of the 54 students taking both the pre and posttests finished instruction with the correct model. 5 out of the 54 students taking both the pre and posttests finished instruction with the eclipse model.

2. Models were mostly consistent. The inconsistencies were found in the models of those students who maintained their eclipse models despite instruction. These students combined correct and incorrect propositions to form models that were occasionally inconsistent. To reduce inconsistency, at least one student changed the newly added proposition from the correct model to conform to his incorrect model.

3. Student knowledge was more complete than it was on the midtest and pretest.

4. Student knowledge was still correct, except for the knowledge of those students who maintained the eclipse model.
Question 2. What changes in the content of students' knowledge can be documented after instruction based on a conceptual change model, and how do those changes compare to the changes predicted by the model?

Refer to Appendix G for pictorial representations of pretest to posttest model changes experienced by students. Also, see Figure 36 on the next page for a summary of the model changes, propositional deletions and additions and the types of changes (accommodation, assimilation, etc.) that occurred from the pretest to the posttest. These changes are discussed further under the headings based upon the students' initial (pretest) model.4

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4The data for seven students who were not present at the posttest are not included in this part of the analysis.
<table>
<thead>
<tr>
<th>#</th>
<th>Model#1</th>
<th>Model#2</th>
<th>Model#3</th>
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<th>DiElab</th>
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<td>-2</td>
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<td>-3</td>
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<td>-1</td>
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<td>Inc Accomm</td>
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<td>-1</td>
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**Figure 3.6.** Pre to post propositional changes.
Key to figure 36:

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<td>The Earth rotation model</td>
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<td>Fragments of the correct model</td>
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<td>Double moon model</td>
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<td>Helioc.</td>
<td>Heliocentric model</td>
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<td>Incomplete accommodation</td>
</tr>
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<td>Accomp</td>
<td>Accommodation</td>
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</table>

The DiCore, DiElab, AltCore and AltElab columns represent the sum of individual core and derived proposition changes that took place between the pretest and the posttest.

DiCORE13 Change in discipline core propositions (DiHaf+DiSee+DiEMS+DiOrb).

DiElabl3 Change in discipline derived propositions (DiExp+DiAll).

AltCORE13 Change in alternative core propositions (EcHaf+EcSee+EcEMS+DiOrb).

AltElabl3 Change in discipline derived propositions (EcExp+EcAll).

The Correct Model

Only one student (#12) started instruction with the correct model, and he maintained his correct model throughout instruction. His core remained unchanged, and he added derived propositions relating to the positions and
explanations of each phase. It would have been impossible for him to add correct core propositions since, by definition, the core proposition set for students with the correct model is complete.) Assimilation of derived concepts to a correct core is apparent.

**Alternative Models**

Three alternative models appeared in the pretest: earth rotation \( n=1 \), eclipse \( n=8 \), and mixed eclipse/correct \( n=1 \). Earth Rotation \( n=1 \)

Only one student (#48) started instruction with the Earth Rotation model. By the posttest, he had accommodated to the correct model. This change, which involved deleting an incorrect proposition relating to his alternative model and adding correct propositions, is a case of accommodation.

#48 had a strong base of correct propositions upon which to build. He added to that base the proposition that the phase depends upon the part of the lit side we can see (DiSee), while subtracting the incorrect proposition related to his previous alternate "Earth rotation" theory.

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5#12 did delete some derived propositions on the midtest. These deletions included references to and explanations of some of the phases.

6The one student starting with the mixed eclipse/correct model was not included in this analysis, since he did not take the posttest.
Although by definition he accommodated, changes that occurred were not wholesale core substitutions; they were the deletion of one incorrect proposition and the addition of one correct proposition (as well as the addition of several consistent derived propositions.) This more subdued example of accommodation is consistent with the "mini-revolutions" described by Kuhn and with Posner's statement that conceptual change occurs against a background of stable propositions. A graphic illustration of these changes can be found in Figure 37 on the next page.
### Eclipse (n=8)

Eight students began instruction with the eclipse model. Half of these students (n=4) accommodated completely to the correct model. Three students underwent incomplete accommodation, and one student underwent no change.

**Accommodation (n=4)**. Of the four students who accommodated completely, one (#50) accommodated as early as the midtest, a second (#26) partially accommodated on the

---

**Figure 37.** Block diagram showing deletion and addition of propositions for #48.
midtest and two students (#53 and #60) did not accommodate until after the midtest.

The student (#50) who accommodated early provides an interesting example of conceptual change. On her pretest, she wrote,

The moon also travelling in orbit move about the earth when the earth is between the sun and the moon we have a new moon phase with no sunlight reflecting off the moon. When the moon is between the Earth and the sun it's full moon with the sun reflecting off or lighting the moon.

Her statement indicates the presence of the eclipse core propositions (EcHaf), as well as an added "earthshine" proposition stating that sunlight reflects off the Earth and lights the moon.7

By the midtest, she had deleted all references to the eclipse cause and had accommodated to the correct model by adding all of the necessary correct model core propositions. Her earthshine notion, although incorrect, 

7The earthshine described by students with the eclipse model would not be bright enough to cause a full moon. Earthshine is, however, a real phenomenon in which the moon is illuminated by the Earth. It is noticeable during crescent phase as a pale blue glow on the unlit portion of the moon. The eclipse and earthshine notions are very compatible, since earthshine explains why the moon would be fully illuminated when it is between the Earth and sun. Students holding the eclipse model who do not refer to the earthshine proposition usually have difficulty explaining all of the phases while simultaneously believing that each phase corresponds to an equal angle around the moon's orbit.
may in this case have helped her accommodate to the correct model; both the correct model and the earthshine notion include the concept that the moon shines by reflected light.

