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ABSTRACT

Some central issues in discussions of creative processes in science are: (1) the mechanism(s) by which hypothesis formation takes place; (2) the sources of new knowledge during hypothesis formation; and (3) the "Eureka" versus steady accumulation (accretion) issue concerning the pace of change during hypothesis formation. This paper attempts to investigate the question of whether data from transcripts of scientists thinking aloud have the potential to speak to these issues. A case study is examined in which the subject generates a new explanatory model hypothesis--a predictive analogy which describes a hidden process explaining a phenomenon. Findings from the case study appear to show that it is possible to study hypothesis formation and creative insight processes in thinking aloud protocols. The present study suggests a view of hypothesis formation in science that is more complex than can be provided by either an inductivist, rationalist, Eurekaist, or accretionist position alone. Recent analyses of Darwin's thought processes are found to be similar in many respects to the present analysis of thinking aloud data. (Author/YP)

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LEARNING VIA MODEL CONSTRUCTION AND CRITICISM: PROTOCOL EVIDENCE ON SOURCES OF CREATIVITY IN SCIENCE

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Abstract: Some central issues in discussions of creative processes in science are: (1) the mechanism(s) by which hypothesis formation takes place; (2) the sources of new knowledge during hypothesis formation; and (3) the Eureka vs. steady accumulation (accretion) issue concerning the pace of change during hypothesis formation. This chapter attempts to investigate the question of whether data from transcripts of scientists thinking aloud has the potential to speak to these issues. A case study is examined in which the subject generates a new explanatory model hypothesis--a predictive analogy which describes a hidden process explaining a phenomenon.

Observations from the case study indicate the following: (1) "Aha!" episodes are observed which lead to creative insights. It is argued that these can involve fairly sudden reorganizations but do not necessarily involve extraordinary or unconscious reasoning. (2) A new hypothesis can be developed and evaluated by a scientist in the absence of new empirical information via thought experiments and other means. Some of the processes used are neither inductive nor deductive. (3) In particular, analogy generation and other divergent processes can play a role in the generation of new hypotheses. (4) Analogous cases are not only produced by associations to existing cases in memory, but by transformations which can generate newly invented cases. (5) A new explanatory model can be invented via a successive refinement process of hypothesis generation, evaluation, and modification, starting from an initial rough analogy. This dialectic model construction process is shown in Figure 4 and includes both empirical and non-empirical elements. (6) Such a cycle can be more powerful than a blind variation and evolution process. For example, when difficulties have been identified in an existing model, subsequent generation and modification processes can serve to remove the difficulties. (7) Philosophers have tended to separate the "context of discovery" (theory generation) from the "context of justification" (theory evaluation) in their discussions of scientific method. The presence of an evaluation component and the observation of very small cycle times for the loops in this cycle (occasionally on the order of a single minute) make it very difficult to separate the context of discovery from the context of justification in the early stages of hypothesis formation. Hypothesis evaluation processes appear to be an inherent part of hypothesis formation down to resolution intervals of a single minute on occasion. (8) The persistence of an initial model that resists replacement and the observed tension between it and a perceived anomaly may be partially analogous to the persistence of a paradigm in the face of anomalies in science. An important function of the strategy of searching for analogous cases is that it may help the subject to break away from such a persistent but inadequate model.

Thus it appears to be possible to study hypothesis formation and creative insight processes in thinking aloud protocols. The present study suggests a view of hypothesis formation in science that is more complex than can be provided by either an inductivist, rationalist, Eurekaist, or accretionist position alone. Recent analyses of Darwin's thought processes are found to be similar in many respects to the present analysis of thinking aloud data.

Figure 4 may provide a useful hypothesis for the process students should use to learn scientific models in science education. As such it may suggest a more explicit meaning for the concept of "knowledge construction". An extended abstract is provided by the summary at the end of the chapter.

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LEARNING VIA MODEL CONSTRUCTION AND CRITICISM: PROTOCOL EVIDENCE ON SOURCES OF CREATIVITY IN SCIENCE*

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INTRODUCTION

There is growing recognition that mental models play a fundamental role in the comprehension of science concepts. The process of learning via model construction appears to be central for science instruction but is still very poorly understood. This chapter uses evidence from case studies, in which a scientist is asked to think out loud, to argue that nonformal reasoning processes that are neither deductive nor inductive can play an important role in scientific model construction. The construction process is complex and involves repeated passes through a cycle of hypothesis generation, evaluation, and modification.

"Aha" episodes are also examined which show that a scientist can generate creative insights via spontaneous analogies and other divergent processes. It is argued that these insights can involve fairly sudden reorganizations in the structure of a mental model but do not necessarily involve extraordinary or unconscious thought processes. The introduction and summary of findings at the end constitute an overview of the chapter.

Questions About the Nature of Scientific Theory Formation

Galileo's theory of motion, Faraday's concept of the magnetic field, Darwin's theory of natural selection, and Einstein's theory of relativity are commonly cited examples of creative achievements in science. Each is a major event in the history of scientific ideas, and in each case something very new emerged that affected the entire scientific community and subsequently affected civilization as a whole. Analyzing how such achievements take place is a worthwhile goal, but achieving this goal has unfortunately proven to be surprisingly difficult. The universally recognized importance of great advances in science has not made the problem of describing the processes by which they were created any easier. In Darwin's case, for example, it is possible to argue that the theory of natural selection was built up gradually through a large number of detailed empirical observations. But on the other hand, it also is possible to argue that the theory was the result of a mental breakthrough well after the Beagle's voyage in the form of an insight that constituted a sudden reorganization of Darwin's ideas. Thus, even with respect to specific historical examples, disagreement emerges as to the basic sources and pace of theory change in science.

At issue here is an important question concerning the nature of science. Cast in its most global and extreme form, the question is: "Does science change in an incremental manner, with a series of many small empirical observations inching it forward, or do occasional large breakthroughs occur in the mind of the scientist in the absence of new data, each causing a great leap forward in the field?" One purpose of this chapter is to determine whether the methodology of protocol analysis has the potential to illuminate some aspects of this question by using data from transcripts of scientists solving problems aloud. I will concentrate most on an example of a breakthrough episode in a thinking aloud case study and discuss the senses in which it is and is not an example of a scientific insight or "Eureka" event. In particular, the case study is used to address elements of the following more specific questions:

1. What is a scientific insight? Can one identify "insight events" or "Eureka events" in thinking aloud protocols? Why do insights occur? Why do periods of slow and fast progress occur in scientific thinking?

2. What processes are involved in the generation of a scientific hypothesis? In particular, are hypotheses always generated as inductions from data? What role do analogies and thought experiments play in creative scientific thinking? What is the role of explanatory models?

3. Are there parallels between the tensions observed in an individual scientist thinking aloud and the tensions Kuhn describes between an anomaly and a scientific paradigm?

4. What impact do findings relevant to the above questions have on the concepts of "knowledge construction" and "discovery learning" in a theory of instruction?

I will attempt to show that empirical evidence can be collected which can speak to certain aspects of these questions.

BACKGROUND QUESTIONS FROM PHILOSOPHY OF SCIENCE

The Source and Pace of Theory Change

Eurekaism vs. accretionism. It is useful to separate out two major issues involved in the controversy over hypothesis formation, the pace of scientific theory change and the source of new theories (represented, respectively, in questions 1 and 2 above). With respect to the pace of theory change, one can contrast Eurekaist and accretionist positions. A Eurekaist claims that a theory can be changed at a very fast pace by an insight that

reorganizes its structure. In its strongest form, Eurekaism is associated with sudden flashes of inspiration, possibly following a period of incubation or non-conscious mental activity. Thus, some ideas may form in and arrive suddenly from the unconscious mind.

An "accretionist" or incremental view of the pace of scientific theory change holds that a scientist gains knowledge in small pieces and puts them together deliberately at a slow and even pace. This process can lead to a smooth progression in the attainment of knowledge--an incremental "march of progress" without large-scale reorganizations.

Rationalism vs inductivism. A second major issue is the source of new theoretical knowledge. The question of the sources of and justification for new knowledge is a central point of controversy between the rationalist and empiricist traditions in Western thought. The rationalist tradition emphasizes the power of reasoning from prior knowledge and greatly values the consistency and beauty of the resulting theories. Reasoning power, coupled with the prior beliefs of the learner are emphasized as sources of knowledge. On the other hand, the empiricist tradition emphasizes the importance of careful observation and greatly values the reliability of repeatable experimental procedures. Here the term induction will denote a process by which a more general principle is abstracted from a set of empirical observations as the source. I will use the term inductivism to refer to the belief that induction is the primary, if not exclusive, source of hypotheses in science. Stated most simply, scientists gradually gather facts, use inductive reasoning to organize them into general statements, and finally build up a pyramid of general empirical laws that summarize all of the gathered data. Theory-driven and data-driven approaches in artificial intelligence can to some extent be thought of as modern inheritors of the rationalist and inductivist viewpoints.

Although they refer to different issues, the Eurekaist vs. accretionist and rationalist vs. inductivist controversies are not independent historically, but tend to interact. Eurekaism tends to be associated with rationalism, while accretionism tends to be associated with inductivism. Thus it is sometimes useful to refer to an individual position as "rationalist-Eurekaist" or "inductivist-accretionist." A rationalist-Eurekaist view of theory change is associated with the idea that scientists at times must be very creative, whereas the inductivist-accretionist view suggests that scientists can make progress by relying on small changes without large creative breakthroughs. This simplified picture of two opposing camps can then be used as a starting point for introducing some important issues concerning the nature of science.

Gould (1980) notes that writers on both sides of this controversy have tried to claim Darwin's theory of evolution as an example. Historically, inductivist-accretionists claimed that it was a prime example of the power of induction, as facts gathered by Darwin during the voyage of the Beagle were slowly pieced together into a grand theory. Rationalist-eurekaists claimed that Darwin had a sudden, crucial insight upon reading Malthus' theory of human population constraints.

But both of these positions run the risk of being oversimplified. As Gould (1980) puts it: "Inductivism reduces genius to dull, rote operations. Eurekaism grants it an inaccessible status more in the domain of intrinsic mystery than in a realm where we might understand and learn from it." The implied challenge here is to find a less simplistic view that helps to explain creative behavior in a non-trivial way. In this chapter accounting for the

data from the case study leads to a more complex view of scientific discovery than any of the extreme Eurekaist, accretionist, rationalist, or inductivist positions can provide. Toward the end of the chapter, I will also review some recent historical studies of Darwin's insights which point to the same conclusion.

Philosophical Positions

I give a brief outline here of how these two broad questions concerning the source and pace of scientific theories interact with some of the major 20th century philosophical positions on the nature of the scientific enterprise.[1] Prior to this century, empiricists focused on observation as the primary source of knowledge in science, and the 20th century logical positivists built on their tradition by attempting to show that scientific knowledge could be grounded firmly in sense experience. In their view careful observations, and the assumptions of a common scientific observation language and the applicability of the laws of logic and probability, could provide science with knowledge of the utmost reliability, if not certainty. Although the logical positivists concentrated on issues surrounding the justification of theories rather than their origin, their empiricism also affected views of the origins of scientific knowledge. Science was described in an accretionist manner as building and extending theories incrementally, approaching truth in a monotonic way. For example, Carnap held the inductivist belief that science advances upwards from particular empirical facts to generalizations which summarize or provide an abbreviation for a body of such facts (Suppe, 1974, p. 15n). Certainly positivism has influenced the methodology of other disciplines (e.g. behaviorism in psychology) in this direction.

Important attacks on the positivist position, such as Popper's success in showing that induction cannot confirm the truth of theories, Hanson's claim that observations are "theory laden", and Kuhn's claim that theoretical advances often precede the empirical findings used to support them in science, have raised serious problems by arguing against the empiricist emphasis on sense experience as the preeminent basis for knowledge. Popper (1959) held that the proper role for data is in the criticism rather than the confirmation of hypotheses. Hypotheses are conjectures made by scientists rather than certainties abstracted from data. But these conjectures can be reliably criticized and falsified by collecting data. This allows science to make progress via a series of conjectural hypotheses and reliable criticisms. Popper's work provided support for the model shown in Figure 1, the hypothetico-deductive method. There are three main stages shown here: (1) a hypothesis is formed by conjecture; (2) predictions deduced from the hypothesis are tested empirically; (3) if the prediction is incorrect, the hypothesis is rejected and the cycle restarted. Popper maintained, contrary to the logical positivists, that a successful empirical test did little to confirm a hypothesis, but that failing such a test was grounds for rejecting a hypothesis. Those hypotheses that survive the gauntlet of repeated testing become accepted laws. Favored laws emerge through the survival of the fittest conjectures, so to speak. However, Popper's emphasis on conjecture also opens up the possibility that a non-inductive, non-accretionist process, or even a Eureka event, could be involved in hypothesis formation.

(Figure 1 about here.)

Popper's views have in turn been criticized in a number of ways. The most relevant shortcoming for the purposes of the present study is that his classic work does not specify mechanisms for generating hypotheses; he relegates this task to psychology and says only that hypotheses must be conjectural in nature. Also, Hanson's notion that observations can be "theory-laden" implies that empirical testing in the hypothetico-deductive method may not be fully reliable and sufficient on its own as a means of hypothesis evaluation. (Other means of hypothesis evaluation that are more rationalist in character will be discussed in the next section.)

With regard to the pace of theory change, Kuhn's ideas of revolution within a scientific discipline and the creative "gestalt switch" required for an individual scientist to move outside of his own paradigm argue against an accretionist view of theory change. In this view, normal science may be accretionist in character, but revolutionary periods in science involve crisis and reconstruction, implying that science progresses at an uneven pace with periods of slow and fast change. On the other hand, critics of Kuhn, such as Toulmin (1972), have in turn questioned the reality of scientific revolutions, arguing for a more continuous view of theory change.[2]

In summary, an inductivist-accretionist view of science sees it as compiling facts and generalizations in a piece by piece fashion. Induction is the primary process of hypothesis generation, with a one-directional flow of knowledge from data upward to theories. In a rationalist-Eurekaist view, on the other hand, significant theoretical developments can occur when a scientist formulates mental constructions at some distance from existing data and can actually develop new ways of looking at old data. Thus knowledge can flow from a newly invented, general theory downward to influence the formation of new specific theories, to reorganize one's view of existing data, and to suggest new places to collect important data. Such reorganizations presumably would require a large degree of creativity, perhaps even extraordinary "Eureka" episodes of insight.

These two views have been the subject of continuing controversy. Philosophers have taken various positions between the extremes, and some have attempted to point to examples from the history of science supporting their position. However, in historical studies it is always difficult to find data saying much in detail about the actual process of hypothesis formation in the individual scientist. In the next section I consider several descriptions of this process as proposed by philosophers, after which I analyze a thinking aloud case study to examine these issues from an empirical base at a more detailed level. In this case study, examples of non-inductive reasoning in the formation of hypotheses will be examined in order to determine whether this type of data can challenge the inductivist position; and an identified "insight episode" will be examined to determine whether it can provide support for or against a Eurekaist position.

SOME POSSIBLE VIEWS OF HYPOTHESIS FORMATION PROCESSES IN THE INDIVIDUAL SCIENTIST

How are Hypotheses Formed?

In this section, it will be useful to concentrate on the more specific question: "What are the mental processes by which hypotheses are formed in an individual?" The answer to this question should involve some sort of model of mental processes being used. Discussion of this narrower question about individuals may be of some interest to those investigating the broader question about science as a whole, even though the latter issue is more complex. In fact, surprisingly little work has been addressed to this

question, especially in comparison to the complementary question: "How are scientific hypotheses tested?" Here I give a brief overview of several possible positions that can be taken on the first question concerning formation.

Popper's position and the hypothetico-deductive method shown in Figure 1 can be taken as a starting point here in the form of a non-answer. The method shows one way in which hypotheses might be tested but does not show how they are generated.

