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MODEL CONSTRUCTION AND CRITICISM CYCLES IN EXPERT REASONING[1]

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Abstract

A case study is described which documents the generation of a new hypothesis in the form of a visualizable model. It is argued that several of the processes used were neither deduction nor induction by enumeration. Rather, a new explanatory model was invented via a successive refinement process of hypothesis generation, evaluation, and modification, starting from an initial rough analogy. New predictions emerged when the subject "ran" the model. Thus it appears to be possible to investigate the model construction processes of experts through thinking aloud protocols..

Previous Work on the Role of Analogies and Explanatory Models in Hypotheses Formation

Role of Explanatory Models in Science

The work of Campbell (1920), Harre (1961) and others suggests that empirical generalizations are not the only form of hypothesis formation in science. They see a distinction between an empirical law hypothesis summarizing an observed regularity and what I will call an explanatory model hypothesis. 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. Rather, they are inventions that contribute new theoretical terms and images which become part of the scientist's view of the world, and which are not "given" in the data. This means that there are at least four levels of knowledge used in science: (1) Observations; (2) Empirical law hypotheses (mathematical or verbal descriptions of patterns in observations); (3) Explanatory model hypotheses; and (4) Formal principles. 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 imageable model of billiard-ball-like molecules in motion. The explanatory 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. In this view, a qualitative, visualizable, explanatory model is a major locus of meaning and power for a scientific theory.

Role of Analogy in Generating Explanatory Models

In this paper the term 'induction' will denote a process by which a more general principle is abstracted from a set of empirical observations as the source. The above authors argue that explanatory models often originate in analogies to familiar situations (e.g. gases are analogous to a collection of colliding balls) as a non-inductive source. Theory formation and assessment cycles using analogies have been discussed by Holland, Holyoak, Nisbett, and Thagard (1986), Darden and Rada (1988), and Falkenhainer (1988). However, these studies do not tie their theoretical findings to empirical think-aloud data, as this paper aims to do.

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SPRING PROBLEM

A WEIGHT IS HUNG 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.

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

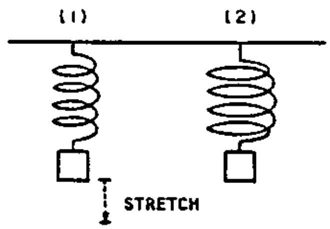

Figure 1

Thinking Aloud Evidence on Model Construction Cycles Using Analogies

Method and Overview of Findings

Ten professors and advanced graduate students in technical fields were recorded while solving the spring problem shown in Fig. 1 out loud. 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." Subjects were also asked to give an estimate of their confidence in their answer. 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. Coding for the occurrence of a spontaneous analogy took place when subjects spontaneously shifted their attention from the original problem to a different situation (referred to as the analogous case) that they believed might have relevant structural similarities to the original target case. A number of subjects used the analogous case of a horizontal bending rod (Figure 2) 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 (1988) 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.

A Case Study of Hypothesis Generation

I will concentrate here on subject S2, who appears to develop, criticize, and modify a number of scientific models for the spring problem until he produces a new hypothesis in the form of an explanatory model for how springs work. In the broader sense of the term, a 'scientific model' (or simply "model") will refer here to a cognitive structure where the subject believes that the model is structurally similar (is analogous to) the target situation and believes that the model can be used to predict or account for observations of the target that are of scientific interest. I will refer to an explanatory model as a specific kind of scientific model where material (non-abstract) entities in the model are taken seriously as candidates for real entities operating in the target.

S2's solution transcript. For the spring problem, subject S2 first generated the model of comparing a long horizontal bending rod with a short one (Fig. 2) (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 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

Figure 2

Figure 3

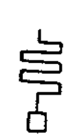

Figure 4

was an appropriate model for the spring. He then constructed the analogous case of the "zig-zag spring" shown in Figure 3, apparently to attempt to evaluate the analogy relation between the spring and the bending rod and to attempt to construct an improved model.

23 S2: A zig-zag spring rather than a coiled spring; that strikes me as an interesting idea (draws Figure 3) 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... I-I have a visualization... Here's...(draws modified zig-zag spring in Figure 4) 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.

There is evidence here 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. Eventually the zig-zag spring is 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. Nevertheless, these attempts provide initial evidence for two passes through a cycle of model construction, criticism, and modification, as shown in the upper five boxes of Figure 5.

Insight section. In the excerpts below, this subject produces an extremely productive series of models when he generates the idea of the

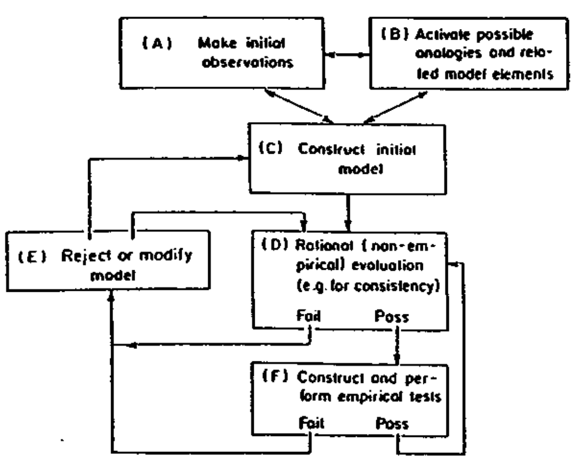

Figure 5

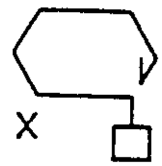

Figure 6

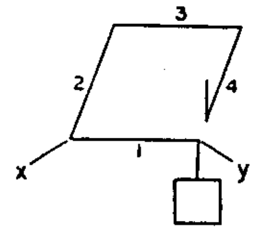

Figure 7

hexagonally shaped coil in Figure 6 and moves from there to the idea of the square shaped coil in Figure 7. Imagining the stretching of these polygonal coils apparently allowed him to recognize that some of the restoring forces in the spring come from twisting in the wire instead of bending-- a major breakthrough in the solution which corresponds to the way in which engineering specialists view springs. Among the solutions collected for this problem, the most impressive 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 insight in the next section to be discussed. Note that his square spring model can in turn be understood in terms of two simpler cases, the twisting rod and the bending rod. That is, pulling the end of the lever "1" down in Figure 7 not only bends rod 1, but it also twists rod 2.