Figure 14 on page 148 shows that on the midtest she had some fuzzy notions mixed with her correct model; she confused the "dark" side with the "far" side.8 Her earlier belief in the earthshine notion may be the cause of this confusion of the dark and far sides since earthshine implies a dark side unlit by the Earth.

Her posttest diagram of Figure 38 on the next page is similar to that of Figure 14, except that her shading shows that she had deleted her fuzzy notions about the shading of the moon; the moon's shading clearly covers the half opposite the sun. She had deleted an incorrect proposition to leave a more clearly correct version of the correct model. A block diagram illustrating the changes undergone by #50 can be found in Figure 39.

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8This misconception is a common one among introductory astronomy students.
Figure 38. #50's posttest model diagram.
Figure 39. Block diagram showing deletion and addition of propositions for #50. The arrow between earthshine and dark side shows possible links between these two propositions.

The case of student #53, who maintained her eclipse model through the midtest before accommodating to the correct model, is also interesting because it provides further insight into conceptual change. On the pretest, #53's apparent commitment to the equipartitioned angles
caused her difficulties in accounting for certain phases. (Refer to Figure 4 on page 121 for #53's pretest diagram.) For example, her statement, "6-8 may actually be describing a solar eclipse," a statement made on an occasion when she presumably knew that a solar eclipse is not the phenomenon she was asked to explain, seems to indicate uncertainty about her answer. She partially solved this particular problem by explaining one of the quarter phases according to the correct model; however, uncertainty may have still existed, especially since the diagram itself is very unparsimonious with regard to the positions of the moon, Earth and Sun: there is no clear orbit to be found.

Eventually, further instruction reinforced the self-generated correct proposition (the illustration of the first quarter moon according to the correct model) that arose in the midtest. Her accommodation to the correct model may then have been guided and made intelligible by this self-created notion. In addition, her accommodation may have received support from correct propositions (that the moon orbits the Earth) that were already firmly understood, since they are part of the eclipse model.

Incomplete Accommodation (n=3). Three students (#32, #17, and #15) were dissatisfied enough with their eclipse cores to drop them, but they did not accommodate to the correct model: they showed only fragments on the posttest.
No Chance (n=1). One student (#14) maintained her eclipse model throughout the course, falsely assimilating correct propositions to her incorrect core.

Fragments (n=12)

Of the twelve students with fragments, ten assimilated correct propositions, and two accommodated incorrect core propositions by the posttest.

Assimilation (n=10).

Ten students starting with fragments assimilated correct propositions by the end of instruction.

Those ending with the correct model (n=3). Three of the students starting with fragments assimilated enough core propositions to form the correct model. Two of these students (#29 and #3) assimilated gradually, showing fragments on the midtest. The third (#24) was not present for the midtest, so her path of assimilation is unknown.

Those maintaining fragments (n=4). Four students (#4, #13, #27, and #52) maintained fragments throughout instruction. Within this group, some propositions were deleted and others added, but the overall change in correct propositions was positive. With the exception of an increase in the DiAll propositions (all phases accounted for, whether explained correctly or not), no obvious pattern to the deletions and additions emerged. The increase in DiAll is due to the instruction students were
given about the sequence of phases; they knew that their model needed to refer to the phases in some way.

Those who developed alternative models. Three other students (#8, #33, and #59) of the fragments group showed alternative (eclipse and heliocentric) core propositions on the midtest but dropped those propositions to return to fragments, while still gaining in the overall number of correct propositions.

Accommodation (n=2)

The other two students starting with fragments accommodated propositions of an alternative (eclipse) model. One student (#16) accommodated the eclipse model as early as the midtest. The other student (#45) developed an alternative (double moon) core on the midtest and changed to the eclipse model on the posttest. As can be seen by comparing her posttest diagram of Figure 40 to her midtest diagram of Figure 25 on page 166, she changed her overall theory very little in switching from the double moon theory to the eclipse theory. The only real switch she made was deleting any written reference to the two moons (new and full) that she had mentioned on the midtest. She still had the same difficulty accounting for certain phases, especially phases in which the terminator should be straight, but the edge of the Earth is round. Her case exemplifies a model type changing due to a minor
propositional deletion, whereas the overall structure remained fundamentally the same.
No Model

The largest subgroup of students began instruction with no model (n=32, counting just those who took both the pretest and the posttest). These students either assimilated correct propositions or underwent no change.

Assimilation

Nearly all students (29 out of 32) who began instruction with no model assimilated propositions to end up with some knowledge of the lunar phases. Two of the students who assimilated added enough propositions to qualify as having the correct model. One of these two students (#35) gradually assimilated, showing fragments on the midtest and the correct model on the posttest. The other student ending with a correct model (#47) was absent for the midtest, so his pattern of assimilation is unknown.
Two other students starting with no model added the wrong propositions, qualifying them for the eclipse model. One of these students, #2, developed the eclipse model for the midtest and maintained this alternative model on the posttest. The other student ending with the eclipse model (#28) was absent for the midtest, so her history of conceptual change is untraceable.

The majority of students starting with no model (25 out of 32) had fragments by the time of the posttest. In fact, 7 of these 25 assimilated fragments by the midtest. Most students in this group did most of their assimilating early; their posttest responses are not more complete than their midtest responses. By the midtest, students within this group learned the fact that the moon orbits the Earth (DiOrb) and that eight phases must be accounted for around the moon's orbit (DiAll).

One case within this subgroup stands out because it involved absolutely no change in the propositions from midtest to posttest. #57 seemed to have a very clear understanding of the cause of the lunar phases but did not extend that understanding to an explanation of any individual phase; therefore, she was never classified as having the correct model. Nevertheless, the strength of her model is evidenced by the fact that she kept the same,
fairly complete and detailed explanation from the midtest through the posttest.

Students who developed alternative cores on the midtest.