(Figure 2 about here)

Answer 1: Hypothetico-Deductive Method Plus Induction

Popper argued convincingly that induction cannot be used to confirm the truth of scientific theories. However, some modern scholars retain some form of induction in their model of scientific method as a way to suggest hypotheses, rather than to confirm them unequivocally. This can be represented by the model shown in Figure 2--combining the hypothetico-deductive method with induction as a source of hypotheses. Here there is no claim for a "logic" of discovery, but only for a fallible method for generating hypotheses. Further experiments are performed in order to evaluate the inductions. Such a diagram is commonly implied in everyday characterizations of scientific method as a combination of induction and deduction. Scholars such as Harre (1983), Achinstein (1970), and Gregory (1981) argue that induction can play a major role in hypothesis formation. However, they believe that other processes can be involved as well. More recently, Langley (1979) has attempted to develop simulation models of data-driven inductive processes for generating certain scientific laws.

Answer 2: "Creative Intuition"

Is some form of induction or guessing the only source of scientific hypotheses? A number of recent authors have answered "no" to this question by pointing to the role of creativity, intuition, and the unconscious in generating hypotheses (Koestler, 1964; Polanyi, 1966; Rothenberg, 1979). Unfortunately, I can only make the briefest mention of these long and detailed works here. Their views can be roughly characterized as replacing the "Hypothesis Formation by Induction" step in Box A of Figure 2 with a process labelled "Hypothesis Formation by Creative Intuition." For example, Polanyi emphasizes the role of intuition and tacit knowledge in science. Rothenberg proposes a process of "Janusian thinking," whereby a person is able to juxtapose seemingly contradictory ideas, as a common element in creative thinking. Koestler points to "bisociative thought"--the ability to connect normally independent frames of reference--and to the role of the unconscious in accounting for creativity.

An interesting controversy has emerged in this area. Perkins (1981) argues that all of these descriptions attempt to point to extraordinary thinking processes; they attempt to supplement ordinary reasoning with something more powerful. He counters this idea with the claim that most creative acts can be explained plausibly by a model where a person uses certain ordinary thinking processes more intensively, or with special goals in mind. In his view, the difference between a creative and an uncreative person is a difference of degree and purpose, not a difference of kind. Perkins also describes authors like Koestler as contributing mainly to the description of

the products of creative thinking; a remaining problem is to specify the processes of creative thinking in more detail.

Answer 3: Analogies and Successive Refinement Cycles as Sources of Explanatory Model Hypotheses

The work of another group of scholars in philosophy of science, including Campbell (1920), Harre (1961), Nagel (1961), and Hesse (1966), suggests that analogies may be a source of hypotheses. They argue that scientists often think in terms of theoretical explanatory models, such as molecules, waves, and fields, which are a separate kind of hypothesis from empirical laws. Such models are not simply condensed summaries of empirical observations but rather are inventions that contribute new theoretical terms and images which are part of the scientist's view of the world, and which are not "given" in the data.

(Figure 3 about here)

As shown in Figure 3, they see a distinction between an empirical law hypothesis summarizing an observed regularity and what I will call an explanatory model hypothesis. Campbell's oft-cited example is that merely being able to make predictions from the empirical gas law stating that PV is proportional to RT, is not equivalent to understanding the explanation for gas behavior in terms of an imagable model of billiard-ball-like molecules in motion. The model provides a description of a hidden process which explains how the gas works and answers "why" questions about where observable changes in temperature and pressure come from. Causal relationships are often central in such models. The model not only adds significant explanatory power to one's knowledge, but also heuristic power which stimulates the future growth of the theory. In this view, the visualizable model is a major locus of meaning for a scientific theory. (Summaries of these views are given in Harre, 1967 and Hesse, 1967).

The above authors, as well as Black (1970), argue that models involve analogies to familiar situations (e.g. gases are analogous to a collection of colliding balls). In Nagel's terms, such visualizable analogue models help scientists "make the unfamiliar familiar." This suggests that analogical reasoning may be an important non-inductive source for generating such hypothetical models. More recently, theory formation and assessment cycles using analogies have been discussed by Clement (1981), Nersessian (1984), Holland, Holyoak, Nisbett, and Thagard (1986), and Darden and Rada (1988).

(Figure 4 about here)

Most of the above authors also emphasize a rational (non-empirical) contribution to hypothesis evaluation, holding that explanatory models are not just tested empirically but also are evaluated non-empirically with respect to criteria such as simplicity, aesthetic appeal, and consistency with other accepted models.

The model construction cycle. Figure 4 represents an attempt to bring together several of these features in a single idealized model of the hypothesis development process for constructing visualizable scientific models. Such a process could be used, for example, to develop an explanation for a newly recognized phenomenon. Essentially, the diagram depicts a cyclical process of hypothesis generation, rational and empirical testing, and modification or rejection. It is difficult to describe so complex a process in a single diagram, but a simplified model will aid in the present analysis. In contrast to Figure 2, in Figure 4, when a hypothesis is evaluated

negatively, it can sometimes be improved through modification, instead of being completely rejected. Thus, it may undergo a series of successive refinements.

The double ended arrows between Make Initial Observations and Construct Initial Model represent the idea that not only does model construction respond to observation but that one's focus of attention during observation can be guided by one's initial model. This and other double ended arrows indicate that the initial model generation process can be highly interactive and complex. It is still poorly understood.

Essentially, the scientist must construct or piece together a conjectured picture of a hidden structure or process which explains why the phenomenon occurred. Peirce (1958) and Hanson (1958) used the term abduction (or retroduction) to describe the process of formulating a hypothesis which, if it were true, would account for the phenomenon in question. The hypothesis can be a guess as long as it accounts for (predicts after the fact) the observations collected so far. Empirical law hypotheses which consist only of a recognized regularity or repeated pattern in the variables, such as those discussed by Langley (1979), might be formed via a more data-driven inductive process. This is possible on those occasions when one has the prior advantage of possessing the right variables, or components of compound variables, to look for. But the explanatory model hypotheses being considered here would be formed by a less data-driven abductive process, possibly for just a single instance of the phenomenon. Such a process might "plagerize" the knowledge structure from an analogous case in memory to form the starting point or core of a new model. Or it might integrate several related model elements--constructing a new model by combining several existing knowledge structures previously known to the subject.

Hypothesis evaluation can take place in two major ways. Empirical testing can add support to or disconfirm a hypothesis. Rational evaluation can also support or disconfirm a hypothesis, depending, for example, on whether it is found to be consistent or inconsistent with other established theories. Evaluation processes cannot provide full confirmation, but can lead a scientist to have increased or reduced confidence in a theory. Once generated, a hypothesis undergoes repeated cycles of rational and empirical testing, and modifications as needed. A limitation of the diagram that is not intended to be part of the model is the order in which rational and empirical evaluation occur; tests can occur in different orders on different cycles.

The endless loops in Figure 4 indicate that ideally, theories in science are always open to new criticisms. However, as Kuhn (1962) points out, scientists will sometimes ignore or discount some criticisms in order to protect a favored theory. In practice, research groups may adopt a "protected core" of theories which they take as givens (Lakatos, 1978).

A missing element in the figure is the influence of the subject's prior theoretical framework. It is difficult to depict, since it could affect so many of the processes shown. Since the scientist operates from a background of broader theoretical assumptions, these may have an early influence on the model elements and analogies which come to mind, and even (according to Hanson and Kuhn), on what is observed.[3]

Summary

In summary, little empirical work has been done on the question of hypothesis formation processes in science, but philosophers have proposed several possibilities, including guessing, abduction, induction, and creative leaps. In addition, Campbell and others have introduced the interesting

distinction between empirical law hypotheses that are summaries of perceived petterns in observations, and explanatory model hypotheses that introduce visualizable models at a theoretical level and that often contain currently unobservable entities. They suggest that analogies may be an important means of constructing the latter type of hypothesis. A possible synthesis of these ideas was proposed in Figure 4. It allows for the possibility that the hypothetico-deductive method, induction, abduction, analogy, rational evaluation, and hypothesis modification may all play important roles at different times in scientific thought.

The idea that analogies can be involved in hypothesis formation is often used to support a Eurekaist view of scientific discovery. If analogy generation is a fast, creative process, and if it is important in hypothesis formation, then it is a promising candidate for a cognitive process underlying insight or Eureka events. This issue will be examined closely in the section following the next one.

EVIDENCE FROM THINKING ALOUD PROTOCOLS ON MODEL CONSTRUCTION CYCLES USING ANALOGIES

Recently, cognitive psychology has begun to study complex human cognition through the use of protocol analysis. This section uses this method to examine the process of hypothesis generation in thinking-aloud protocols. Several examples of spontaneous analogies will be examined, as well as a breakthrough episode which appears to be an example of insight behavior. Instead of working backwards from historical records and outcomes, a more direct analysis of the processes operating in the thinking scientist will attempted here.

The great difficulty of course, is to have a video camera trained on the scientist at one of the rare moments when he or she formulates a hypothesis. One way to overcome this difficulty is to pose conceptually challenging, but not overwhelming problems to the subject which allow for the formulation of hypotheses and explanations. The data discussed here were taken from interviews in which advanced doctoral candidates or professors in technical fields were asked to think aloud as they solved such problems. Although the problems do not concern issues on the frontier of science, in many cases they ask subjects to give a scientific explanation of a phenomenon with which they are unfamiliar (i.e., a problem on the frontier of their own personal knowledge). Thus, it is plausible that the thought processes analyzed will share some characteristics with hypothesis formation and model construction processes used on the frontiers of science.

Use of Analogies and Models in Expert Problem Solutions

In this section evidence will be presented indicating that analogies can be involved in a significant way in generating the solution to a scientific problem, and more specifically that they can sometimes lead to a new model of the problem situation.

(Figure 5 about here)

Wheel problem. I will first present a very brief description of a solution to the "Wheel Problem" illustrated in Figure 5. It poses a question about whether one can exert a more effective uphill force parallel to the slope at the top of a wheel or at the level of the axle (as in pushing on the wheel of a covered wagon, for example). Subject S2 compared the wheel to the

analogous case of pushing on a heavy lever hinged to the hill (Figure 6b). He reasoned that pushing at the point higher up on the lever would require less force. He then made an inference by analogy that the wheel would be easier to push at the top (the correct answer). Here the lever is used as a model in some sense for the wheel.

(Figure 6 about here)

Use of the terms 'analogy' and 'model'. This initial example motivates the following ways of using the terms analogy and model. I will refer to the occurrence of a spontaneous analogy when the subject spontaneously shifts his attention to a different situation (called the analogous case) that he believes may have relevant structural similarities to the original target case. When this is true, the subject's cognitive structures representing the target and the analogous case will have at least one structural relationship in common. In what follows I will refer to the lever situation as the analogous case and to the structural similarity relationship between the lever and the wheel as the analogy relation.

Some analogies are used casually for "decorative" purposes only. By contrast, the following definition of a scientific model as a predictive analogy is intended to identify analogies that are used for serious scientific purposes. Here, in the broad sense of the term, a scientific 'model' will refer to a cognitive structure, where the subject believes that the model situation is analogous to the target situation and believes that one may be able to use the model to predict or account for observations made in the target.

One way in which models are distinguished theoretically from rote facts or procedures is by virtue of having a richer set of relational interconnections within their structure as opposed to being a collection of independent facts. A model M gives the scientist a way of thinking about a target situation T that can predict how T behaves under certain conditions (whether this happens before or after the behavior is observed is not important for the definition). The lever analogy for the wheel is a scientific model in this sense. Well developed and successful scientific models are valued for being precise, unambiguous, general, and predictive. In addition, scientists often prefer models which are visualizable, causal, simple, and which contain familiar entities. (In a later section the narrower category of an explanatory model will be defined as one that posits a material similarity where elements of M are assumed to actually be hidden or non-obvious elements in T.)

Improving the model for the wheel. The subject was confident that it would be easiest to move the heavy lever in Figure 6b by pushing at point X, but he was not so confident that it was a good model for the wheel; he criticized the model by questioning whether there was a valid analogy relationship between it and the case of the wheel. Can one really view the wheel as a lever, given that the "fulcrum" at the bottom of the wheel is always moving and never fixed? A second improved analogue model described by this subject was the spoked wheel without a rim shown in Figure 6C. The spokes allow one to view the wheel as a collection of many levers, thereby reducing any worries about the moving fulcrum. This is a useful model of the wheel for many purposes, including the present problem.

In summary, after criticizing the "lever" model, the subject was able to produce a second, more elaborate analogous case which provided an improved

model. This provides an initial example of a hypothesis gen ration, evaluation, and modification process leading to the formation and improvement of a mental model via an analogy.

Creative aspect of analogies. As mentioned above, an analogy is a related case that the subject believes is structurally similar to an original case. However, the case also must differ in a significant way from the original problem to be counted as an analogy. By this I mean that one or more features commonly assumed to be fixed in the original problem are different in the related case. In order to generate an analogy like the lever analogy, the subject must break away from the original problem context. This "breaking the set" of the original problem appears to be one of the main reasons that generating an analogy is considered a creative act and is most likely one reason that model construction via analogies is not the most common method for solving problems.

(Figure 7 about here)

Spring problem. A second example concerns the "Spring Problem" shown in Figure 7. That the wide spring will stretch farther seems to correspond to most people's initial intuition about this problem. However, carefully answering the question about why the wide spring stretches more (and explaining exactly where the restoring force of the spring comes from) is a much more difficult task. Because it asks 'why', this is largely an explanation question rather than a question with a single, well-defined answer. Thus, it is less like an everyday "puzzle" problem and more like a theoretical "why" question in science where the answer is an explanation.

In a study of expert qualitative reasoning, I recorded ten professors and advanced graduate students in technical fields while solving the spring problem out loud (Clement, 1988). They were told that the purpose of the interview was to study problem solving methods and were given instructions to solve the problem "in any way you can." After they reached an answer, subjects were asked to give an estimate of their confidence in their answer. They were then asked if there was any way they could increase their confidence, and this often led to further work on the problem. Probing by the interviewer was kept to a minimum, usually consisting of a reminder to keep talking. Occasionally the interviewer would ask for clarification of an ambiguous statement.

Some of the solutions were quite complex and took up to 50 minutes to complete. All subjects favored the (correct) answer that the wide spring would stretch farther, but the subjects varied considerably in the types of explanations they gave for their prediction. A number of subjects considered the analogous case of a horizontal bending rod (shown in Figure 8) or variations thereof. Most subjects had a strong intuition that a longer rod would bend more than a shorter rod under the same weight, and this suggested to them that the wider spring would stretch more. A number of other analogies attempted in this problem are discussed in Clement (in press-b) including: two foam rubber blocks, one with large and one with small air holes in the foam, springs in series, springs in parallel, series circuits, parallel circuits, and molecules in different crystals. Altogether, 31 significant analogies were observed. They were generated by seven of the ten subjects. Thus, a large number of spontaneous analogies were generated for this problem.

(Figure 8 about here)

A Case Study of Hypothesis Generation

In the remainder of this section, I will focus on the case study of subject S2, who appears to develop, criticize, and modify analogous cases for the spring problem until he produces a new hypothesis in the form of an explanatory model for how springs work.

Purpose of case study. One of the main reasons for doing an in-depth case study is to develop and refine a basic vocabulary of concepts for describing psychological observations and theories. The initial challenge of such a study is to develop and describe the "units" of behavior to be used in observation and to propose an initial cognitive model in the form of a set of cognitive structures and processes that can account for the behavior and that is both plausible and consistent. For simpler types of behavior, such modeling can be fairly detailed, and in some cases can be expressed as a computer simulation. For more complex or poorly understood phenomena, an initial step in modeling can be achieved by formulating a general description of structure and process features--the basic units or cognitive objects to be used in the model, the outline of a model, and a set of "design criteria" that a more detailed model would need to fulfill. The analysis of the case study discussed in the remainder of this paper will be aimed at the latter level.