Torsion insight.

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, you get a <u>torsion</u> effect...

122 S: <u>Aha</u>! 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..

(One way to comprehend this idea is to view rod 1 as a wrench that is twisting rod 2.) The same is true for all other adjacent rod pairs. Thus, twisting is an important type of deformation in the spring wire in this model. This also resolves his original problem of not finding cumulative bending in the spring coil.

DISCUSSION

Thus by starting from a rough analogy (the bending rod), S2's central achievement was the generation of a new explanatory model-- a model of hidden mechanisms (force causing twisting and torsion causing stretching in the spring) that he had not observed. This achievement includes 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). (A more extensive discussion of explanatory models and the sense in which this is a scientific insight is given in Clement, 1989).

Major Processes Identified

The following processes are hypothesized in order to explain patterns in the observations in this transcript.

(1) Novel analogue models generated. The subject generates a number of visualizable analogue models. The novelty of several of these argues that the models are constructed by the subject rather than retrieved from memory.

(2) Model construction cycles. The protocol also indicates that the process of model construction can be much more complex than forming a single simple analogy. In particular, the growth in S2's ideas appears to have occurred via a cyclical process of model generation, criticism , and modification (or rejection), shown in the upper five boxes of Figure 5. The double ended arrows at the top indicate that the process of generating an initial model can be highly interactive and complex. It is still poorly understood. When a hypothesis is evaluated negatively, it can sometimes be improved through modification in a series of successive refinements, instead of being completely rejected. Table 1 summarizes evidence from the protocol that S2's progress is a result of this kind of cyclical process. (Process B in Table 1 is also implicated in a rapid search for analogies such as "molecules, polyesters, and car [leaf] springs" in another section of the transcript.) Thus it appears that protocol evidence can be gathered to document the presence of such scientific reasoning processes as those shown in Fig. 5. Two major types of hypothesis evaluation are shown, but empirical testing was not used here. Rational evaluation was used to support or disconfirm hypotheses; for example, bending was seen as an implausible mechanism for the spring. 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 or in different cycles.

(3) Major model generation processes were neither inductive nor deductive. 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 build 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 <u>prior</u> observations, but he does not appear to recall observing bending, twisting, zig-zags, or square coils in springs, instead these appear to be newly imagined models. The novelty and non-observability of the square 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 prior observations. Empirical law hypotheses which consist only of a recognized regularity or repeated pattern in the variables, such as those discussed by Langley (1979) may sometimes 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 models being examined here were apparently formed by a less data-driven and more abductive process. The process began by "plagiarizing" the knowledge structure from an analogous case in memory to form the staring point or core of a new model. Methodologically, the role of this case study is like an "existence proof" in showing the possibility that non-inductive construction processes can be very important in the formation of explanatory model hypotheses.

(4) Emergent knowledge from simulations. Furthermore new conclusions emerged from his "running" his model of the square coil such as: seeing that the twisting in each segment produces increments of stretching in the spring which add together (and similarly for the bending in each segment); and seeing that the bending in each segment will not produce cumulative bending (increasing slope) along the stretched spring. Apparently he is able to run simulations of novel cases like the square coil and obtain conclusions from such simulations that are emergent in the sense that there are unlikely to be explicit rules which generate those conclusions. Furthermore these go beyond inferences about static locations in space to include the coordination and summation of various dynamic movements in space. Thus it appears that part of the model-running process is non-deductive as well. The nature of this type of dynamic simulation process is poorly understood and is an important area for further investigation.

Educational Implications

The expert model construction cycle in Figure 5 may also be useful as a description of processes which need to take place in students learning and applying scientific models. 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 alone. Instead, this study underscores processes which aid abduction and refinement as an essential complement to inductive and logico-mathematical processes. For example, Clement (1991) argues that analogies based on physical intuitions can be used effectively as starting points for model construction in dealing with preconceptions in physics. In conclusion, the cycle depicted in Figure 5 can be documented in experts and may prove useful as an higher-lever outline of relevant learning processes for guiding educators in designing and evaluating instructional activities concerned with the learning of scientific models.

Table 1. Location of evidence for a model construction cycle of hypotheses 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 # and Hypothetical model	Process
5) Horizontal bending rod	G: Initial analogy
5) Horizontal bending rod	C: Bending in rod, but not in helix
23) Square Coil	G:
23) Zig-Zag #1	M: Modifies square to produce zig-zag model
23) Zig-Zag #1	C: Joints confounded
23) Zig-Zag #2 with stiff joints	M: Modifies zig-zag #1 to produce #2
	[C*] Bending in zig-zag, but not in helix
25) Zig-Zag models	D: Drops models
57) Rod Model	R:
87) Rod Model	C: Bending in rod but not in helix
117) Square Coil	R:
119) Hexagonal Coil	M:
121) Hexagonal Coil	M: Makes torsion discovery in hexagon
122) Hexagonal Coil	C: Hexagon geometry too complex
122) Square Coil	R: (Leads to successful prediction of restoring forces without cumulative bending in spring wire)

* Inferred in absence of direct evidence in protocol

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