Twelve of the 25 students who changed from no model to fragments temporarily added eclipse cores as of the midtest but accommodated the correct model incompletely, ending with fragments. Between the midtest and the posttest, students in this group deleted eclipse core and eclipse-derived propositions and added mostly correct derived propositions. The eclipse proposition most commonly deleted was the central causal proposition that the darkening on the moon is caused by blockage of sunlight by the earth or by the Earth’s shadow (EcHaf). The correct propositions most commonly added related to the positions of the moon at the various phases (DiAll). For example, #46's midtest and posttest diagram and accompanying statements, seen in Figure 41 on the next page, show deletion of reference to the eclipse cause and change to the correct positions for the phases. Within this subgroup, alternative core propositions were deleted; the propositions added were the discipline-derived ones.
"The moon reflects the sun and when the earth is in the way it shades out part of the moon."

"The moon going around the Earth."

No Change (n=3)

One student, #58, began instruction with no model, did not take the midtest, and ended instruction with no model.
Two students (#61 and #23) assimilated a few fragments of the correct model and then deleted those fragments by the posttest, returning them to the state of having no model. If these students' paucity of correct propositions is related to a weak understanding of the correct model, then it is not surprising that they deleted those few propositions they did have.

#61's response to question 2 on the posttest, which asks students to describe their models, was blank. #23's response showed an unnamed celestial body orbiting the sun. Both may have felt enough dissatisfaction about their own models that they decided to draw no diagram or an ambiguous diagram in answer to these questions. Perhaps the instruction caused these students to be dissatisfied with any existing models they may have had, not because they were wrong but because they were clearly incomplete and incapable of solving problems. The students may have failed to act on that dissatisfaction by assimilating more correct propositions or by substituting an intelligible alternative.
Knowledge Claims Derived From Question 2 Results

Several knowledge claims derive from the results of Question 2:  

1. Eight of the nine students beginning with alternative frameworks (and therefore expected to accommodate) did accommodate to the correct model by the end of instruction. This result was found to be significant, using the binomial test, at better than the 0.02 level.  

2. Ten of the twelve students beginning with fragments (who were therefore expected to assimilate) did assimilate correct propositions by the end of instruction. This result is significantly better than what would be predicted by chance, under a $\chi^2$ test with 1 df, at better than the 0.05 level.  

3. Twenty-nine out of the thirty-three students beginning instruction with no model added correct propositions by the posttest.  

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9 The numbers given in this section are for the 54 students who took both the pretest and the posttest.  
10 The binomial test was used because of the small expected frequencies. For more information about this test, refer to Siegel (1956), pages 36-42, and page 250.  
11 The Chi-Square test was again conducted on a 1 X 2 matrix, with one column for assimilation and one for non-assimilation. (The expected value according to chance was 6 students per column.) With the Yates correction applied, the resulting $\chi^2$ value would be 4.08, and 3.84 is the value of $\chi^2$ at $p=0.05$. 
4. Conceptual change theory does not predict that students would develop alternative models during instruction, but it does predict that they should accommodate any alternative models they do have. Fifteen of the eighteen students who began with fragmentary knowledge or no knowledge and developed an alternative framework did not sustain that framework under the instruction. This result is significant, using the $\chi^2$ test with 1 df, at better than the 0.05 level.\textsuperscript{12}

5. For those who began with fragmentary knowledge or no knowledge and did not develop an alternative view early (n=25), the average increase in core propositions was from 13\% to 50\%, and the average increase in derived propositions was from 3\% to 42\%. (Refer to Figure 42 on the next page.)

\textsuperscript{12} The Chi-Square test was once again conducted on a 1 X 2 matrix, with one column for accommodation (or incomplete accommodation) and one for non-accommodation. (The expected frequency according to chance was 9 students per column.) With the Yates correction applied, the resulting $\chi^2$ value would be 6.72, and 3.84 is the value of $\chi^2$ at p=0.05.
Figure 42. Pretest and posttest completeness of core and derived propositions for students who never developed alternative models.

6. Overall, students who began instruction with alternative models gained the greatest number of propositions by the posttest. The one student with the Earth Rotation model increased his core and derived propositional sets from 0 to 75%, a value significant at better than 0.01. The eight students having the eclipse model increased their core propositions from 16% to 78%, and their derived propositions from 2% to 68%, both results significant at better than 0.01. In contrast, students with fragments (n=12) increased their cores from 46% to 56%, a change

13 The significance values given in this section were calculated using the Kolmogorov-Smirnov test (Siegel, 1956.)
significant at $0.01 < p < 0.05$, and their derived proposition sets from 8% to 45%, a change significant at better than 0.01. Students starting with no model ($n=32$) increased their cores from 0% to 36%, and their derived proposition sets from 0% to 40%, both changes significant at better than the 0.01 level (Refer to Figure 43 on the next page).
Figure 43. Percent core and derived completeness, pre and post, as a function of model type.

7. When accommodation was seen, it was not the wholesale accommodation analogous to the paradigm shifts initially described by Kuhn, but the step-by-step accommodation analogous to the mini-revolutions described by Kuhn.
Chapter 5
DISCUSSION OF RESULTS

Posner et al (1982) propose the elements of a theory of conceptual change. According to their theory, conceptual change in students is analogous to the larger scale conceptual change that takes place in science as a whole. Specifically, Posner et al focus on the conceptual change process of accommodation, which they view as analogous to Kuhn's paradigm shifts. They suggest teaching for accommodation in order to create the radical change necessary to overcome the misconceptions so prevalent and tenacious in science students.

Certain predictions can be derived from the Posner et al theory. These relate to cases for which teaching for accommodation was intended, to cases for which it was not intended, and to the general nature of accommodation.