S2's protocol. In the spring problem subject S2 first generated the model of comparing a long horizontal bending rod with a short one (a weight is attached to the end of each rod) inferring that segments of the wider spring would bend more and therefore stretch more. However, he was concerned about the appropriateness of this model because of the apparent lack of a match between seeing bending in the rod and not seeing bending in the wire in a stretched spring. One can visualize this discrepancy here by thinking of the increasing slope a bug would experience walking down a bending rod and the constant slope the bug would experience walking down the helix of a stretched spring. This discrepancy led him to question whether the bending rod was an appropriate model for the spring. He then constructed the analogous case of the "zig-zag spring" shown in Figure 9, apparently in order to attempt to evaluate the analogy relation between the spring and the bending rod and to attempt to construct an improved model. The full transcript is quite long; therefore verbatim excerpts are presented here. (Brackets in transcript indicate my comments.)

(Figures 9 and 10 about here)

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5 S2: I have one good idea to start with; it occurs to me that a spring is nothing but a rod wound up uh, and therefore maybe I could answer the question for a rod. But then it occurs to me that there's something clearly wrong with that metaphor because if I actually took spring wire and it was straight instead, it certainly wouldn't hang down like a spring does. ..It would droop ..and its slope would steadily increase as you.. went away from the point of attachment, whereas in a spring, the slope of the spiral is constant.

7 S2: Why does a spring stretch?..I'm still led back to this notion... of the spring straightened out [a bending rod]...(e) I'm bothered by the fact that the slope doesn't remain constant as you go along it. It seems as though it ought to be a good analogy, but somehow, somehow it doesn't seem to hold up...

23 S2: I feel I want to reject the straightened spring model- as a bad model of what a spring is like. I feel I need to understand the nature of a spring in order to answer the question. Here's a good idea. It occurs to me that a single coil of a spring wrapped once around is the same as a whole spring...In the one-coil case, I find myself being tempted back to the straightened spring [rod] model again...

I still don't see why coiling the spring should make any difference... Surely you could coil a spring in squares, let's say, and it... would still behave more or less the same. Ah! from squares, visually I suddenly get the idea of a zig-zag spring rather than a coiled spring; that strikes me as an interesting idea (draws Figure 9... Might there be something in that idea..

I see a problem with this idea. The problem...is that..the stretch..has to do with.. the joint. But the springiness of the..real spring is a distributed springiness;.. So...I wonder if I can make the [zig-zag] spring..where the action.. isn't at the angles..it's distributed along the length... And I'm going to do that; I-I have a visualization... Here's a stretchable bar; (draws modified zig-zag spring in Figure 10) a bendable bar, and then we have a rigid connector... And when we do this what bends...is the bendable bars...and that would behave like a spring. I can imagine that it would.

Here there is evidence that the subject is generating a series of analogue models for the spring--from the rod to the angular zig-zag spring to the rectangular zig-zag spring with stiff joints. The zig-zag spring is eventually dropped, presumably because he was still critical of this model and could not reconcile the bending going on in sections of the zig-zag spring with the lack of change in slope in the original helical spring. However, these attempts do provide evidence for another thought pattern in the form of a repeated dialectic process of model construction, criticism, and modification.

Next, he considers the analogy of a double-length spring instead of the double-width spring appearing in the original problem.

37 S2: This rod here: as the weight moves along, it bends more and more the further out the weight is...Hmmm, what if I imagined moving the weight along the spring...would that tell me anything? Would that? I don't know. I don't see why it should. What if the spring were twice as long...instead of twice as wide?...It seems to me pretty clear that the spring that's twice as long is going to stretch more... Now if this is the same as a spring that's twice as wide, then that should stretch more...Uhh, but is it the same as a spring that's twice as wide? Again, I just don't see why...the coiling should make any difference. It just seems geometrically irrelevant to me somehow... But I..can't-- I have trouble...bring that into consonance with the behavior of an actually stretched out spring...the slope problem anomaly

[increasing slope in the rod, but not in the spring]-- If I could resolve that snomaly... then I would feel confident of my answer...but this snomaly bothers me s lot.

Again, he seems critical of the appropriateness of the double-l-ngth spring anslogy.

57 S2: I feel ss though I'm reasoning in circles. I think I'll make a deliberate effort to break out of the circle somehow. What else could I use thst stretches...like rubber bands...what else stretches...molecules, polyesters, csr springs [leaf springs]...what about a...two-dimensional spiral spring? Thst doesn't seem to help.

At this point, the bending rod, double-length spring, and zig-zag spring analogies have each pointed S2 to the correct swer to the problem, yet he remsins unsatisfied with his understanding. In line 57, he continues to search unsuccessfully for a more satisfactory analogous case.

Insight section. Subsequently, this subject produces sn extremely productive analogy when he generates the idea of the hexagonally shaped coil in Figure 11 snd moves from there to the idea of the square shaped coil in Figure 12. Imagining the stretching of these polygonal coils appsrently allowed him to recognize that some of the restoring forces in the spring come from twisting in the wire instead of bending-- s major breakthrough in the solution which corresponds to the wsy in which engineering specialists view springs. Much of the remsinder of this chapter will focus on this insight.

(Figures 11 snd 12 about re)

The impressiveness of the reasoning displayed by different subjects in solving the spring problem depends on the depth of understanding sought by the subject and on the subject's prior knowledge. The first level of depth in understanding is simply to state an intuition that the wide spring will stretch more; a second level is to give some plausible justification for this.

For subjects who have previously learned thst there is twisting in the spring wire during stretching, they can, with some effort, achieve s third quantitative level in identifying three csussl, linesr factors lesding to the result that the stretch is proportional to the cube of the coil diameter. Probably the most difficult achievement occurs when the subject does not know about the invisible twisting in the wire, but is somehow able to construct that hypothesis. S2 achieves this in the next section of the protocol to be discussed.

To see why his square spring model is helpful, note that it can in turn be understood in terms of two simpler csses, the twisting rod and the bending rod, as shown in Figure 12. That is, pulling the end of the lever "1" down not only bends rod 1, but it also twists rod 2. (One way to comprehend this idea is to view rod 1 as a wrench thst is twisting rod 2.) The same is true for all other sdjacent rod psirs. Thus, twisting is sn important type of deformation in the spring wire in this model.

This part of the protocol is reported in sections as follows:

1) Subject is still in conflict sbout whether spring wire is bending
2) Generates s series polygonal coil snalogies
3) Torsion discovery
4) Evaluates and sdapts squsre coil as s preferred model of the spring
5) Comments on his increased understanding

(Figure 13 sbout here)

Section 1: Subject is Still in Conflict sbout Whether Spring Wire is Bending

57 S: I just...have the intuition thst s ...strsight rod ought to in some sense be a good model for s spring. But there are these snomalies that won't go awsy. And yet I can't see...s better model.

79 S: ...I'm just trying to imagine the coil...(traces circle sbout 7 inches in diameter in sir in front of self) s circle with s bresk in it...

81 S: (has just drawn Figure 13)...you could just hold it there...and apply a force there, and the spring stretches... I'll be damned if I see why it [the coil] should be any different from that case [the rod]...

87 S: ...if you start with a helix and unwind it...you should get a bow [bend], but you don't. I mean visually imagining it, you don't. I don't see how you could make the bow go away- just to wind it up- Damn it!

111 S: Darn it, darn it, darn it...why should that [the difference between a rod and a coil] matter?... I'm visualizing what will happen when you just take this single coil and pull down on it and it stretches; and it stretches...

(The subject spends a considerable amount of time trying to resolve this issue without making progress.)

Section 2: Generates a Series of Polygonal Coil Analogies

117 S: (40 minutes into the protocol) I keep circling back to these same issues without getting anywhere with them....I need to..think about it in some radically different way, somehow. Let me just generate ideas about circularity. What could the circularity [in contrast to the rod] do? Why should it matter? How would it change the way the force is transmitted from increment to increment of the spring? Aha! Now let me think about; Aha! Now this is interesting. I imagined; I recalled my idea of the square spring and the square is sort of like a circle and I wonder....what if I start with a rod and bend it once (places hands at each end of rod in Figure 8 and motions as if bending a wire) and then I bend it again.

119 S: What if I produce a series of successive approximations to... the circle by producing a series of polygons! Maybe that would clarify because maybe that, that's constructing a continuous bridge, or sort of a continuous bridge, between the two cases [the rod and the coil]. Clearly there can't be a hell of a lot of difference between the circle and say, a hexagon...

121 S: ...or even a triangle...square..(draws hexagon in Figure 11)...Now that a [hexagon] is essentially a circle. I mean, surely springwise that [hexagon] would behave pretty much like a circle does.

Section 3: Torsion Discovery

121 S: Now that's interesting. Just looking at this it occurs to me that when force is applied here, you not only get a bend on this segment, but because there's a pivot here (points to x in Figure 11), you get a torsion effect...

122 S: Aha! Maybe the behavior of the spring has something to do with twist (moves hands as if twisting an object) forces as well as bend forces (moves hands as if bending an object). That's a real interesting idea.. That might be the key difference between this [bending rod] which involves no torsion forces, and this [hexagon]. Let me accentuate the torsion force by making a square where there's a right angle. (Draws a Figure 12). I like that. A right angle...that unmixes the bend from the torsion.

123 S: Now...I have two forces introducing a stretch. I have the force that bends this...segment [1] and in addition I have a torsion force which twists [segment 2] at vertex, um, X...[in Figure 12] (makes motion like turning a door knob with one hand)

Section 4: Evaluates and Adopts Square Coil as a Preferred Model of the Spring

129 S: (b)...Does this (points to square-shaped coil) gain in slope—toward the bottom?...

130 S: (c)..indeed we have a structure here which does not have this increasing slope as you get to the bottom...(e)...it's only if one looks at the fine structure; the rod between the Y and the X, that one sees the flop effect [downward curvature]

132 S: (b)..Now I feel I have a good model of sp- of a spring...Now I realize the reason the spring doesn't flop is because a lot of the springiness of the spring comes from torsion effects rather than from bendy effects...

133 S: And now I think I can answer the stretch question firmly by using this...square model of the spring. What does it mean, in terms of the square model to increase the diameter of the spring?.. Now making the sides longer certainly would make the [square] spring stretch more.

135 I: How can you tell?

136 S: a) Physical intuition...and also recollection.. the longer the segment (moves hands apart) the more the bendability (moves hands as if bending a rod)... b) Now the same thing would happen to the torsion I think, because if I have a longer rod (moves hands apart), and I put a twist on it (moves hands as if twisting a rod), it seems to me--again physical intuition--that it will twist more...

143 S: ...So...doubling the length of the sides.. it will clearly stretch more. Both for reasons of torsion and for reasons of the segment [bending].

Section 5: Comments on His Increased Understanding

144 S: And my confidence is now 99%...I now feel pretty good about my understanding about the way a spring works although I realize at

the same time I could be quite wrong. Still, there seems to be something to this torsion business; I feel a lot better about it.

[illegible] S: Before this torsion insight, my confidence in the answer was 95% but my confidence in my understanding of the situation was way way down, zero. I felt that I did not really understand what was happening; now my confidence in the answer is near 100% and my confidence in my understanding is like 80%.

(Figure 14 about here)

Analysis of Transcript

Models used by S2. A hypothesized outline of the cognitive events producing S2's new understanding in this last section is shown in Figure 14. The figure shows hypothesized "snapshots" of a series of S2's final models as they develop over time, with solid lines showing confirmed analogy relations, and dotted lines showing tentative analogy relations. Poorly understood situations are shown in dotted boxes with well-understood situations shown in solid boxes.

Figure 14a (Line 81): S2 has already reduced the spring situation to the equivalent single circular coil situation as shown by the solid line labeled (1) in the diagram. Also there is a tentative analogy relation shown as a dotted line labeled (2), from the single coil to the well understood bending rod model.

Figure 14b (Line 117): S2 then recalls his idea of a square spring and generates the model of a hexagonal coil. In his words, this is "constructing a continuous bridge or sort of a continuous bridge, between the two cases [of the circular loop and bending rod]."4

Figure 14c (Line 121) While analyzing the hexagon in terms of bending effects, it occurs to him ("Aha!") that there will also be twisting effects. At this point he shifts to the simpler square model.

Figure 14d (Line 123) By the final stage, S2's understanding of the underlying structure which makes a spring work has changed significantly. He now appears to have a mental model of the spring as working like a square coil which contains elements that bend and twist. His physical intuitions about the difficulty of (1) bending, and (2) twisting a long vs short rod seem to play a role similar to axioms; they are basic assumptions on which the rest of his conclusions are founded.

In what follows I will refer to the square, hexagonal, and many-sided coil models collectively as polygonal coil models. To anticipate, some of the conclusions I wish to draw from this example in the remainder of this chapter are that:

(1) The recognition of torsion in the polygonal coil is a significant scientific insight in his attempt to understand the spring;

(2) S2 uses analogies to invent a model for how the spring works in the form of the polygonal coil;

(3) This model can be classified as an explanatory model as opposed to an expedient model because it proposes torsion as a causal factor actually operating in the spring.

(4) The subject produces models and insights via a successive refinement process of hypothesis generation, evaluation, and modification or rejection. His process is non-inductive.

(5) The model generation process here is neither a pure Eureka phenomenon nor a simple, smooth, methodical buildup of information.

(6) Several divergent processes are used in generating hypotheses.

(7) The recognition of an anomaly sets up a tension condition which "drives" the dialectic process, and which is partially analogous to the tension between an existing paradigm in the face of anomalies in science.

Insight behavior. The short transcript excerpts displayed here do not convey the fact that the subject spent a considerable period of time (over 25 minutes) alternately questioning and trying to justify the initial bending rod model of the spring. After this frustrating struggle, the invention of the polygonal coil with the subsequent torsion discovery is a candidate for being termed a significant scientific insight for several reasons.[5] First, the idea is productive in the sense that it leads immediately to a considerable amount of cognitive activity. In fact one is given the impression of a "flood" of ideas occuring immediately afterward. Progress is made rapidly, as if the polygonal coil idea were a "trigger" that stimulates a series of further ideas. Second, the torsion idea appears fairly quickly, with little warning. Third, the subject changes his hypothesized model of stretching--by considering torsion the subject introduces a new causal factor into the system. Torsion constitutes a very different mechanism from bending for explaining how the spring resists stretching. (S2 is the only subject out of 10 studied who clearly progressed from no awareness of torsion in the spring to an understanding of it as a factor.) Fourth, the subject says that he is now able to resolve the paradox of the apparent lack of bending in a helical spring and states that he feels he has achieved an increase in his understanding of the system. Of course, his "theory of springs" could be developed further beyond the polygonal coil idea, but the fact remains that this model is a significant advance over the single bending rod models.[6] Fifth, the subject reacts emotionally to his ideas, calling them "interesting" and exposing a "key difference," as well as producing some emphatic "aha" expressions with a raised tone of voice. Later in this chapter, I will

attempt to formulate a more careful definition for the term "insight" that is motivated by these factors.

The Formation of an Explanatory Model via Analogies

Explanatory vs. non-explanatory models. As discussed earlier, philosophers of science have developed an important distinction between explanatory models and either empirical law hypotheses or formal quantitative principles, as shown in Figure 3. It will now be useful to specify a more precise definition for the term explanatory model in order to say whether S2 has developed one. Recall the proposal to use the term model to refer to a cognitive structure M, where the subject believes there is a predictive analogy between some important relational aspects of the model M and some aspects of the target situation T. One kind of model then is merely an expedient and often temporary analogy which predicts some aspects of the target's behavior. M may happen to behave like T, and therefore provide a way of predicting what T will do. Such an expedient model may not provide a satisfying explanation for why T behaves as it does. It may say nothing about the underlying process which explains T's behavior. An explanatory model, on the other hand, should explain how T works, leading to a feeling of "understanding" T.