1. Under optimal conditions students with alternative theories should accommodate when they are taught in a way that is consistent with the Posner et al conceptual change model. The optimal conditions are that a student must experience intended anomalies as such, must believe that reconciling the anomaly with his or her current conceptions is important, must accept that inconsistencies need to be reduced, and
must not falsely assimilate new information into an incorrect core.

2. Since Posner et al and other conceptual change theorists recommend teaching for accommodation without restriction, one might assume that this method will work for all students, regardless of their initial state of knowledge. Moreover, since Posner et al view assimilation and accommodation as different only in degree, one can predict that teaching for accommodation should also work for those who need to assimilate. In addition, this suggests that this method might work best for those with alternative models.

3. Posner et al state that accommodation takes place against a background of current conceptions; therefore, one should see evidence that accommodation involves additions and deletions of propositions against a background of stable propositions.

Few studies have evaluated these predictions by trying instruction according to the Posner et al theory and evaluating the outcome in light of this theory. In this study, the instruction incorporated the four basic elements suggested by Posner: Dissatisfaction was created by having students try to answer questions on a pretest, to explain their observations of the moon, and to experience anomalies
as they try to explain the phases using their alternative models. **Intelligibility** was created by giving students the opportunity to use a model that was concrete and understandable from the Earthbound (geocentric) perspective. **Plausibility** and **fruitfulness** were assured by keeping the explanations concrete and by showing how well they explain the observations and allow for prediction of other observations.

The outcomes of instruction were evaluated by using the definitions of accommodation and assimilation derived from the Posner et al theory to analyze the changes that occurred as shown by the tests. Results could then be compared to the predictions of that theory.

The results of this analysis indicate that changes which occurred in students' knowledge were consistent, though in some cases in unexpected ways, with the predictions suggested by the Posner et al theory. These predictions are restated below, followed by discussion of the results that are congruent or incongruent with these predictions and by the implications these results suggest.
Prediction #1: Under Optimal Conditions Students With Alternative Frameworks Should Accommodate When Taught in a Way that is Consistent with the Posner et al Conceptual Change Model

Accommodation as defined in this study occurs when students change their core concepts by deleting their incorrect causal propositions and replacing them with the correct ones. A weaker form of accommodation, partial accommodation, involves deleting those incorrect propositions but not adding enough of the correct ones to build a complete correct core.

According to the Posner et al model, teaching for accommodation should help students who have alternative frameworks overcome those misconceptions by accommodating to the correct model. In this study, nine students began instruction with alternative frameworks and were therefore expected to be the primary beneficiaries of this instructional method. ¹

Consistent with the prediction that they should accommodate, eight of the nine students starting instruction with alternative models did not sustain those alternative models throughout instruction. This result is significant at the 0.02 level using the binomial test.

¹Ten students began instruction with alternative frameworks, but only nine students completed instruction.
These eight students deleted their incorrect core proposition sets; hence, they accommodated either completely or partially. Four of these eight students accommodated completely: they ended instruction with the correct model. The other four accommodated partially: they deleted their alternative cores but did not adopt the correct model. These four students were left with fragments of the correct model, but in every case they added both correct core and correct derived propositions to their proposition sets.

These results suggest that teaching for accommodation has promise, especially in cases where students enter instruction with alternative models. It appears to be an effective means of causing students to let go of their incorrect propositions, add correct propositions, and in some cases go on to develop the correct model.

**Prediction #2: Teaching for Accommodation Should Work for Everyone. Although It Should be Most Effective for Students Who Have Alternative Models**

The results of this study indicate that teaching for accommodation did work for everyone. Accommodation is the desired outcome for students with alternative models. Students who needed to accommodate did accommodate (see prediction #1 above). Assimilation, which is the adding of core or derived propositions that are consistent with the
current core, is the desired outcome for students with fragments of the correct model. Students who needed to assimilate did add core and derived propositions that were consistent with their current cores as a result of teaching for accommodation. Ten of the twelve students beginning with fragments did assimilate by the posttest. This result is significant at the 0.05 level using the $\chi^2$ test with 1 df. Of the 33 students who began instruction with no model, 29 added correct propositions by the posttest.

The gains of students who assimilated by the posttest are discussed below, according to whether or not they developed alternative models during instruction. In addition, the overall gains for all students, with and without initial alternative models, are discussed.

Students Who Developed Alternative Models During Instruction

In 18 cases, students who began instruction with no knowledge or fragments unexpectedly developed alternative models by the midtest. Consistent with the earlier prediction (#1 above) that students with alternative models should accommodate, 15 out of these 18 students deleted their cores by the posttest. This result is significant at the 0.05 level using the $\chi^2$ test with 1 df. All 15 students partially accommodated, ending instruction with fragments of the correct model. Seven of these 15 students went on
to add correct core propositions, and 13 of these 15 went on to add correct derived propositions.

Posner does not address the issue of alternative frameworks that arise during instruction, but the problem of emerging alternative frameworks clearly needs to be solved and can be addressed by teaching for accommodation. This study indicates that in cases in which these alternative models arise, teaching for accommodation can help to overcome these misconceptions.

Students Who Did Not Develop Alternative Models During Instruction

Consistent with prediction #2, teaching for accommodation was moderately successful for the 25 students who began with fragmentary knowledge or no knowledge and did not develop an alternative view early on in the instruction. The average increase in core propositions was from 13% to 50%, and the average increase in derived propositions was from 3% to 42%. (Refer to Figure 42 on page X.) Teaching for accommodation helped in the sense that students assimilated new propositions to make more complete core and derived proposition sets.

Although not addressed by conceptual change theorists, some aspects of conceptual change theory that apply to accommodation may, then, also apply to assimilation. First, dissatisfaction with existing conceptions could
drive assimilation of additional propositions just as easily as it drives accommodation of a new core. This is because dissatisfaction in the simplest form may be the simple inability to describe and explain the observations. Second, new correct propositions would presumably be readily intelligible and plausible since these propositions are already consistent with students' initial (though limited) knowledge. Finally, fruitfulness in explaining and predicting would reinforce the correct core students are building and encourage them to use their model in new situations. The implication here is that teaching for accommodation may be tried with students who need to assimilate since this teaching method may work for them as well.

A second implication is that more research needs to be done to refine conceptual change theory as it applies to assimilation: much of what little knowledge students had upon entering instruction was correct and would therefore have served as an appropriate base upon which new propositions could have been assimilated.

Gain in Knowledge of Students Beginning with Alternative Models Compared to Those Who Did Not

Overall, students who began instruction with alternative models gained the greatest number of propositions by the posttest. The one student with the
Earth Rotation model increased his core and derived propositional sets from 0 to 75%. The eight students having the eclipse model increased their core propositions from 16% to 78% and their derived propositions from 2% to 68%. In contrast, students with fragments (n=12) increased their cores from 46% to 56% and their derived proposition sets from 8% to 45%. Students starting with no model (n=32) increased their cores from 0% to 36% and their derived proposition sets from 0% to 40% (Refer to Figure X on page X.) Consistent with prediction #2, students with alternative frameworks learned the most under instruction designed to create accommodation.

The striking implication of the results described under predictions #1 and #2 above is that although instruction was designed to benefit the students starting instruction with alternative models the most, and it did (they both accommodated and added the most correct propositions), it also, in accord with prediction, benefited other students in various ways not addressed directly by Posner et al. Students who developed alternative models during instruction partially accommodated to the correct model. Students who did not develop alternative models still gained correct propositions. Therefore, virtually all students benefited in some way from instruction designed according to the Posner et al theory of conceptual change.
Prediction #3: We Should See Evidence that Accommodation Involves Additions and Deletions of Propositions Against a Background of Stable Propositions

To determine whether changes involving proposition addition and deletion occur against a background of stable propositions, it is necessary to examine, at high magnification, the cases of accommodation and partial accommodation, keeping track of propositions that change and those that remain. If cases can be found where a base of propositions remain but one or two propositions change, this would be evidence that prediction #3 is supported.

Consistent with prediction #3, in several cases discussed in the results chapter, change occurred in the piecemeal manner described above. In these cases, propositions often were found to bridge two successive models.

Sometimes correct notions appeared in earlier tests that may have helped the student to bridge the gap between his or her model and the correct model. For example, one student had a midtest eclipse model diagram in which some of the phases were correctly explained. These correctly explained phases could have served as advanced organizers to help make the new model more intelligible.

In many cases incorrect models incorporated several correct propositions, making accommodation less drastic and
hence easier. The eclipse model is one such model; it includes the correct proposition that the moon orbits the Earth. To accommodate to the correct model, students with the eclipse model need only subtract their incorrect eclipse proposition and add more correct propositions.

These results suggest that teaching for accommodation isolates just those propositions that need to be changed and helps students build new models based upon the correct propositions they already have. This implication is especially important, since Posner et al recommend teaching for accommodation as a general strategy for creating major changes in conceptual structure. Although one of the tenets of conceptual change theory is that new knowledge is constructed using current knowledge, the Posner et al strategy makes no reference to the base of existing correct knowledge.

Implications for Teaching

The practical implications of this study established so far are:

1. Teaching for accommodation has promise in cases where students enter instruction with alternative models. The findings of this study suggest that teaching for accommodation will encourage students to let go of their incorrect propositions, add correct propositions, and in some cases go on to develop the correct model.
2. Teaching for accommodation has promise even in cases in which the majority of students may not initially have alternative models, since some proportion of those students may develop alternative models during instruction. The results of this study indicate that teaching for accommodation will at least help these students delete their incorrect propositions and add correct ones.

3. Teaching for accommodation works moderately well in cases in which students do not initially have alternative models; students assimilate some correct propositions.

4. Students who have alternative models usually have a base of correct propositions. Teaching for accommodation should focus not only upon changing the incorrect propositions in these alternative models (as the Posner et al strategy suggests) but upon adding new correct propositions to that base of current correct propositions.

Other practical implications that are not derived directly from the discussion in this chapter are nevertheless important:

5. Testing of prior knowledge is essential for understanding what propositions need to be challenged and what propositions need to remain.

6. Although not discussed by Posner et al, having students develop a base of observations before they develop their own models is important; this base gives students
something to explain and a framework upon which to organize their explanations. Many students who began instruction with no model were unable to formulate a model without knowing the observations to be explained.

Directions for Further Research

In addition to these practical implications, this study suggests directions for further research.

1. Research is needed to refine conceptual change theory as it applies to assimilation. In this study, those who had alternative models deleted their incorrect propositions and surpassed those who had correct but very incomplete knowledge. Conceptual change theory can suggest methods that would focus on those who do not have alternative models so these students have the same chance to form the complete, correct model as those who began with alternative models.

2. Three closely related group processes influenced the students in this study and should be investigated in future studies:

   a. Group communication and conceptual change theory. Future studies could investigate the spread of ideas among members of a group engaged in learning based upon conceptual change. It is possible that most individuals who showed alternative models on the midtest developed these models spontaneously.
However, it is more likely that, since students were learning in groups, one or two people in each group developed the wrong idea, and it spread to the rest of the group members.\(^2\)

b. **Collective rationality.** Future studies could investigate rational decision making by groups. Shulman and Carey (1984) suggest that the "collective rationality" of a group can overcome the individual's rational limitations. In this study, the group-derived alternative models shown on the midtest were incorrect, but they were more rational models than individual models revealed by the pretest. (These models could explain at least some of the observations.)

3. **Conformity and Peer Pressure.** Future studies could investigate the effects that conformity and peer pressure have on groups exposed to instruction based upon conceptual change theory.\(^3\) In this study, there was very little disagreement among group members as they discussed their models.