S2 makes a clear distinction between confidence in his answer to the problem and confidence in his understanding of the spring:

144 S: ...There seems to be something to this torsion business; I feel a lot better about it...

178 S: Before this torsion insight, my confidence in the answer was 95%, but my confidence in my understanding of the situation was way, way, down, zero. I felt that I did not really understand what was happening; now my confidence in the answer is near 100%, and my confidence in my understanding is like 80%.

This perceived increase in understanding is one indication that the polygonal coil has become an explanatory model for the subject, not just an expedient analogy for generating the answer to the problem. (Karmiloff-Smith and Inhelder [1975] have documented a related distinction in children's thinking.)

Hesse (1967) and Harre (1972) identify two types of scientific analogue model: (1) a model which shares only its abstract form with the target (Hesse cites hydraulic models of economic systems as one example); I call this an 'expedient model'; and (2) a model that has become in Harre's terms a "candidate for reality," where a set of material features, instead of only the abstract form, is also hypothesized to be the same in the model and the target situations. I will refer to the latter type of model M as an <u>explanatory model</u> (or <u>structural hypothesis</u>), M_e, if some of the basic objects, attributes, and concrete relations in M are hypothesized by the subject to be part of T and to underlie the behavior of interest in T.

This ordinarily means that the subject can attain some degree of ontological commitment to (belief in the reality of) M_e if empirical and rational support are obtained for it. M_e is thought of as a hidden structure within T which provides an explanation for T's behavior. Usually M_e contains some entities that are initially not directly observable or obvious in T at that point in time.

This concept helps to account for the remarkable ability of scientists to formulate and propose hidden structure and processes in nature before they are observed more directly, such as atoms, black holes, and the "bending" of light rays. An explanatory model can allow the scientist to see a phenomenon in a new way via an analogy to a hypothesized visualizable structure that is considered to be hidden in the target situation to be explained. This is something that empirical law hypotheses cannot do.

In the case of the present protocol the polygonal coil qualifies as explanatory, since the subject believes that twisting and bending effects may actually be operating in the spring wire to produce its behavior. Twisting and bending are features that are not ordinarily observed in springs. In this sense, the model expresses for the subject a hypothesis concerning the hidden structure underlying the way stretching produces deformation and restoring forces in the spring wire. Furthermore, the square coil model removes the anomaly of a potentially critical dissimilarity in the original bending rod model--that of the lack of cumulative bending in the spring. All of these factors presumably increase S2's feeling of understanding and of having a satisfying explanation for the behavior of a spring, as expressed in lines 144 and 178 quoted above.

For the above reasons, the polygonal coil with torsion model qualifies as an explanatory model which provides a hypothesis about the nature of springs. His statements lead one to believe it has become a preferred model of the spring that he will retain in memory. In this sense S2's protocol is an example of learning via the construction of an explanatory model.[7]

<u>An explanatory model can develop from an initial non-explanatory analogy</u>. A further hypothesis is suggested by S2's problem solution: an expert can develop an explanatory model via the modification and refinement of an initial model that is merely expedient or has low explanatory status. In this view, whether a model is explanatory is a matter of degree. The explanatory status of a model depends on the degree to which one believes that the model contains elements that are like elements hidden in the target to be explained.

It is reasonable that when an analogous case is first proposed, it will often be <u>unclear</u> whether it has potential as an explanatory model--whether its elements could be something like the hidden elements in the target or not. Its explanatory status may grow gradually rather than in one decisive jump. Improvements in the model may also raise its explanatory status. Indeed, this seems to be what occurred in S2's case. He used the bending rod early on as a model, which gave him a prediction in which he was highly confident. However, he said his resulting understanding was very low. The recognition of the bending anomaly appeared to prevent him from accepting it as an explanatory model. Cumulative bending is an important material property which is present in the model, but not in the target. A successive refinement process then led to a number of alternative models, culminating with the polygonal coil model. The identification of torsion in the polygonal coil raised his feeling of understanding significantly. This is consistent with the interpretation that S2 had then acquired some confidence that torsion is a real, but hidden mechanism operating in the spring. Thus, S2 appears to take an initial, non-explanatory analogy (the bending rod model) and develop it, via criticisms and modifications, into a model that in fact does have explanatory status for him.

(Figure 15 about here)

<u>Simplifying function of models.</u> Toward the end of the protocol S2 considers a multisided coil, but is unable to make further progress in his analysis before quitting. Figure 15 shows the set of polygonal models referred to by S2 placed in order of increasing simplicity or analyzability from left to right. Note that these models attain a higher degree of perceptual resemblance to the spring in the opposite direction from right to left. Of the models shown, the bending and twisting rod models on the right

are the simplest to understand, but appear to be least like the spring coil. One might be tempted to call the multigon in (b) the only "really" explanatory model in the sense that it is seen as actually present in the spring, while the others are not. But even in the multigon, there are material elements which are not present in the spring, such as fulcrum points and straight line segments. Apparently even the multigon model is not a full candidate for the mechanism in the spring.

Hesse (1967) and Harre (1972) describe some models in science as <u>simplifying</u> models where the scientist intentionally uses a model with features that are different from those in T in order to make M simple enough to analyze. S2's polygonal spring models appear to be simplifying models which are partially explanatory; he sees the spring as probably really twisting, as in the square c..., but not as really square. The square provides a simplifying geometry--but S2 recognizes that ordinary spring coils are not square or polygonal. In summary, this appears to be a case where modifications of an initial analogy with low explanatory status led to the development of a model with considerably higher explanatory status. However, the polygonal coil model is still a simplifying model, since some of its elements are recognized as not being present in the helical spring.[8]

<u>Two roles for analogy</u>. Even the most successful models can be questioned as to their ontological status--whether they are "really true" of T. It is reasonable to take the point of view that a model can never be fully confirmed as true in a universal sense and should always be open to question. Another way to say this is that even in well-established scientific models, the relation between the idealized model and a real-life example is one of analogy, or partial resemblance, leaving open the possibility that other more refined or useful alternative useful models may be developed in the future.

This means that analogy can play a role in the generation of new hypotheses in at least the following different ways: (1) an analogous case can serve as a rough initial model of the target situation that is later developed and refined; (2) a developed explanatory model, whatever its origin, should in the end be linked by an analogy relation to the target situation.

(Figure 16 about here)

Summary of Evidence for a Model Construction Cycle as a Non-Inductive Source for Hypotheses

The growth in S2's ideas appears to have occurred via a cyclical process of analogy generation, criticism, and modification (or rejection), shown in Figure 16. This is a more general reasoning pattern that can help account for the transitions between the states shown in Figure 14. Table 1 summarizes evidence from the protocol that S2's progress is a result of this kind of cyclical process rather than being a result of either a convergent series of deductions or an induction from observations. Figure 16 is therefore a model of the processes producing the observed behaviors shown in Table 1. Here I assume that the bending rod and zig-zag spring models are simplifying models, that the extent to which they are explanatory is unknown to S2 at the time he proposes them, and that they are part of his attempts to develop an explanatory model.

Note that the cycle in Figure 16 corresponds to the non-empirical processes B, C, D, and E in Figure 4, the model construction cycle discussed earlier. Process B is also implicated in the rapid search for analogies such as "molecules, polyesters, and car [leaf] springs" in line 57 of the transcript. Thus, there is evidence in this case study which supports the existence of the non-empirical processes proposed in the model of hypothesis

development shown in Figure 4. We therefore appear to be in a position where real-time protocol evidence can be gathered to evaluate the plausibility of such models of scientific reasoning.

Non-inductive hypothesis generation. I will now examine more carefully the claim that S2's final model is neither the result of a convergent series of deductions nor an induction from observations. When S2 generates analogue model hypotheses, they appear not to be deduced logically from prior principles--they are essentially reasoned conjectures as to what might be a fruitful representation for analyzing how a spring coil works. The reasoning involved does not carry the certainty associated with deduction.

Nor, apparently, are they built up inductively as abstract generalizations from observations. S2 is unable to collect new data during the interview, and consequently his reasoning is independent of new empirical processes. One can also consider whether he might be making new inductions on perceptual memories of prior observations, but he does not appear to recall observing bending, twisting, zig-zags, or squares in springs; instead these appear to be newly imagined models. The novelty and non-observability of the polygonal coil with torsion model, and its evolution from criticisms of the earlier horizontal rod model argue that the hypothesis generation process in this case was an imaginative construction and criticism process rather than one of induction from observations. Quite possibly, S2 would have made some new observations of springs as well, had they been available (although it is doubtful that he would have observed torsion effects). But the present case study at least demonstrates the possibility that impressive progress in explanatory model construction can be made via non-inductive processes.

Of course, it is highly likely that empirical information was involved in the original development of the prior knowledge he uses. In attempting to speak to the rationalism vs. inductivism issue it is important to identify the time period of focus For the purposes of this analysis, the focus is on the new knowledge developed during the hour or so of reasoning in the interview rather than on the origins of the prior knowledge he uses. For example, he uses prior knowledge in the form of the concept of twisting. One assumes his earlier learning of the concept of twisting involved empirical experiences with wrenches, cranks, knobs, etc. His new model of the polygonal spring with torsion uses his old concept of twisting as one of its elements, but the total structure of the model is a larger new construction. The point is that the new knowledge developed by S2--the construction of a new explanatory model hypothesis for how a spring works--was apparently formed by processes during the protocol which were non-empirical.

I do not wish to say here that s... form of suggestion from patterns perceived in data cannot be involved in some types of scientific hypothesis formation. Rather, the case study acts more like an "existence proof" in showing the possibility that non-inductive construction processes can be very important in the formation of e... 'anatory model hypotheses.

An explanatory hypothesis ... to an empirical hypothesis. The final model of the polygonal coil with torsion raises S2's confidence in the empirical law hypothesis that (other factors being equal) wide springs will stretch more than narrow springs. Apparently this is a case where the development of a convincing explanatory model hypothesis can establish high confidence in an empirical law hypothesis in the absence of new empirical information. Kuhn (1962) discusses examples of this pattern in the history of science.

Argument for not separating the context of discovery and the context of justification. Finally, I want to consider a potential criticism of the model

construction cycle shown in Figure 4. It is traditional in philosophy to separate the contexts of hypothesis formation and hypothesis testing and evaluation in science. If I claim to be portraying hypothesis formation process in Figure 4, then why does it include hypothesis evaluat...n processes as well? The answer concerns the observation that loops in the cycle can at times be traversed extremely rapidly. For example, S2's criticism of the bending rod in line 5 indicates that the time interval between model generation and criticism can be as small as 15 seconds. In addition, his modification of the zig zag spring model in line 23 indicates that an entire generation, criticism, and modification cycle can take place within 90 seconds. While an evaluation in the form of a carefully designed laboratory experiment can take days or even years, other evaluation processes such as certain non-empirical checks for consistency can take place much more rapidly. In this sense, evaluation is an inherent part of the hypothesis formation process. Stated in traditional terms, it may often be impossible to separate the "context of justification" from the "context of discovery." History of science tends to look at developments over a time scale of years or weeks. From this perspective it may be impossible to separate these two contexts in the early stages of hypothesis formation when the grain size of the time scale one is using is greater than fractions of an hour.

In addition, generative techniques appear to be used in the service of evaluative goals in this protocol. The initial generation of the zig-zag and square spring ideas, for example, appear to be attempts to evaluate the appro...iateness of the bending rod model. Subsequently these become candidates for replacing the rod model.

In sum, the reason that evaluation processes appear in the model of hypothesis formation is that they appear to be an inherent part of hypothesis formation down to time periods of less than a single minute on occasion. In such cases, one sees a rapid, dialectic interplay between generation and evaluation processes.

EUREKA OR ACCRETION? THE PRESENCE OF INSIGHT IN S2'S PROTOCOL

I can now move to the second issue outlined in the introduction--the pace of theory change: "Does S2's reasoning contain Eureka events that involve sudden reorganizations, or does he make progress smoothly in an incremental manner?" The answer to this question is not obvious. It seems to be possible to argue in either direction from this protocol. One can point to what appear to be sudden insights, but on the other hand, sections precede these insights in which the subject prepares the context and groundwork for having them. Sometimes his methods appear to be systematic, but at other times ideas arrive in a rush, as if they are outside of his control. Thus, there seem to be mixed signals in the protocol on this issue.

Defining a Pure Eureka Event

In order to say something useful about the Eureka question, one needs to become more precise about the meaning of a Eureka event. Here I will propose an initial definition of the extreme case of a pure Eureka event as an extremely sudden, reorganizing, extraordinary break away from the subject's previous ideas. I use the term 'extraordinary' here to refer to processes such as unconscious or supernormal reasoning that are different from those used in ordinary thinking. If the appearance of a new hypothesis constitutes a break in the train of thought--if the hypothesis comes "out of the blue" and appears unconnected to the subjects' previous ideas in the protocol--this

would constitute one kind of evidence for an extraordinary and probably unconscious thought process. The accretion vs. Eureka question in extreme form then becomes: Is the subject's accomplishment the result of a smooth, incremental, controlled, buildup from previous ideas? Or is it a sudden, reorganizing, extraordinary break with his previous ideas? I will consider two sub-issues of this question expressed by the two pairs of key words in it: sudden reorganizing, and extraordinary break. In this section I would like to use the analysis of the protocol as an initial test bed for concepts developed to describe the quality and pace of structural change in creative hypothesis generation activities. Some of these concepts may also prove useful for analyzing structural change in theoretical models in real scientific research.

Is There A Sudden Reorganizing Change in S2's Understanding?

This subquestion itself can be broken down into two parts: Is there a significant structural change? and: Is it a sudden change? For the latter part, a pertinent time period must be identified over which the change takes place, and a pertinent concept of "rate of hypothesis formation or modification" must be defined. I will conclude that although the torsion discovery was not a "blinding insight"--an instantaneous reorganization of his ideas--it certainly was an impressive and relatively sudden breakthrough. The problem is to develop a relatively precise language for saying this.

Is there a significant structural change? One first needs to ask about the size of the change in representation or understanding produced by the torsion insight. Does it simply add on a small new fact or is it a complete reorganization? The type of change in understanding to be discussed here is a structural change (change in relational structure as opposed to surface features) in a currently assumed mental model.

It is clear that the polygonal coil with torsion insight does not constitute a reorganization in his understanding of any domain larger than the "theory of springs" (such as the "theory of elastic materials"). However the insight does appear to add more than a simple fact; it appears to constitute the addition of a significant set of structural relations to the subject's hypothesized model of the spring system, including the new causal chain of weight causing twisting and torsion, which in turn causes resistance to stretching; and the new global effect of finding no cumulative effect of bending throughout the square spring.

Can the insight be characterized as a reorganization of the subject's mental model? In some senses it can, although the shift could have been larger. Torsion is a completely different geometric deformation than bending and constitutes a significantly different hypothesis. The case here would be clearer, though, if the subject had switched more completely from the view of spring forces coming from bending to the engineer's view that spring forces come primarily from torsion. He did not go this far; instead he switched from using bending alone to using bending and torsion together in his explanations. But he did raise the question of which of these two effects predominates. Although he was unable to reach an answer to this last question in the interview, when asked at the end about whether the stretch could be due completely to torsion, he felt that it was perfectly plausible. Given more time, the fuller transition might very well have taken place. Clearly the potential for a complete replacement of the deformation mechanism in the spring has been created.

What one can say then is that the subject achieved a major breakthrough in adding a major chain of casual factors to his model of the spring. This can be considered to be a reorganization in the sense that a new system of

relationships was created. Thus the structural change in this subject's model of the spring appears to be of intermediate size. The change process was characterized by imaginative attempts to switch to different problem representations, most of which failed. When a productive representation is found (the polygonal coil), it leads to the recognition of a system of new relationships involving force, torsion, and twisting. But it is not a "revolutionary" change in the sense of rejecting and replacing a large, previously assumed body of established knowledge structures. However it does allow us to imagine the possibility that such a rejection and replacement could occur in science via a similar process.