Studies of these kinds would be especially relevant to the Posner et al theory since their theory, while it

\(^2\) The wrong (eclipse) model may have been as contagious as it was because it is simpler than the correct model.

\(^3\) For further discussion of group effects such as conformity and group polarization, see Myers (1987, 1978).
addresses accommodation and assimilation in individuals, is based upon conceptual change occurring in a community of scientists.

This study demonstrates, through rich description of changes in student knowledge, that instruction based upon conceptual change theory as described by Posner et al was effective in encouraging accommodation in students who needed to accommodate and assimilation in students who needed to assimilate. The results of this study suggest that teaching for accommodation is appropriate in all cases, whether students begin with alternative frameworks or not. This study also suggests two promising directions for future research: studying the application of conceptual change theory to assimilation and exploring the effects of group processes upon accommodation and assimilation of individuals.
REFERENCES


## Appendix A. Table Propositions from textbooks

<table>
<thead>
<tr>
<th>PROPOSITION</th>
<th>ABELL</th>
<th>PASACH.</th>
<th>TYPE OF PROPOSITION</th>
</tr>
</thead>
<tbody>
<tr>
<td>moon not luminous-illuminated by sun</td>
<td>x</td>
<td>1/2</td>
<td></td>
</tr>
<tr>
<td>only 1/2 illuminated</td>
<td>x</td>
<td>x 1/2</td>
<td></td>
</tr>
<tr>
<td>1/2 facing sun illuminated</td>
<td>x</td>
<td>x 1/2</td>
<td></td>
</tr>
<tr>
<td>phase depends upon how much of illuminated 1/2 we see</td>
<td>x</td>
<td>SEE</td>
<td></td>
</tr>
<tr>
<td>moon same direction of sun-daylight part turned away</td>
<td>x</td>
<td>EMS</td>
<td></td>
</tr>
<tr>
<td>dark side faces us when daylight part is turned away</td>
<td>x</td>
<td>x SEE</td>
<td></td>
</tr>
<tr>
<td>dark side is not visible</td>
<td>x</td>
<td>SEE</td>
<td></td>
</tr>
<tr>
<td>when not visible, we see new moon</td>
<td>x</td>
<td>x SEE, DIAL, DEXP</td>
<td></td>
</tr>
<tr>
<td>next, moon rotates to 45°</td>
<td>x</td>
<td>EMS</td>
<td></td>
</tr>
<tr>
<td>we now see a small part of daylight part</td>
<td>x</td>
<td>x SEE</td>
<td></td>
</tr>
<tr>
<td>when we see small part of daylight part-waxing cres.</td>
<td>x</td>
<td>x SEE, DIAL, DEXP</td>
<td></td>
</tr>
<tr>
<td>when we see half of daylight part-first quarter</td>
<td>x</td>
<td>x SEE, DIAL, DEXP</td>
<td></td>
</tr>
<tr>
<td>sun's rays to Earth and moon are parallel</td>
<td>x</td>
<td>SEE</td>
<td></td>
</tr>
<tr>
<td>after 1/4 moon, we see more of daylight part-wax. gibb.</td>
<td>x</td>
<td>x SEE, DIAL, DEXP</td>
<td></td>
</tr>
<tr>
<td>2 weeks after new moon-moon opposite sun</td>
<td>x</td>
<td>x EMS</td>
<td></td>
</tr>
<tr>
<td>when moon opposite sun, we see full moon</td>
<td>x</td>
<td>x EMS, DIAL, DEXP, DISEE</td>
<td></td>
</tr>
<tr>
<td>moon is a sphere</td>
<td>x</td>
<td>x 1/2</td>
<td></td>
</tr>
<tr>
<td>side facing away from sun is dark</td>
<td>x</td>
<td>x 1/2</td>
<td></td>
</tr>
<tr>
<td>depends upon relative orientation of M, S, E</td>
<td>x</td>
<td>EMS</td>
<td></td>
</tr>
<tr>
<td>phases continue, new amount of light decreases-waning</td>
<td>x</td>
<td>SEE, DIAL</td>
<td></td>
</tr>
<tr>
<td>after full, waxing gibbous</td>
<td>x</td>
<td>SEE, DIAL</td>
<td></td>
</tr>
<tr>
<td>1 week after full, 3rd quarter</td>
<td>x</td>
<td>x SEE, DIAL</td>
<td></td>
</tr>
<tr>
<td>after that, waxing crescent</td>
<td>x</td>
<td>SEE, DIAL</td>
<td></td>
</tr>
<tr>
<td>back to new, 29.5 days later</td>
<td>x</td>
<td>DIAL</td>
<td></td>
</tr>
<tr>
<td>moon goes around the earth</td>
<td>x</td>
<td>x Dio</td>
<td></td>
</tr>
<tr>
<td>each phase explained</td>
<td>x</td>
<td>x DIAL</td>
<td></td>
</tr>
<tr>
<td>Direction of motion counterclockwise as seen from N.</td>
<td>x</td>
<td>x DIRECTION</td>
<td></td>
</tr>
<tr>
<td>Appearance of each phase shown pictorially</td>
<td>x</td>
<td>x SHAPE-COMPLETE</td>
<td></td>
</tr>
<tr>
<td>Shapes of each phase are correct</td>
<td>x</td>
<td>x SHAPE-CORRECT</td>
<td></td>
</tr>
<tr>
<td>Direction of phase cycle shown from wax. to waning</td>
<td>x</td>
<td>x SHAPE-DIRECTION</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix A. Key to Table

<table>
<thead>
<tr>
<th>Proposition Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2 (DiHaf)</td>
<td>Half of the moon is illuminated by the sun.</td>
</tr>
<tr>
<td>See (DiSee)</td>
<td>We see part of the illuminated half.</td>
</tr>
<tr>
<td>EMS (DiEMS)</td>
<td>The relative positions of the Earth, Moon, and Sun determine the portion of the half we see.</td>
</tr>
<tr>
<td>DiALL</td>
<td>Each phase is represented in some way.</td>
</tr>
<tr>
<td>DiExp</td>
<td>Each phase is explained.</td>
</tr>
<tr>
<td>DiOrb</td>
<td>The moon orbits the Earth.</td>
</tr>
<tr>
<td>Direction</td>
<td>Direction of moon's motion counterclockwise as seen from North.</td>
</tr>
<tr>
<td>Shape-Complete</td>
<td>Each phase drawn.</td>
</tr>
<tr>
<td>Shape-Correct</td>
<td>Appearance of each phase shown correctly.</td>
</tr>
<tr>
<td>Shape-Direction</td>
<td>Direction of phase cycle shown from waxing to waning if starting at new moon.</td>
</tr>
</tbody>
</table>
Appendix B. The pretest.

Name____________________

PHASES OF THE MOON- PART I

1. In the circles below, shade out the parts that are not visible to show the complete sequence of the moon's phases, as seen from here on Earth. If you know the names of these phases, give them in the spaces provided (after the word phase), beginning with the new moon. If you know how many days it takes to get from new moon (#1) to each phase, indicate that number in the spaces provided (after the word #Days).

#1  #2  #3  #4

Phase_____ New Phase_____ Phase_____ Phase_____

#Days__ #Days__ #Days__ #Days__

#5  #6  #7  #8

Phase_____ Phase_____ Phase_____ Phase_____

#Days__ #Days__ #Days__ #Days__
2. Draw a diagram and explain in your own words what causes the sequence of phases that you described above. In your diagram, please refer to the phases you shaded above by number (1, 2, 3, 4, 5, 6, 7, 8), explaining how each of those phases were caused. Use arrows to show the direction(s) of motion for any celestial bodies that move.
3. In what direction does the sun appear to move during the day?______

4. Above is a picture of the southern sky, showing the moon. Approximately what time was this picture made? (Circle one)

   6am  9am  12noon  3pm  6pm  9pm  12midnight  3am

   Explain how you arrived at your answer, using both words and diagrams.
5. It is 6 PM and the moon is in the position indicated by the "X" shown in the diagram below. Draw the moon near the X, showing what phase it would be in. Explain how you arrived at your answer, using both words and diagrams.
6. The moon is full and it is midnight (12:00AM). On the diagram below, show what you think the moon will look like and where you think it will be. Explain how you arrived at your answer, using both words and diagrams.

Full moon at midnight.
Name_______________________

PHASES OF THE MOON- PART II

7. Is the moon ever visible during daylight hours? Yes No
Explain your answer, using both words and diagrams.
8. What time is it when the sun is directly South?

9. On the picture below, indicate (by writing “A” and “B” directly on the diagram) the approximate position of the sun at about (A) 3PM and (B) 6PM in early Spring.
10. The picture above shows the Earth and moon as seen by a satellite many thousands of miles above the North Pole of the Earth.

11a. What phase is the moon as seen from the Earth? (Shade out the part that is not visible in the circle below.)

11b. In your own words, and by drawing directly on the diagram at the top of the page, explain your answer to question 11a.
12. Please use the diagram below to answer questions a through e.

12a. What phase is the moon in the picture above?

12b. Indicate (by drawing the letter "A" directly on the diagram above) where you think the moon will be the next day at the same time.

12c. What will the moon look like the next day at the same time? (Shade out the part that is not visible in the circle below.)

12d. Indicate (by writing the letter "B" directly on the diagram at the top of this page) where you think the moon will be about seven days later, at the same time.
12e. What do you think the moon will look like seven days later, at the same time? (Shade out the part that is not visible in the circle below.)

13. When the moon is full, what must be the phase of the Earth as seen from the moon? Please explain your answer, using both words and drawings.
14. The sun is far off to the right of the box. Draw several arrows from the right hand side of the box to show the path (or paths) the sun's light takes to the Earth and the moon.
15. Each diagram below shows the Earth, Moon, and arrows indicating light rays coming from the Sun.

A  B  C  
D  E  F

Which of these diagrams is correct? _____.
Appendix C. Rationales for instructional activities.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Lesson#</th>
<th>Rationale from Conceptual Change Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretest</td>
<td>1</td>
<td>1. Make models explicit, activating prior knowledge, which will be either changed through accommodation or built upon by assimilation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Create dissatisfaction at not being able to explain observations.</td>
</tr>
<tr>
<td>Observing Project</td>
<td>1</td>
<td>Provide observational data base (observations to be explained) that can be used to create dissatisfaction with existing models and satisfaction with new more fruitful model.</td>
</tr>
<tr>
<td>Establish Phases Order</td>
<td>2</td>
<td>Sort phases and establish order of phases according to observations made by class. This set of observations becomes the new set of data to be explained by their current theory and/or the theory they will learn as a result of instruction.</td>
</tr>
<tr>
<td>Group Model Discussions</td>
<td>2</td>
<td>Make models as explicit as possible, activating prior knowledge which will either be changed through accommodation or be built upon by assimilation.</td>
</tr>
</tbody>
</table>
Rationales for instructional activities, continued.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Lesson#</th>
<th>Rationale from Conceptual Change Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midtest Part 2</td>
<td>2</td>
<td>Create dissatisfaction at not being able to explain the now clearly defined observations. (Assuming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>students internalize observations and do not compartmentalize observational and theoretical knowledge.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Also, assuming students are dissatisfied with inconsistencies in their own models as they attempt to</td>
</tr>
<tr>
<td></td>
<td></td>
<td>explain observations using the wrong model.)</td>
</tr>
<tr>
<td>Discussion of Models</td>
<td>3</td>
<td>Make models explicit. Create dissatisfaction by pointing out ways in which observations contradict</td>
</tr>
<tr>
<td></td>
<td></td>
<td>model.</td>
</tr>
<tr>
<td>Cause of Phases Demo</td>
<td>3</td>
<td>Make correct model intelligible, plausible, fruitful by using a plausible analogy (illuminated ping-pong</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ball) that explains phases well.</td>
</tr>
<tr>
<td>Making Predictions</td>
<td>3</td>
<td>Elaborate upon model, making it even more fruitful by having students successfully make predictions.</td>
</tr>
</tbody>
</table>
Appendix D. Part of a page from the catalogue of student responses.