<u>The pace of change in understanding</u>. I have taken a high rate of change in the currently assumed model as one defining characteristic of a pure Eureka event. This rate of change could be defined as the ratio of the size of the change in the model's structure to the time interval over which the change takes place. The latter concept may not be easy to operationalize as an observable variable, depending on the comparisons being made and the complexity of the protocol, but it should at least play a clarifying role at the theoretical level.

It is a challenging task to point to a specific time interval in the protocol representing the "period of insight" because of the difficulty in defining the latter. As an upper limit, the time for the subject's total solution was 52 minutes. Thus, it is certain that the subject changed from the rod model of the spring to the square coil with torsion and bending in a period smaller than this time. Viewed on a large time scale appropriate to the history of science, this would certainly be considered a tiny interval that indicates a relatively sudden structural change.

But much of this time was spent testing the simpler rod model and trying out other analogies, most of which were blind alleys. Can one identify a shorter period of insight within the protocol? The bending rod model was proposed within 1 minute after reading the problem. Then a long period without lasting progress in model development of about 40 minutes ensues as the rod model is questioned, the "zig-zag" models are proposed and rejected, and other analogies are tried. Finally, there is a breakthrough in a four minute period during which the subject refers to the square hexagonal coils, makes the torsion discovery, and incorporates it into his final square coil model of the spring. When the subject finally generates the hexagonal coil toward the end of the protocol, it takes less than 80 seconds for him to recognize the torsion effect, and less than another two minutes to settle on the square coil as his final model of the spring. This four minute period is therefore a candidate for the period of insight.

However, the square coil idea was first considered very briefly--only about six minutes into the protocol. But it was quickly dropped in order to consider the zig-zag spring. 34 minutes later, it was taken up again and leads to the torsion insight. Should this 34 minutes between the dropping and reemergence of an idea be counted as part of the period of insight? I will assume not, since the subject was following separate ideas during this time which turned out to be blind alleys. If one makes this assumption, one can point to this four minute segment as a relatively sudden "period of insight." But the difficulties involved in defining the period of insight here are clear. The benefit of this exercise, however, is that it forces one to develop some useful distinctions between concepts such as structural change in a model, the period of insight, and the rate of structural change in a model.

On the other hand, the insight was not instantaneous, and criticism and modification processes did occur during this four minute period as shown in Figure 16 and Table 1. This means that from a microscopic perspective which looks at the fine grain in the data, the insight appears to be "unpackable" into potentially understandable subprocesses. This leads me to describe it as "fairly sudden," rather than as an extremely sudden "bolt from the blue." This is the first sense in which the insight fails to qualify as a "pure Eureka event."

In summary, there appear to be periods in the protocol where progress is made slowly or not at all and others where progress is quite rapid. Those periods where little progress is made are frustrating to the subject but they in fact may provide necessary preparation for the later insight. The pace of structural change is uneven rather than consistent, and progress comes intermittently. When it does come, it is in the form of a relatively sudden breakthrough that involves a significant structural change in the subjects' hypothesized model.

Does the Subject Use Extraordinary Reasoning Processes?

The second major subquestion to the main question of whether there is a pure Eureka event in the protocol is whether S2 used extraordinary [illegible] processes during his breakthrough. If the processes are found not to be extraordinary, one can also ask the opposite question of whether the subject's thinking is highly controlled in the sense that he always pursues a series of well defined, conscious plans and procedures. I will conclude that the torsion-polygon insight was neither due to an unexplainable, extraordinary process, nor due solely to a planned, methodological procedure. Rather, it was the result of a dialectic process of conjecture, criticism, and rejection or modification, involving relatively uncontrolled divergent associations and playful transformations on the one hand, as well as relatively controlled strategies for mounting attacks on the problem. But these are all ordinary reasoning processes. His association and recognition processes in particular can be viewed as divergent and creative, but these processes are neither conscious plans nor extraordinary.

Extraordinary thinking. By extraordinary thinking, I mean the use of special processes which are outside of the set of normal reasoning processes used in everyday learning and problem solving. From a psychological point of view, this means I cannot imagine a plausible explanation for a particular thought process based on an ordinary sequence of inferences, associations, guesses, estimates and criticisms, etc. Two ways extraordinary thinking could occur during a problem solution, then, are: if the subject performs some supernormal feat of synthesis without preparation; or, more generally, if there is a break in the train of thought--a jump into a new train of thought that has no apparent connection to any previous thought. This last kind of event might be evidence for unconscious processing.

Two types of "breaks." However, it is important to distinguish between a break away from the subject's currently assumed model, and a break in the train of thought. Clearly, S2 "breaks away from his initial model" of the problem. The torsion insight represents a real break (in the sense of "breakthrough") with his previous bending rod model for understanding the problem.

On the other hand, S2's work does not contain an obvious "break in the train of thought." It does seem possible to construct a believable psychological account of his thought process as a series of connected conscious ideas. The growing series may actually look more like a branching

tree or network than a single chain, and there may be jumps of attention from the end of one branch to the end of another, but the essential point is that a new idea does not appear from nowhere; it is always plausible that it was an outgrowth of the subject's previous conscious ideas.

Two major parts of S2's insight in the solution are the generation of the square coil analogy and the discovery of torsion. A plausible explanation for the torsion discovery can be given as follows. As S2 was examining adjacent sides in the newly constructed hexagonal coil model, an existing mental schema for dealing with twisting situations was activated. Such a recognition process is a common event in everyday problem solving and should not be considered extraordinary. It does happen to be a key event in the solution to this problem. He was not certain about this conjectured recognition at first, and needed to examine it critically, which led him to consider a square coil as an easier case.

In the case of the original square coil analogy, recall that it was generated while S2 was thinking about whether there was a difference between a bending rod and a single spring coil:

23 S2: "Why should the coil have anything to do with- ? it's just so arbitrary. Why does it have to be a [circular coil]? Surely you could coil a spring in squares, let's say, and it.. would still behave more or less the same."

This is a highly creative idea but not one that necessarily involves extraordinary reasoning. Here the subject appears to be imagining ways to bend a piece of wire into a spring. The plausible ordinary process is one of imagining a simple transformation one could perform with one's hands.

The worth of this idea was not recognized immediately. Only after thinking hard about and confirming the lack-of-bending anomaly in the spring does S2 return to the square coil idea in line 117 and use it productively.

Here there is a branch in the train of thought, but the return to the square coil idea can be seen as connected to its earlier appearance.

In some cases, the connection to a previous idea may be a weak one--a loose association or conjectured recognition or playful transformation rather than deductive inference or a precise subquestion. Associations, transformations and recognitions in this light are divergent, unpredictable, and sometimes highly creative processes, but not extraordinary ones in the sense of being unconnected to the network of current representations. I consider S2's overall achievement--the marshalling and orchestration of a large number of reasoning processes to produce the invention of a new explanatory model--to be extraordinary in the sense of being unusually productive and creative. However, I can see no evidence that the reasoning processes he uses, taken individually, are extraordinary. The train of thoughts S2 reports weaves a "coherent story" in the sense that each new idea appears connected to previous ideas and is therefore at least weakly constrained by previous ideas.

S2's ideas are also connected by the specific relationships implied in Figure 4 in which new ideas can grow out of modifications of or reactions to past ideas. This is an even more specific sense in which his insight did not emerge from "out of the blue," and it will be discussed further in the section on creative processes below.

It should be noted that Tweney (1985) cites evidence to discredit the idea that Faraday's discovery of induction was a "bolt from the blue," as some have thought; and Perkins (1981) came to the conclusion, after reviewing the literature on insight in creative thinking, that there is no convincing body of evidence that insights occur via special or extraordinary processes. This does not eliminate the possibility that such special processes might exist,

but it does indicate that it is difficult to find convincing evidence for them.

Defining "Insight"

I have discussed some senses in which S2's protocol does not provide evidence for a pure Eureka event. In this section I will propose some criteria for a less extreme kind of event I will term a "scientific insight." In order to sort out the different senses in which S2's solution is and is not an example of insight behavior, it will be useful to refer to the following list of the features of his polygon with torsion breakthrough which are insight-like.

I. The breakthrough is an important idea:

   A. It is a key idea--an important component of a solution;

   B. It overcomes a barrier that blocked progress; it comes after a frustrating series of false leads and blind alleys- after a period where little progress has taken place; it resolves an anomaly.

II. The breakthrough adds significantly to the subject's knowledge. It produces a large structural change in the subject's model where he:

   A. identifies new variables or causal factors in the system;

   B. identifies a new hypothesized mechanism in the form of an explanatory model;

   C. states that it increased his understanding.

III. The subject's ideas are generated fairly quickly during the breakthrough, and he achieves rapid subsequent progress towards a solution.

IV. The breakthrough is accompanied by more complex phenomena:

   A. It is accompanied by indicators of emotional response- surprise, joy, satisfaction,

   B. The subject realizes immediately that something important has been discovered in the torsion idea.

The following are senses in which S2's breakthrough was not a Eureka event:

I. The breakthrough idea was not generated extremely suddenly without preparation.

II. It did not involve the total replacement of one hypothesized model with another.

III. It is explainable via ordinary reasoning processes; there is little evidence that it was:

A. an extraordinary thought process;
B. an unconscious process;
C. a break with all previous trains of thought.

One can now use the criteria developed in the above list to define three categories of insight behavior. These definitions are, of course, to some extent arbitrary; the goal is to try to define some useful categories that will help to make finer distinctions that can aid in analysis. The categories (designed to refer to hypothesis development activities) are "breakthrough," "scientific insight," and "pure Eureka event," defined in increasing order of specificity and unusualness so that the "breakthrough" category includes "scientific insight," and the "scientific insight" category includes "pure Eureka events."

A breakthrough is a process that produces a key idea--an important component of a solution--and that overcomes a barrier that can block progress toward a solution.

A scientific insight is a breakthrough occuring over a reasonably short period of time leading to a significant structural improvement in one's model of a phenomenon. That is, it constitutes a shift from the subject's previous way of representing the phenomenon and leads to an increase in understanding of the phenomenon, as determined by the evaluation process in Figure 4. This is the descriptor that appears most appropriate for S2's breakthrough.

A pure Eureka event is a scientific insight where: (1) there is an extremely fast emergence of a new idea with little evidence of preparation; (2) the new idea is a whole structure replacing the subject's previous model or understanding of a situation; (3) the process is not explainable via ordinary reasoning processes; extraordinary thought processes or unconscious thought processes are involved.

This recasts the earlier initial definition of a pure Eureka event (an extremely sudden, reorganizing, extraordinary break from the subjects' previous ideas) in a way that relates it to other types of insight behavior. For some purposes, reducing everything to these three categories may be less important than having something like the above list of features for describing different ways in which an idea can be insightful. But the three terms may provide a useful shorthand for some purposes.

Summary

This section has attempted to answer the question: "Was the polygonal coil with torsion breakthrough more like a sudden Eureka event or an example of steady accretion?" The case against accretion is the following. When one examines the thinking aloud case study microscopically over tens of minutes on a small time scale, one sees an arduous dialectic process of conjecture, evaluation, and rejection or modification of hypotheses that precedes the breakthrough, as opposed to an event that takes place instantaneously and effortlessly. Thus, in terms of effort alone, there is certainly a long and steady expenditure of energy on the part of S2. However, the issue of central concern here is not the expenditure of energy, but the construction of new knowledge. With respect to the formation of an explanatory model, progress did not take place as a smooth, incremental evolution of new knowledge.

Progress appears to be blocked when the subject is "locked into" his current conceptualization of the problem for long and sometimes frustrating periods. Most of the approaches he tries during this period must be thrown away; they are not used later as pieces of the final model. One analogy generated by the subject then led to a fairly sudden insight which led to the formation of a new hypothesized model. Thus, insight process were found which are not accretionist in character and which support a view of scientists as capable of significant reorganizations in a relatively short period of time.

On the other hand, the major case against a pure Eureka event is that these processes do not appear to be supernormal or unconscious ones. It was concluded that S2's breakthrough can be considered a relatively sudden and structure- [illegible]g event that includes relatively divergent and creative processes, but that it should not be considered extraordinary. The upshot of the present analysis, then, is that rather than being an example of an accretion or Eureka process, the pace of progress is uneven, with "more revolutionary" and "less revolutionary" periods of work. S2's breakthrough can be characterized in the above terms as a scientific insight but not as a pure Eureka event.

CREATIVE MENTAL PROCESSES

The various processes in the model construction cycle can be divided into two main categories, the productive processes of generation and modification and the evaluative processes of empirical testing and rational evaluation. In this section I examine questions about these individual processes and how they interact. Evaluative processes will be discussed first with respect to the role of anomalies, leading to the view that a tension condition indicated in the protocol is partially analogous to the motivating tension between an

anomaly and a persistent paradigm in science. In a second section I discuss the role of transformation and invention in analogue hypothesis generation, processes which create the possibility of provoking the recognition of a new principle in a novel construction. In a final section I discuss the role of divergence and constraint in productive processes, leading to the view that these processes are less constrained and convergent than established procedures, but more constrained and "intelligent" than a blind selection and variation process.

Anomalies and Persistence in Protocols and Paradigms

In this section, I attempt to provide a deeper level of explanation for the phenomenon of extended periods of little progress between insights in the protocol in terms of the dialectic view of model construction as a cyclical process of generation, evaluation, and modification. Table 1 outlines evidence in the protocol for the presence of such a dialectic process. One of the more subjective observations one can make of S2's overall behavior in the tape is to point to the impressive amount of strenuous activity that S2 poured into this process. Even for those who admit that analogies can play a role in scientific discovery, a common view is that a subject may be passively reminded of an analogous situation C, and be able to transfer a prediction from C back to the problem. The image is of the insight "coming to the subject" as a passive receiver. In the present case, the subject is much more active and aggressive: inventing tentative analogies, rejecting a number of them, pursuing those that have promise by criticizing them aggressively, and modifying them in a series of thought experiments until he is satisfied he has a valid model. A more apt informal image here is a constructivist one of the subject "aggressively constructing and testing different models in an effort to capture an understanding of the phenomenon."

What drives all this strenuous activity? In particular, why does the subject persist in criticizing his understanding when he is already 90% sure that the wider spring will stretch more? What drives the hypothesis formulation process, and keeps it working in the face of little progress? Why is there a period of very little progress followed by a period of insight in this protocol? For the last question, one could simply say there are a large number of possible paths to consider and that it is just a matter of luck that determines when one will find a successful path. But there may be a deeper reason connected in at least one way with Kuhn's idea of intermittent progress in science (periods of normal science and revolution.) In this section, I attempt to speak to these questions in terms of conflict between a persistent model and a perceived anomaly.

Dialectic tension. There is a palpable tension obvious in the first section of the video tape that is conveyed only to a limited extent by the transcript: a frustration with not being able to resolve the anomaly of the lack of bending in a helical spring. For example in lines 87 and 111, he says:

87 S: ...if you start with a [stretched] helix and unwind it...you should get a bow [bend], but you don't. I mean visually imagining it, you don't. I don't see how you could make the bow go away- just to wind it up- Damn it!

111 S: Darn it, darn it, darn it...why should that [the difference between a rod and a coil] matter?

The tension apparently occurs between the rod model, and the lack-of-bending anomaly. This tension or disequilibrium condition appears to provide a driving force that keeps the subject actively attacking the problem even though he claims he is already 90% sure of his answer. It bothers him enough to drive him to search for a way to modify the rod model or replace it. This

search takes up the better part of the 52 minute interview which is peppered with expressions of frustration. Line 178 provides evidence that the reason for his dissatisfaction has to do with an important difference between having a confident prediction and having a feeling of understanding. He speaks of having low confidence in his understanding because the rod model predicts a property that he feels should not occur in real springs, even though he has high confidence in his predicted answer. I take this as an interesting example of a situation where good performance is not equivalent to deep understanding, and, because of the subsequent events which raise his confidence, I take the important difference to be the lack of a satisfying explanatory model.