1.10. 11a. Phase of moon as seen from Earth
1.10.1. $11a.$

1.10.2. new moon

1.11. 11b. Explanation
1.11.1. $11b.$

$11b.$

WE SEE THE DARK SIDE

1.11.2. We can only see that part of the moon
1.11.3. that is getting light from the sun.
## Appendix B: Codebook for evaluating student responses.

<table>
<thead>
<tr>
<th>File Category</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Student's name.</td>
</tr>
<tr>
<td>Model Type</td>
<td>Type of model, defined below.</td>
</tr>
<tr>
<td>No Model</td>
<td>No responses to questions: 2, 7, 11b, 13, 14, 15, that give any clues as to the student's internal state of knowledge.</td>
</tr>
<tr>
<td>Correct</td>
<td>DIOrb must be 1, and DIHaf, DISee, or DIEMS must also be 1, at least 1 on DIExp.</td>
</tr>
<tr>
<td>Eclipse</td>
<td>The cause of the phases is related to the shadow of the Earth falling on the moon. EcHaf must be 1.</td>
</tr>
<tr>
<td>Fragments</td>
<td>Elements not definitive of any model in particular are present.</td>
</tr>
<tr>
<td>Heliocentric</td>
<td>Phases are caused by the moon orbiting the sun-earth combination.</td>
</tr>
<tr>
<td>DISha</td>
<td>The shapes of the phases shown are drawn correctly.</td>
</tr>
<tr>
<td>DISha Ref</td>
<td>(Discipline shapes, reference.)</td>
</tr>
<tr>
<td>DICom</td>
<td>Phases shown at right are included. 1 point is given for each phase.</td>
</tr>
<tr>
<td>DIDir</td>
<td>Phases go from waxing to waning when starting at new moon.</td>
</tr>
<tr>
<td>DIHaf</td>
<td>Half of the moon (the half facing towards the sun) is always illuminated.</td>
</tr>
<tr>
<td>DISee</td>
<td>The part of the half that we see determines the phase.</td>
</tr>
<tr>
<td>DIEMS</td>
<td>The relative position of the Earth (E), Moon(M), and Sun(S) determines the part of the half that we can see.</td>
</tr>
<tr>
<td>DIOrb</td>
<td>Some indication is given that the phases have something to do with the moon orbiting the Earth.</td>
</tr>
<tr>
<td>DIExp</td>
<td>One point for each phase explained (This is a measure of completeness &amp; correctness.)</td>
</tr>
<tr>
<td>DIAII</td>
<td>All phases are portrayed. One point for each phase shown in correct position.</td>
</tr>
<tr>
<td>DIPar</td>
<td>Rays from the sun are parallel. One point for answering each question (14 and/or 15).</td>
</tr>
<tr>
<td>DII, DII2</td>
<td>Additional, correct propositions.</td>
</tr>
<tr>
<td>EcHaf</td>
<td>The part of the moon in the shadow of the earth is dark.</td>
</tr>
<tr>
<td>EcSee</td>
<td>Phases are determined by the extent to which the moon is in shadow.</td>
</tr>
<tr>
<td>EcEMS</td>
<td>The extent to which the moon is in shadow is determined by the relative position of the E, M, and S.</td>
</tr>
<tr>
<td>EcExp</td>
<td>The position of the moon at each phase is explained in a way that is consistent with the eclipse model.</td>
</tr>
<tr>
<td>EcAll</td>
<td>All phases possible, given the eclipse model, are explained. 1 point for each phase included.</td>
</tr>
<tr>
<td>OII, OII2</td>
<td>Other (wrong) propositions, inconsistent with any plausible model.</td>
</tr>
</tbody>
</table>
Appendix F. Distribution of model types on all tests.

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Pretest</th>
<th>Midtest</th>
<th>Posttest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct</td>
<td>1</td>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>Double Moon</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Earth Rotation</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Eclipse</td>
<td>8</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td>From Above</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>From Sun</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Written</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eclipse/Correct</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fragments</td>
<td>13</td>
<td>21</td>
<td>35</td>
</tr>
<tr>
<td>DiOrb</td>
<td>6</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>NonDiOrb</td>
<td>7</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>DiHaf</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>NonDiHaf</td>
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<td>16</td>
<td></td>
</tr>
<tr>
<td>Heliocentric</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>No Model</td>
<td>37</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Missing</td>
<td>0</td>
<td>12</td>
<td>.7</td>
</tr>
</tbody>
</table>
Appendix G. Figure 1.
Pretest to posttest model change for students with the correct model.
Appendix G. Figure 2.

Pretest to posttest model change for student starting with Earth Rotation model.
Appendix G. Figure 3.

Pretest to posttest model changes for students starting with the eclipse model.
Appendix G. Figure 4.

Pretest to posttest model changes for students starting with fragments of the correct model.
Appendix G. Figure 5.

Pretest to posttest model changes for students starting with no model.

Correct
n=1
Earth Rot.
n=1
Eclipse
n=8
Fragments
n=12
No Model
n=32

Correct
n=11
Eclipse
n=9
Fragments
n=35
No Model
n=3