Persistence of the initial model. Line 87 above is indicative of the fact that the subject finds it very difficult to give up the bending rod model. The persistence of the bending rod model, with its image of the spring coil made of segments, each of which are bending, appears to be an example of an Einstellung effect; a problem space dominates the subject's thinking, and prevents him from generating necessary new ideas. In order to make progress, the subject must redescribe the problem using new descriptors; he needs a new problem representation. But the rod model keeps reappearing in the transcript. Even though he proposes rejecting the model several times, he is repeatedly tempted to return to it. It is as if the idea has an autonomous "life of its own."

A powerful anomaly. Pitted against this persistent model is a powerful anomaly. Bending in the vertical plane is central to the rod model, but he cannot imagine a way for bending to take place in a helical spring. Here I am using the term anomaly in the broad sense of a new finding which conflicts with previous ideas, whereas in some narrower usages, its referent is limited to a new non-conforming observation. In summary, the symptoms of tension observed in the subject appear to be the result of a conflict between a persistent initial model and a powerful anomaly.

Analogy to the persistence of a paradigm. When the polygonal coil with torsion model is found, it appears to finally break the tension. There may be a partial analogy here to Kuhn's idea of the persistence of a paradigm in science (Kuhn, 1962). Even when anomalies are known to exist, it is difficult to reject a paradigm until something better is found to replace it. But this is very difficult to do since it requires breaking out of the current, stable point of view. Here the bending rod model is hard to reject until the better model is found, and this requires a great deal of imaginative effort. Compared to a problem on the frontier of science, the scale here is, of course, very much smaller and easier. For example, there are no social forces to reinforce the stability of the subject's initial model. Nevertheless, this tension between a persistent initial model and a recognized anomaly, which helps to explain the long period of slow progress followed by a period of scientific insight in the protocol, is reminiscent of Kuhn's descriptions.

Tension from an anomaly as a source of motivation. Furthermore, the tension associated with his dissatisfaction with his understanding apparently drives him to keep reattacking the problem repeatedly until he makes a breakthrough. In the present situation the generation of a new or sharply modified model is required in order to break the deadlock; and it is in such cases that analogies should prove to be particularly useful, since they help the subject break away from his current model. When they are successful, they apparently can lead to fairly large and rapid changes in a mental model. S2 considers no less than 12 analogous cases during the protocol, including some that do not appear in the transcript excerpts given here, and this high degree

of generative activity can be seen largely as a response to the tension urging him to find a more satisfying model. Thus, this example suggests that the tension between a previously established model and a prominent anomaly can be a major driving force behind hypothesis generation.

Here it appears to require something as divergent as analogy generation to break out of the Einstellung effect formed by a persistent inadequate model. This provides an important connection between the previous two major sections of this chapter on model construction via analogy and the presence of insight in S2's protocol. The process of analogy generation, motivated by the recognition of an anomaly, appears at times to be powerful enough to break away from a persistent but inadequate model or view. This is one way in which a scientific insight can occur. Thus the phenomenon of intermittent progress involving periods of little progress punctuated by occasional insights can be seen as a natural outcome of psychological processes.

Transformations, Invention, and Memory Provocation

Transformations as a source of creativity. In this section I move to a discussion of hypothesis generation processes, and of analogy generation via transformations in particular. It should be noted that association apparently is not the only source of creative or divergent ideas in this protocol. For example, after considering the bending rod case, in line 23, S2 says: "Surely you could coil a spring in squares, let's say, and it would still......." Here the subject seems to be constructing a new case by transforming the [illegible] into a square coil rather than making an association to an existing idea in memory. Also, in line 37 the double length spring analogy originates from the transformation of sliding a weight along a wire. A transformation occurs when the subject alters features previously assumed to be fixed in an existing problem representation to create a new representation. In a previous study, it was found that of the analogies generated by 10 subjects in solving the spring problem, more were generated via a transformation than were generated via an association (Clement, 1988). In that study, the term transformation was used to refer to a general type of cognitive operation in the form of the alteration of a representation for any situation in working memory, including an original target situation. Thus, the modification process referred to in Figure 4 is a transformation applied to the previously hypothesized scientific model. Although association often is cited as a primary source of creativity, it may be that transformations are just as important, if not more important, in scientific problem solving.

Invention of analogous cases. The novelty of the zig-zag and polygonal springs supports the claim that they are invented cases. For example, the square coil was apparently constructed via a transformation, not recalled from memory. Although analogous cases typically are thought of as schemas already in long term memory which are activated or retrieved during problem solving, it can also happen that the analogous case is invented along with the analogy relation. Models generated by inventing an analogous case are in this sense even more creative than those generated by being reminded of an analogous case.

The polygonal coil is a new problem representation amenable to a new method of analysis (torsion). In such an instance, the knowledge that one gains from an analogous case C need not be "stored in" C. Thinking about C may activate a useful schema (such as torsion) which has not previously been applied either to the original situation to be explained or to C. This instance provides some support for Black's view that the interaction between the original and analogous cases can produce knowledge in the form of an

insight that was not residing beforehand in either the original or the analogous cases: "It would be more illuminating in some of these cases to say that the metaphor creates the similarity than to say that it formulates some similarity antecedently existing" (Black, 1979, p. 37). In the present case study, in contrast to the usual view of analogy generation, the recognition of the key relationship (torsion) in the analogous case occurs well after the generation of the analogy. The analogy plays a provocative role in activating a principle whose applicability was previously unrecognized, rather than a "direct source of transferred information" role. This issue is discussed further in Clement (1988).

Thus some analogies are invented rather than recalled, and some play a "provocative" role in accessing new information rather than a "direct transfer" role.

Constrained Successive Refinement vs. Blind Variation

In this section I turn to hypothesis generation and modification processes as sources of creativity within the model construction cycle. I want to begin to examine the extent to which these processes are random or constrained. In fact, much of the protocol preceding the torsion insight can be viewed as divergent exploration to find clues for a new direction for analysis. Some relatively unconstrained divergent processes that occur in the protocol are associations, transformations of the problem space, the activation of analogous cases in memory, and the invention of new analogous cases. These processes can lead to multiple suggestions with no guarantee of success or even relevance. They are much less constrained and systematic than an established, convergent procedure for solving a problem. This leads to the following question: "Are S2's processes so divergent as to constitute a random trial and error process"?

Certainly S2's divergent thinking seems to be less systematic or formal than either logical deduction or methodical procedures of induction. And yet this less formal method of conjecture, criticism, and modification allows the subject to make impressive progress in his understanding. In this process, it does not matter so much if one makes a faulty conjecture; it may still be possible to transform it into a successful conjecture by carrying out a series of criticisms and modifications. In this section I discuss the sense in which this successive refinement process goes beyond a random trial and error strategy.

In its weakest form, the cycle in Figure 4 can be described as a random trial and error process. By this I mean that the old hypothesis is discarded and a totally new random hypothesis is tried on each cycle, without any learning or attempts at modification between cycles. A less divergent strategy would be to randomly modify part of the previous hypothesis and keep the remainder in each cycle. This is analogous to a random variation theory of evolution. (See Campbell, 1960, for an exposition of this analogy.) However, there is evidence that the generation and modification processes are not random ones in the case of S2, and that they are more powerful than the above two processes.

The first type of evidence is the general observation of spontaneous analogy generation as a hypothesis generation strategy. Analogous cases are generated by association or transformation processes which means that they are connected in some way to the target. The connection may not be a strong one, but this is better than no connection at all.

The second type of evidence indicates that at times, a conscious constraint is held in mind when generating a new association or transformation. For example in line 57, S2 appears to focus on the idea of stretching as a constraint as he generates several tentative analogies by association after asking himself, "what else stretches"? In a second example in line 117 he generates polygonal coils after attempting to "generate ideas about circularity...why should it matter? How would it change the way the force is transmitted," in the spring? The use of conscious constraints during generation is one sense in which the model construction cycle can go beyond a random variation and selection process.

A further type of evidence is the observation of an intelligent modification process in the cycle. Most of the analogies generated by S2 were rejected in the end. But several did clearly serve as stepping stones by preparing the way for suggesting better ideas later on. This gives the cycle the property of successive refinement, in which one can learn from the mistakes of the past. For example, the first zig-zag spring in line 23 is criticized as a model because of the contaminating effect of bending at the joints. This is then modified into a second zig-zag model with stiff joints which is aimed at removing the criticism. As a second example, the bending rod model is criticized because of an assumed lack of cumulative bending in the spring. The introduction of the square coil model solved this problem by eliminating the cumulative bending effect. In these instances the subject seems to generate or search for modifications which remove particular difficulties that the evaluation process has identified in an existing model. Thus the cycle involves intelligent modification based on information about prior difficulties. This is a particularly powerful way in which generation and modification processes can be constrained. (I have only scratched the surface of these issues here. See Darden (1983), Rada (1985), and Darden and Rada (1988) for a further discussion of non-blind hypothesis generation, including the use of interrelations between scientific fields as a heuristic. Also, Holland, Holyoak, Nisbett, and Thagard (1986) discuss goal weighted summation of activation as a possible mechanism for guiding retrieval of relevant information, while Lenat (1977, 1983) discusses heuristics for learning by discovery in mathematics. From a broader perspective, in case studies of Faraday's and Darwin's thought, respectively, Tweney (in press) and Gruber (1974) have proposed that breakthroughs which appear to result from a fortunate "chance interaction" of several ideas were in fact significantly favored by a network of prior activities in the scientist's life.)

Finally, it should be noted that comparison and selection between previously generated models can also occur. For example, S2 settles on using the square coil as a model over the hexagonal coil, apparently because the square is simpler to analyze. This is a classic type of rational assessment criterion.

Less constrained methods. Not all generation methods are highly systematic or constrained. The generation of the double-length spring analogy in line 37 provides an interesting example. Here the the analogy originates from the idea of sliding a weight along a rod. He then imagines this transformation happening on the spring itself, as if it were simply an "inter[illegible]ing to try." There is some evidence here that the subject [illegible] exploring new and uncertain directions rather than trying to achieve a specific goal using a conscious strategy of generation under constraints. Although the analogy in this case does not lead to a breakthrough, one cannot rule out the possibility that the ability to think playfully in a relatively unconstrained manner would at times be a powerful method.

Summary. Thus I arrive at an intermediate position concerning the nature of the subject's hypothesis generation and modification processes. Compared to a pure Eureka event, they form a more ordinary and connected train of thoughts. Compared to a problem solving process governed by established procedures, they are divergent processes that are relatively unconstrained. They can produce novel inventions like the polygonal coil as well as a presumably infinite variety of other representations. As they occur here within the model construction process however, they often appear as part of an intelligent successive refinement process rather than a blind variation and selection process.

DARWIN'S THEORY OF NATURAL SELECTION

Having reviewed some philosophical views of hypothesis formation processes in science and having presented some current findings from expert protocols, I will consider a third approach to the study of creativity in science: the analysis of notebooks and other historical documents produced by innovative scientists. I return to the example of Darwin's theory of natural selection mentioned at the beginning of this chapter. Gould (1980) noted that earlier writers had described the origin of this discovery as the net result of a gradual buildup of information--a process of accretion that occurred during Darwin's voyage on the Beagle, principally in South America. However, Gruber (1974) debunks this view by pointing to evidence in Darwin's notebooks indicating that after the Beagle's voyage, he, like a number of other naturalists, believed in the existence of evolution (gradual change [illegible] species) but still had no model to explain it. He lacked the theory of natural selection. It was only after a year and a half of conceptual struggle after his return to England that Darwin was able to formulate a satisfactory theory. A particularly famous piece of evidence arguing against the accretion view is the important role of an analogy that occurred to Darwin when he read Malthus. In his autobiography (written much later) he wrote:

> I happened to read for amusement Malthus on population, and being well prepared to appreciate the struggle for existence which everywhere goes on from long-continued observation of animals and plants, it at once struck me that under these circumstances favorable variations would tend to be preserved, and unfavorable ones to be destroyed. (Darwin 1892, p. 42-43)

Darwin saw that factors similar to those that limited population growth in man (such as a limited food supply) might be a source of a selection factor in a survival of the fittest model for animals. Thus, the accretion by induction view is hard to maintain in Darwin's case.

Does the Malthus episode then provide evidence for a Eurekaist view of Darwin's achievement? The recent analyses of Darwin's private notebooks carried out by Gruber (1974) and Schweber (1977) argue against this conclusion as well. They show that Darwin struggled long and hard, considering several hypotheses and gradually modifying and fitting a number of pieces together into the theory of natural selection. The notebooks indicate the analogy from Malthus was only one event in a complicated process of generation, evaluation, and modification.

Darwin read widely in fields outside of biology, and apparently drew analogies from these fields in constructing his theory, including the ideas of variation and selection (from breeding in domestic husbandry), and the idea of natural competition (from Malthus as discussed above) (Darden, 1983). Gould believed Darwin also was influenced by the laissez faire economics of Adam Smith which showed that an ordered and efficient economy could emerge from free competition. An analogy can be made to evolution here via the common idea of positive group change coming out of individual struggle. In addition,

Gruber (1974) cited Darwin's early geological theories on the growth of Pacific barrier reefs over tens of thousands of years as fertile preparation for the idea that small individual forces acting over long periods of time could effect vast changes in nature.

Thus historical evidence in Darwin's case now supports a more complex view than either inductivism or Eurekaism. Both the fertile empirical ground of careful observations and the and non-empirical insights formed by key analogies to other fields were apparently crucial in Darwin's case. This analysis suggests that a more realistic hallmark of genius than pure Eureka episodes is the ability to generate a variety of tentative analogue models as a starting point and then to carry out the long struggle of repeated conjectures, criticisms, rejections, and modifications necessary to produce a successful new theory. Although the time scale is much longer in Darwin's case, it is interesting that these are the same distinguishing criteria that emerge from the most impressive cases of model construction in the protocols discussed earlier. This suggests that perhaps the most viable powerful form of scientific reasoning lies not in the ability to "hit" on a perfect model at the outset, but in the ability to engage in such a dialectic, successive refinement cycle.

FEATURES OF CREATIVE THINKING AND IMPLICATIONS FOR FUTURE RESEARCH

Creative Thought

To the extent that an extended analysis can remove the initial subjective impressiveness of an event, perhaps I am in danger here of seeming to trivialize the processes of analogy generation, model construction, and insight as hypothesis development activities, and I would like to avoid giving that impression. Clearly, once one has thought through the answer to a problem, the solution process can appear to be less impressive or even obviou from hindsight. While one is actually solving a problem, however, creative reasoning such as that exhibited by S2 is impressive in a number of ways:

(1) First, there is the insight in the protocol which seems to lead to a "flood" of ideas. The speed of progress during this episode is impressive.

(2) S2's central achievement is the generation of a new structural hypothesis -the invention of a new mod. l of hidden mechanisms in the spring that he has never observed. This involves the identification of new causal variables in the system (such as torsion) and new causal chains, as well as the identification of a new global effect (lack of cumulative bending).

(3) An important factor in producing this achievement is the subject's desire to ask "why" questions and to seek a deep level of understanding beyon what is requi:·d for the solution of the immediate problen. Presumably, this urge to penetrate surface features and conceptualize an unoerlying explanator model at the core of a phenomenon is a basic motive underlying creative theor; motive formation i.. science.

(4) He exhibits a remarkable persistence in this quest in the face of recognized internal in sis.encies and repeated failures. There is somethin of an existential twist here: although the problem has no practical significance for the subject, he puts enormous energy into the problem of understanding as a challenge for its own sake.

(5) His playful and uninhibited inventiveness in producing conjectures and modifications of the problem is impressive. The analogous cases he generated in searching for a better way tc represent the problem included the bending rod, polyester molecules, leaf springs, watch springs, two types of zig-zag springs, two or more types of polygonal springs, and double-length springs. He displays an ability to think divergently and the flexibility to

modify thought forms in novel ways. In the author's experience, this kind of flexibility appears to be a prominent characteristic of creative physicists and inventors.

(6) There is a willingness to vigorously criticize and attack the validity of his own conjectures. S2 is able to engage in a dialectic conversation with himself, proposing new ideas on the one hand, and criticizing them on the other. This seems to require viewing the failure of any single idea as not very important; although as has been shown, the apparent failure of seven or eight ideas to produce a breakthrough does lead to some degree of frustration for S2.

(7) With respect to Figure 4, one can contrast the productive function of the generation and modification processes with the evaluative function of the rational and empirical testing processes. The divergent and creative generation processes (such as the use of analogies) represent a significant departure from the more systematic, rule-governed processes of theory growth envisioned by inductionists, who would tend to see them as much too unrestrained to be part of the disciplined scientific enterprise. However, the generation processes are not entirely unconstrained, as has been discussed, and the evaluation processes in Figure 4 provide some strong restraints which can in fact act to control the enterprise of model construction. Thus, alternating between generative and evaluative modes in scientific thinking is seen as a powerful method, even when the generative methods are divergent in character and new empirical tests cannot be performed.

(8) Perhaps S2's awareness of his own ability to criticize ideas, and the resulting faith in himself as a self-correcting system, allows him a freer hand--allows him to be more uninhibited in generating conjectures and

considering directions to pursue. It may be that generative ability and critical ability are mutually supporting. Critical ability gives one the freedom to be unusually associative or inventive. Generative inventiveness, or the ability to replace and repair what one removes gives one the confidence or assurance to be critical of and to at times tear down existing ideas. S2 seems willing to consider "risky" analogies such as the double-length spring and the bending rod that appear to be very different from the original problem. However, it has been shown that even when a risky initial analogy does not turn out to be explanatory, modifications of it may lead to an explanatory model. Realization of this potential for debugging or redesign via criticism and modification may allow one to feel freer to explore more imaginative models or a wider range of models. This freedom in turn would appear to be an important tool in the difficult job of breaking out of [illegible]ious conceptions of the target situation. Again, rather than the ability to hit on the best possible idea in one stroke, it may be that it is the ability to engage in a cycle of hypothesis construction and improvement that is the most powerful form of scientific thinking.

The above qualities appear to be some of the most impressive characteristics of creative thinking visible in the case study.

Implications for Future Research

The conclusions reached here suggest that creative hypothesis formation processes are still poorly understood, but not outside the realm of possible study. Mansfield & Busse (1981) give examples of five aspects of the creative process in science: (1) problem selection; (2) extended effort; (3) setting theoretical, empirical and methodological constraints; (4) changing constraints; and (5) verification and elaboration, including a process of formulating new constraints and testing them. Two areas which the present

case study does not address are problem formulation and empirical and methodological constraints.[9] These are important problems for future research.

There are also other areas where observations were made in the case study that the present analysis has said very little about. The first is the overall complexity in the details of S2's thought processes, including the presence of multiple goals, returns to previously attempted solution paths, the balancing of divergent and convergent processes, and the resolution of competing influences. In addition, each of the subprocesses shown in Figure 4 is in need of much more detailed study. Second, the subject can exhibit an "Aha" reaction that something important has been discovered, even before its implications have been developed and articulated. For example, the Aha episode upon considering the square coil in line 117 is of this form. Third, subjective observations from the videotape that are hard to capture in print are the exuberance present in his "Aha" episodes and the tone of frustration present during his periods of failure. This adds an emotional dimension to the process that is distinctly human. Fourth, I have only touched on the problem of how "guided" conjecture is guided--why one person's initial conjectures are much more fruitful in the long run than those of others. Fifth, S2's strong drive to ask "why" questions mentioned earlier (a kind of curiosity) certainly has not been explained. Sixth, very little has been said about rational evaluation. Of particular importance is the problem of how one evaluates the validity or appropriateness of a proposed analogy. Matching "important" features is one method, as has been illustrated, but there may be others as well (Clement, 1986). Finally, S2's flexibility in inventing new problem representations is hard to model. His image of the spring appears to be malleable; he appears able to modify it into an infinite number of forms and variations. In fact there are a number of spontaneous imagery reports in the protocol which suggest that certain forms of spatial reasoning on spatial representations may be central to S2's thinking here. Although the discussion of these reports is beyond the scope of this study, this opens up a large and important question for future research on the nature of these processes and the role they play in scientific thinking (Clement, in press [a] and [b]).

The above phenomena are not well understood, and indicate that we are far from formulating adequate explanations for many aspects of creative processes. They still inspire awe, pointing to areas where the science of psychology remains quite weak and where further research is needed.

EDUCATIONAL IMPLICATIONS

Learning via model construction is an area of utmost importance to mathematics and science education, and an area that is very poorly understood. The present study is essentially a study of learning via model construction in scientists. Thus the study will have interesting educational implications if it can tell us more about processes that need to be fostered when students are learning scientific models.

Essentially, I will propose that the model construction cycle in Figure 4 may be useful as a description of processes which need to take place in students learning to comprehend scientific models. Due to space limitations I can only present a brief sketch of this idea here. The cycle is relevant to three major educational goals: the content goal of comprehending established scientific models; the process goal of learning to solve ill-structured problems; and the even more ambitious process goal of learning scientific method or scientific inquiry skills. By attending to these different content and process goals, educators may be able to design instructional activities more effectively.

Content goals: comprehending scientific models. With respect to the first goal of comprehending established scientific models, several points can be made. First, as has been discussed, many modern scholars have argued that explanatory models are an essential part of scientific understanding. As shown in Figure 3, explanatory models are a separate type of knowledge from either empirical laws or formal quantitative principles. Easley (1978) and others have noted the unfortunate tendency of educators to associate "real" scientific thinking with only the latter two types of knowledge.

A second point is that students learn complex models via an internal construction process, not via a direct transmission process during lecture. I cannot support this assumption fully here, but current research in science education is providing an increasing amount of evidence in this direction. The complex, tacit, non-observable, and sometimes counterintuitive nature of scientific models means that misconceptions or "bugs" will be the rule rather than the exception during instruction, requiring critical feedback and correction processes. This means that the learning of complex, unfamiliar, or counterintuitive models in science requires a kind of learning by doing and by construction and criticism rather than by listening alone.

In this light Figure 4 is seen as a potential model for the learning of scientific concepts by construction in the classroom. Educators inspired by Piaget and others have advocated approaches based on the construction of knowledge, disequilibrium, and accommodation. Unfortunately, the application of these concepts to instructional design suffers from a lack of precision and consistency. The present approach may lead to a more explicit model of the process of learning scientific models. The findings from this study lend support to an educational strategy where rather than "swallowing" packaged ideas in a whole" in lecture, students are seen as developing partial models, questioning them in face of anomalies, and working from their initial model to construct a more adequate model. The term "knowledge construction" has been much used in discussions of education. Perhaps the concepts of using prior knowledge (e.g. analogies), modifying models, and the successive refinement cycle can provide a more explicit picture of construction processes.

A third point is that explanatory model construction takes place in the scientist via a set of processes that are different from those used either in formal deductive proof, in the manipulation of quantitative expressions, or in

inductions from data. The present study speaks perhaps most strongly to this last point. It underscores the importance of processes which aid abduction, such as: using analogue models for developing understanding; fostering disequilibrium in order to motivate efforts toward model construction; and fostering criticism and modification (or rejection) processes for overcoming difficulties occuring in students' models which contain misconceptions. Very valuable non-empirical criticism and modification processes can take place when students attempt to give explanations and argue about them in large or small group discussions (Clement, et.al., 1987). This simple implication is probably greatly underemphasized in instruction. Educators need to distinguish between activities aimed at forming explanatory models, and those aimed at forming empirical law hypotheses or formal quantitative principles, since the cognitive processes involved may be quite different. If this is correct, students are unlikely to learn explanatory models from laboratories aimed at inductive reasoning. Nor are they likely to learn them from the study of formal quantitative principles.

Problem solving and inquiry skills. Figure 4 can also be thought of as a model of the process of constructing a representation for an ill-structured problem. (Here, memories of prior experiences can play a role in empirical testing if no new empirical information is available). In the case of content goals as discussed above, considerable support might be given by the teacher in guiding students through such a cycle. However, in order to learn problem solving skills, students eventually need to be able to generate problem representations by going through construction cycles without teacher support. Despite this difference, Figure 4 provides the basis for seeing some significant overlapping in the strategies for achieving content and process (problem solving and inquiry) goals in science education.

Finally, the most ambitious goal in science education is that of teaching scientific investigation or inquiry skills. In fact, it is extremely rare to find a class in which students are asked to propose and test scientific hypotheses for phenomena. Here again, it seems important not to assume that "discovery learning" by induction from data is the predominant process in the scientific method. Model criticism and modification processes would seem to be of crucial importance in the design of inquiry activities.

Thus the most general point to be made is that the cycle outlined in Figure 4 may prove useful as an outline of relevant learning processes for guiding educators in designing and evaluating instructional activities concerned with the learning of scientific models. Here I have only been able to sketch some possible implications along these lines; further educational research and development efforts are very much needed.

SUMMARY

This chapter began by posing two questions concerning the origins of hypotheses in science and the role of insight or Eureka events in creative scientific thinking. I have attempted to show that protocol evidence can be used to argue against an overly inductionist view of the source of hypotheses. It can also be used to argue against either a pure accretionist or a pure Eurekaist view of the pace of change in scientific hypothesis formation. Instead it has led me to take a less simplistic view of hypothesis development, illustrated in Figure 4, emphasizing the possibility of both empirical and non-empirical sources of hypotheses and multiple passes through a cycle of generation, evaluation, and modification (or rejection). In this cycle, evaluation can also originate from both empirical and non-empirical sources. In such a system powerful scientific insights can occur when a new

model is developed that leads to a "flood" of new ideas. But this can happen without necessarily involving the extraordinary or unconscious reasoning processes associated with the term "Eureka event." The present data support the view that the methods used by scientists are varied and complex, and that the hypothetico-deductive method, rational evaluation, abduction, analogy, and induction may all play important roles at different times in scientific thought.

Recent work in philosophy of science was drawn on to make several useful distinctions. The term scientific model was used to refer to a predictive analogy. The term explanatory model was used to distinguish those scientific models which are intended to represent non-obvious entities present in the situation to be explained. The latter term allows one to distinguish between two types of scientific hypothesis: a hypothesis in the form of a predictive, explanatory model which introduces new entities that have not previously been (and may never be) observed directly, and an empirical law hypothesis which summarizes patterns in observations.

These distinctions helped to describe creative processes in the case study of subject S2 working on the problem of whether a wide spring stretches more than a narrow spring. S2's central achievement was the generation of an explanatory model--the invention of a new model of hidden mechanisms in the spring that he had not observed. This involved the identification of new causal variables in the system (such as torsion) and new causal chains, as well as the identification and explanation of a global effect (lack of cumulative bending).

The conclusions of the study are organized into five categories below: sources of hypotheses; the role of analogies; the Eureka vs. accretion question; creative mental processes; and educational implications.

Sources of Hypotheses

)A new scientific hypothesis in the form of an explanatory model can be developed via non-inductive means in the absence of new empirical information. This lends support to the importance of a non-inductive component in the hypothesis generation process.

)The model construction process observed was one of successive refinement, involving repeated cycles of generation, evaluation, and modification or rejection. Table 1 summarized evidence from the protocol that S2's progress is a result of this kind of cyclical refinement process rather than being a result of either a convergent series of deductions or inductions from observations.

)Such a cycle can be more powerful than a blind trial and error or blind variation and evolution process. For example, when difficulties have been identified in an existing model, subsequent generation and modification processes can serve to remove the difficulties.

)Hypothesis evaluation processes appear to be an inherent part of hypothesis formation down to resolution intervals of minutes on occasion. History of science tends to look at developments over years or weeks. From this perspective the case study observation of very small cycle times for the non-empirical criticism and modification loop in Figure 4 (as small as 90 seconds here) makes it very difficult to separate the "context of discovery" from the "context of justification" in the early stages of hypothesis formation. In such cases it is possible to have a rapid, dialectic interplay between generation and evaluation processes.

)The development of a convincing explanatory model hypothesis can also lead to the formation of an empirical law hypothesis in the absence of new empirical information: in this case the final model of the polygona coil with torsion supports the empirical law hypothesis that (other factors being equal) wide springs will stretch more than narrow springs

Spontaneous Analogies

)Subjects were observed to generate and use spontaneous analogies as predictive models.

)Many of the observed analogies apparently were generated via a transformation of another situation. Although association is often cited as a primary source of creativity, it may be that transformations are just as important, if not more important.

)In a successful model construction cycle, an initial analogy with low explanatory status can be developed and modified to become an explanatory model which proposes the presence of a hidden structure operating in the target situation.

)This means that analogy can play a role in the generation of new hypotheses in at least the following two different ways: (1) an analogous case can serve as a rough initial model of the target situation that is then developed and refined; (2) a developed model, whatever its origin, is linked by an analogy relation to the target situation since it posits that elements and relations in the model are like elements and relations in the target. This appears to contribute to a feeling of understanding when elements in the model are familiar.

)Rather than always being stored as cases that are activated in memory, some analogies (e.g. revised mental models) are novel, invented cases.

)In some instances the knowledge one gains from an analogy is not stored in the analogous case. The analogy can play a provocative role by triggering the application of a principle which has never before been applied to either the target or analogous cases. In these instances the most important relationship in the analogous case is recognized after the generation of the analogous case.

The Eureka vs. Accretion, or Pace of Conceptual Change Question:

)Three possible levels of insight were defined: a breakthrough, which overcomes a barrier that has blocked progress; a scientific insight, which is a relatively sudden breakthrough leading to a significant improvement in a model; and a pure Eureka event, which is an insight that is not explainable via ordinary reasoning processes.

)Aha! episodes were observed in association with a scientific insight involving the formation of a new explanatory model. Such an insight can be quite powerful and impressive and can lead to a rapid improvement in conceptual understanding. However, although insights can involve creative thinking, when they do occur: (1) they can involve preparation and confirmation efforts; and (2) they do not necessarily involve unconscious or other extraordinary thought processes which are outside the domain of normal reasoning operations--they do not involve a sudden break in the train of thought that would indicate a pure Eureka event. The train of thoughts S2 reports weaves a "coherent story" in the sense that each new idea is connected to previous ideas and is the referred at least weakly constrained by previous ideas That he appeared to use the processes in Figure 4, in which new ideas can grow out of modifications of or reactions to past ideas, is an even more specific sense in which his insight did not just emerge from "out of the blue."

)This does not prove that important unconscious or non-ordinary processes cannot occur--Poincaire's famous insight upon entering a bus may have been one example--but it does indicate that insights can be generated in the absence of evidence for such special processes.

)S2's insight occurred after a long struggle resulting from the conflict between a first-order model and a recognized anomaly. The conflict or disequilibrium condition between a persistant model and an anomaly appears to provide a motivating force for a more intense level of activity for hypothesis development, not dependent on other external motives. The persistence of the subject's initial model and the tension between it and the perceived anomaly may be partially analogous to the persistence of a paradigm in the face of anomalies in science. An important function of the strategy of searching for analogous cases is that it may help the subject to break away from such a stable persistent model. This helps to explain the presence of intermittent periods of negligible progress and rapid change or insight in such protocols.

Creative Mental Processes

)A subject can use relatively unconstrained, divergent, hypothesis generation processes which can lead to insights, including analogy, association, transformation, and invention processes.

)Divergent and creative processes represent a significant departure from the more systematic processes of hypotheses generation envisioned by inductionists who would tend to see the former as much too unrestrained to be part of the scientific enterprise. However, the evaluation processes in Figure 4 can provide some strong restraints. Thus, alternating between generative and evaluative modes in scientific thinking is seen as a powerful method, even when the generative methods are divergent in character and new empirical tests cannot be performed.

)Divergent processes are relatively unconstrained compared to other processes, but there is evidence that generation and modification processes can be guided by some constraints. This makes the model construction cycle more powerful than a blind selection and variation process.

)Recent analyses of Darwin's notebooks have suggested that a more indicative hallmark of genius than pure Eureka episodes is the ability to generate tentative analogue models as a starting point and then to carry out the long struggle of a cycle of repeated generation, criticism, and modification or rejection that is necessary to construct a successful new theory. In fact, there are the same prominent features which emerged from an analysis of model construction in the thinking aloud case study. It was conjectured that the most viable powerful form of scientific reasoning may lie in the ability to engage in such a dialectic cycle, rather than in the ability to invent a completed model in one stroke.

)Thus the examples discussed here motivate a conception of advanced scientific thinking which includes non-deductive, non-inductive, and divergent processes. These processes can play an important role in producing predictive, explanatory models which are novel inventions.

Educational Implications

)The above findings suggest an educational strategy where rather than "swallowing packaged ideas as a whole" in lecture, students are helped to develop partial models, criticize them, and work from their initial model to construct a more adequate model.

)They also underscore the importance of: using analogue models for developing understanding; fostering disequilibrium in order to motivate efforts toward model construction; and criticism and modification (or rejection) processes for overcoming difficulties occuring in students' models which contain misconceptions.

)Explanatory models are an essential part of scientific understanding that is a separate type of knowledge from either empirical laws or formal quantitative principles. Educators need to distinguish between activities aimed at forming empirical laws or quantitative principles and those aimed at forming explanatory models, since the cognitive processes involved may be quite different. For example, students are unlikely to learn explanatory models from laboratories aimed at inductive reasoning or from lectures on formal quantitative principles.

)The learning process outlined in Figure 4 attempts to give an explicit cognitive meaning for the term "knowledge construction". As such it may be useful as a model of relevant learning processes for guiding curriculum planners and practitioners in designing and evaluating instructional activities in science education.

In conclusion, it appears to be possible to develop models of creative hypothesis formation processes that are tied to empirical information from thinking aloud protocols. Many aspects of creative reasoning processes remain poorly understood: "guided" conjecture, anticipation in the "aha" phenomenon, the apparent malleability of the spatial imagination, emotional factors, question asking, and sources of curiosity, to name just a few. They still inspire awe. Nevertheless, creativity is a more accessible object of study than some would claim; it is not always an "instantaneous crystalization transmitted from the unconscious." Current techniques make the process of studying creativity a productive and exciting one: by using protocol analysis and other methods, significant progress can be made in increasing our understanding of it. Exactly how much we will be able to understand and explain in this complex domain--how far our model construction cycles will take us--remains to be seen.

Notes

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1. Placing different scholars on these two broa spectra ignores many differences between them and requires a number simplifications. For example, some scholars (e.g. positivists and Popper) tend to concern themselves with the formal justification of theories while others (e.g. Hanson. Kuhn) also focus on their psychological origin; arguments also vary as to whether they refer to science as a whole or to the individua scientist.

2. Since this chapter focuses on thinking in the individual scientist, I wil not discuss here important work which emphasizes social factors in the development of scientific ideas. While these factors are undoubtedly significant, I believe that studying hypothesis generation processes in the individual scientist is an effective heuristic strategy for investigating a crucial part of the problem.

3. The form of Figure 4 was itself developed via an extended successive refinement process, and was also designed to account for empirical data from protocols like the ones to be discussed, not just as a summary of prior literature.

4. The idea of "bridging" between analogous cases with a new intermediate analogous case is an interesting non-empirical strategy in itself for evaluating the validity of the analogy relation between two cases and i discussed in Clement (1986).

5. There are actually two parts to this insight: the construction o. he polygonal coil; and the recognition of torsion in the coil. The first part makes possible the second part, and both are accompanied by "ahas. The first part constitutes the generation of a new representation for the target problem; the second is the new activation of a principle tha can be applied to the new representation. In much of what follows, it will be convenient to treat these together as a single insight.

6. In fact, twisting is the predominant source of s retching in a helical spring. The idea that the spring wire bends is also partially correct. By imagining the extreme case of a single circular coil of a spring stretched out into an almost straight wire, one can see that stretching produces some unbending as it removes the circular curvature originally put into the wire when it was coiled. However, there is no bending in . vertical plane. Twisting in the square coil can also be used to predict that the stretch varies with the cube of the coil diameter.

7. In one sense I am appropriating the term 'explanatory' here since, as Kuhn (1977) points out, what counts as explanatory is different for Aristotle, Newton, and quantum physics. I am proposing that what counts for S2 in this problem fits the definition given--an analogue model that has material elements which are hypothesized as "candidates for reality." The sharing of material elements between model and target can be termed material correspondence, and this assumption seems to be a minimal requirement for something to have potential as an explanation. Whether a satisfying explanation is actually attained, however, will also depend on other factors such as the support for and comprehensibility of the model.

8. Many sequences of mathematical models, especially in applications of the calculus, have the form shown in Figure 15. In this view, mathematical limit arguments, which examine properties as one passes from an analyzable simpler model and approaches the limit of the target situation, are sophisticated attempts to justify the intuitive validity of the analogy between the model and the target situation. The role of analogies and models in mathematical understanding has been discussed by Fischbein (1987).

9. Lenat (1983) describes an attempt to develop a simulation model for the process of selecting "interesting" problems (theorems for analysis) in mathematics.

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LOCATION OF EVIDENCE FOR A MODEL CONSTRUCTION CYCLE OF HYPOTHESIS GENERATION, CRITICISM, AND MODIFICATION OR REJECTION

Key
G = Generates Hypothesized Model
C = Criticizes Model
M = Modifies Model
R = Reconsiders Model
D = Drops or Rejects Model

Line	Process	Hypothetical Model	Comments
5	G	Horizontal Bending Rod	Initial analogy
5	C	" "	Bending in rod, but not in helix
23	G	Square Coil	
23	M	Zig-Zag #1	Modifies square to produce zig-zag model
23	C	" "	Joints confounding
23	M	Zig-Zag #2 with Stiff Joints	Modifies zig-zag #1 to produce #2
	[C*]		Bending in zig-zag, but not in helix
	D	Drops Zig-Zag Models	
57	R	Rod Model	
87	C	" "	Bending in rod, but not in helix
117	R	Square Coil	
119	M	Hexagonal Coil	
121			Makes torsion discovery in hexagon
122	C	" "	Hexagon geometry too complex
122	R	Square Coil	(Leads to successful prediction of restoring forces without cumulative bending in spring wire)

* Inferred in absence of direct evidence in protocol.

TABLE 1

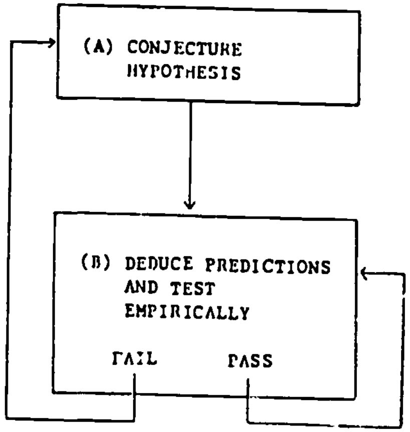
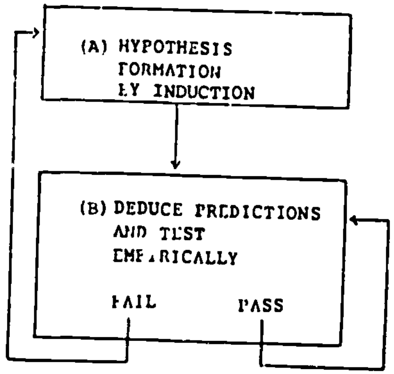


Figure 1



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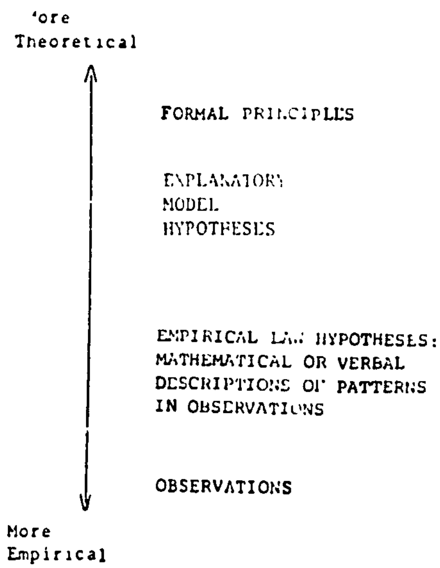

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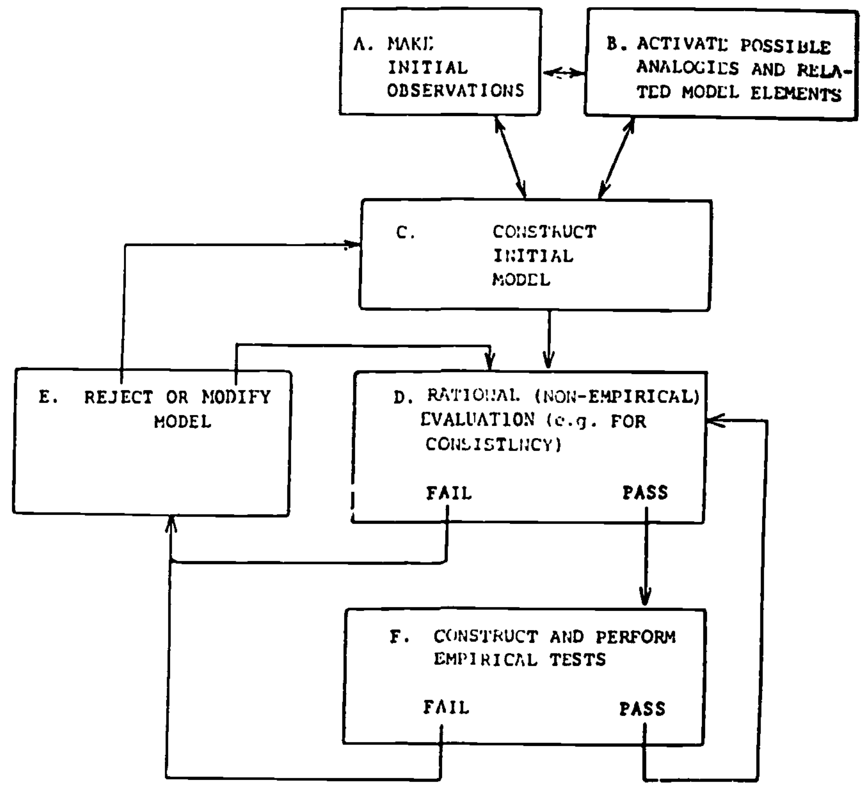


Figure 4

[illegible]

YOU ARE GIVEN THE TASK OF [illegible] A HEAVY WHEEL UP A HILL. DOES IT TAKE MORE, LESS, OR THE SAME AMOUNT OF FORCE TO ROLL THE WHEEL WHEN YOU PUSH AT X, RATHER THAN AT Y?

ASSUME THAT YOU APPLY A FORCE PARALLEL TO THE SLOPE AT ONE OF THE TWO POINTS SHOWN, AND THAT THERE ARE NO PROBLEMS WITH POSITIONING OR GRIPPING THE WHEEL [illegible] THAT THE WHEEL CAN [illegible] WITHOUT [illegible] IT AT EITHER [illegible]

Figure

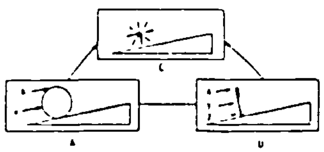


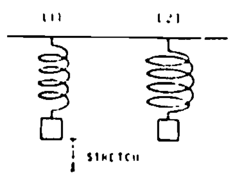
Figure 6

[illegible]

[illegible] ON A SPRING. THE ORIGINAL SPRING IS REPLACED WITH A SPRING

- MADE OF THE SAME KIND OF WIRE,
- WITH THE SAME NUMBER OF COILS,
  BUT WITH COILS THAT ARE TWICE AS WIDE IN DIAMETER

[illegible] SPRING STRETCH FROM ITS NATURAL LENGTH, MORE, LESS, OR THE SAME [illegible] THE SAME WEIGHT? (ASSUME THE MASS OF THE SPRING IS NEGLIGIBLE [illegible] TO THE MASS OF THE WEIGHT.) WHY DO YOU THINK SO?



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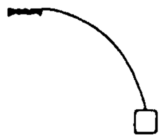
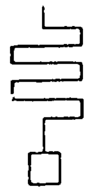


Figure 8

Figure 9



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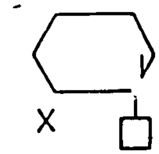

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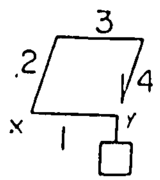

Figure 12

Figure 13

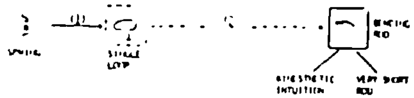

Figure 14 A

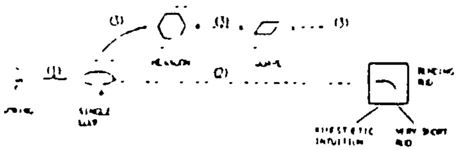

Figure B

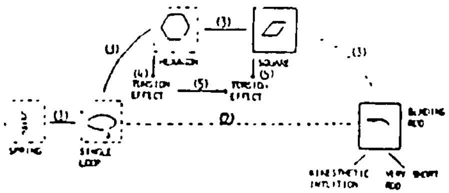

Figure C

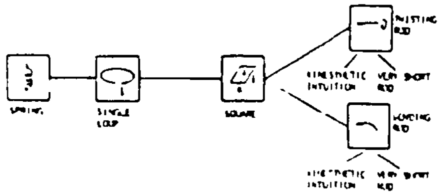

Figure D

FIGURE 14

THE PROGRESSIVE CONSTRUCTION OF A MENTAL MODEL USING ANALOGIES

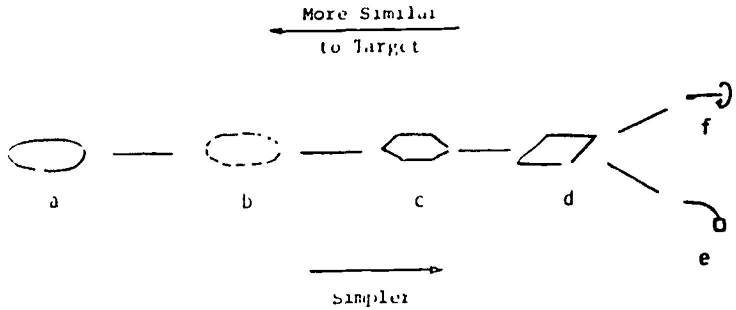

Figure 15

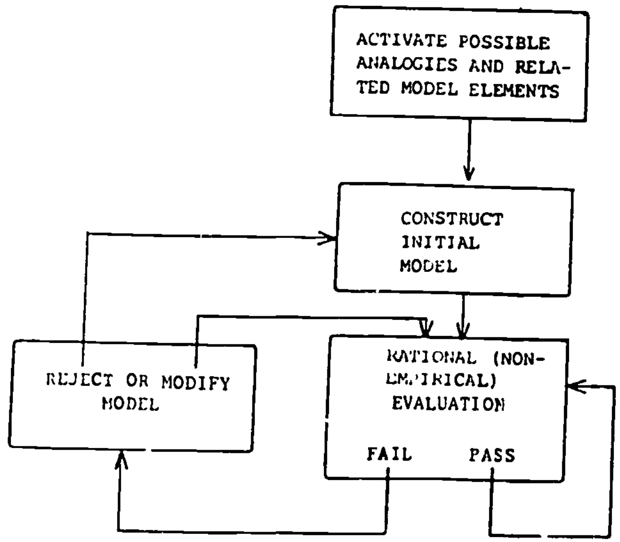

Figure 16