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UNDERSTANDING THE MICROSTRUCTURE OF SCIENCE: AN EXAMPLE[1]

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The present paper is intended to demonstrate the feasibility of a cognitive approach toward understanding real-world science through the intensive analysis of a scientific diary. The approach draws on many concepts of contemporary cognitive science, especially protocol analytic (PA) techniques. As Ericsson & Simon (1984) emphasize, not every verbal record of thought is amenable to such analysis. Generally, PA is applied to "think aloud" protocols gathered during the solution of a problem. In most cases, the problem subjected to analysis has been a carefully designed task with a clear goal state, a minimum of background information needed for solution, and a level of difficulty which can be solved by most subjects within one hour or less. The classic examples meet these criteria; for example, the DONALD & GERALD problem and proof problems in symbolic logic.

In applying PA to the analysis of a working scientific diary, there is frequently no clear problem space, more than one problem space is often under exploration, and the background knowledge brought to the task is extensive and often not easy to characterize. Specific diary entries (unlike utterances in a think aloud protocol) may reflect either the contents of working memory or retrieved information brought from long term memory. The temporal sequence of a diary is generally clear, but the fullness of the record is very suspect. Finally, it is very likely that keeping a diary is reactive.

In spite of these problems, it is possible to modify conventional PA to permit meaningful analysis of the microstructure of a scientific diary. Our basis for this claim is a modified PA of a portion of the scientific diary of Michael Faraday (1791-1867), the eminent English physicist who discovered electromagnetic induction in 1831. Part of Faraday's diaries have been published (Faraday, 1932-1936); a fragment of the published portion served as the source protocol for the present analysis.

Goal states in the present paper are taken to be empirical observations of phenomena which had not previously been observed by Faraday. States and operators were defined as corresponding roughly to "ideas" and to "actions," respectively. Throughout the series, Faraday was acting upon some mental representation in the hope of transforming it into another mental representation. Thus, a state can refer to a highly abstract construal of a theoretical notion or to a very specific, concrete record of an empirical observation. The operators which apply to these states possess a similar range from highly abstract mental transformations (analogies, metaphors, instances of formal and informal reasoning, etc.) to very specific manual operations upon apparatus.

Analysis focused on a sequence of over 100 experiments conducted by Faraday between August 29, 1831 and November 4, 1831. The first experiment in the series recorded his discovery of induction. Taking an iron ring wound with two coils, he found that a brief transient current was generated in one coil whenever a battery current was turned on or off in the second coil. Over the next several months, Faraday explored the properties of the new phenomena, finally reading a paper on November 4 to the Royal Society. Two previous papers have dealt with the problem of what constitutes an experiment in this context (Tweney, 1984) and with the general problem of where the idea for the experiment came from (Tweney, 1985). The present account demonstrates that the microstructure of experimental exploration of the new discovery is also amenable to analysis.

Each record was first segmented into unitary propositions. Segmentation was highly reliable (in excess of 90% agreement for two independent coders). Each segment was classified as representing a state alone, an operator alone, or a combination of one or more states and one operator. Distinguishing states and operators was highly reliable among independent coders. However, classifying operators into specific categories proved only moderately reliable (about 60% agreement between the two authors working independently). Repeated attempts to refine the classification system resulted in no gains in reliability, probably because many of the judgements depend upon contextual knowledge of the relevant physics, Faraday's overall goals, and the heuristics used by Faraday (Tweney, 1985). Disagreements were resolved by discussion and reference to prior historical accounts of Faraday's experimentation. The most frequent operators were DO, OBSERVE, INFER, COMPARE and USE ANALOGY.

DO operators were generally followed by OBSERVE operators. In the early portion of the record, non-DO operators were much less frequent than DO operators, all of which involve some form of manipulation of physical entities; in later portions, Faraday sometimes used very few DO operators. A "Problem Behavior Graph," PBG, for the first two days of the record is shown in the figure. Each geometrical shape corresponds to an operator located in the numbered segment printed within the shape. The graph explicitly shows only those operators which culminate a sequence of manipulations having some sort of consequence, either an observation (shown by a square box) or some other operator (shown by a circle). Time is shown in the diagram by movement either rightward or downward. Rightward movement was used whenever a new empirical observation was made; downward movement was used in all other cases. If an observation was made which Faraday judged to be spurious (either then or later), then the temporal sequence was jumped backward to the last non-spurious observation, and moved downward to the next operator. Thus the overall shape of the graph is moving rightwards when Faraday was learning new things, downwards when he was not observing new things, and backwards when he was temporarily "tricked" into believing something which later turned out to be false.

Similar graphs were prepared covering the entire sequence of experiments, and inspected. The graph moves rightward at a generally high rate initially, at a low or zero rate during the middle, rightwards again toward the end of the series, and straight downward at the very end. Very little "branching" exists; this PBG is far less "foliated" than PBGs developed from laboratory studies of problem solving. In general, Faraday does not look as if he were blindly searching a problem space, gradually tracing a path to a solution by eliminating blind alleys. Instead, he appears to have had very little patience with unproductive results. If a particular set of manipulations failed to produce new results very quickly, then Faraday abandoned the line of inquiry and turned to another. This appears to be a kind of "working forward" generally not observed in laboratory studies of human problem solving.

Tweney (1985) argued that Faraday's 1831 researches could be understood as the application of specific scripts applied to specific schemata and guided "in the large" by powerful heuristics that regulated search for confirmatory and for disconfirmatory results. The present analysis extends such a view by tying it to lower-level states and operators. DO operators reflect instantiations of specific scripts; during the analyzed series there is reason to believe that Faraday is in the process of developing a new script, "Produce an induced current," which figured extensively in his subsequent research. States in our analysis most often instantiate perceptual information, but on a few occasions represent instantiations of a slowly developing schema concerning the nature of forces as field-like phenomena. Faraday's greatest theoretical contribution to science is implicit here, since he is generally considered to have developed the first truly non-Newtonian conception of field forces (Miller, 1984; Nersessian, 1984). Gooding (1985) argued that Faraday typically proceeded from fairly loose "construals" to tightly defined scientific "concepts," via a series of studies that culminated in clear-cut, simple demonstration experiments. The present analysis displays such a sequence.

The most striking implications for cognitive science concern the differences between the present analysis and other recent accounts of science. Klahr & Dunbar (in press), for example, demonstrated that the process of discovering how an electronic device worked could be represented as a dual search through two problem spaces, an hypothesis space and an experimental space. Such a view is inadequate as a description of Faraday's work because it is not helpful to construe Faraday as searching through an experimental and an hypothesis space; no finite list of hypotheses or experiments can capture the boundless possibilities facing him after the initial discovery in 1831. Instead, Faraday's activity is better construed as a multi-level search in which large numbers of promising lines of exploration are abandoned in favor of lines which coincide with higher level goals (to elaborate a field-like theory of force, say). In contrast to Klahr & Dunbar's problem, there is not one definable goal state but many overlapping goals.

Langley, et al. (1986) focus upon the pursuit of intermediate goals via selective search of intermediate situation trees. Such a representation proves to be extremely cumbersome for Faraday, however, because one needs to postulate a new intermediate tree every few experiments. In effect, each new observation opens a new situation tree. We prefer a schematic approach via the redefined notion of goal, and we believe that such an approach holds out more promise for the successful analysis of the kind of science which Faraday conducted.

FOOTNOTE

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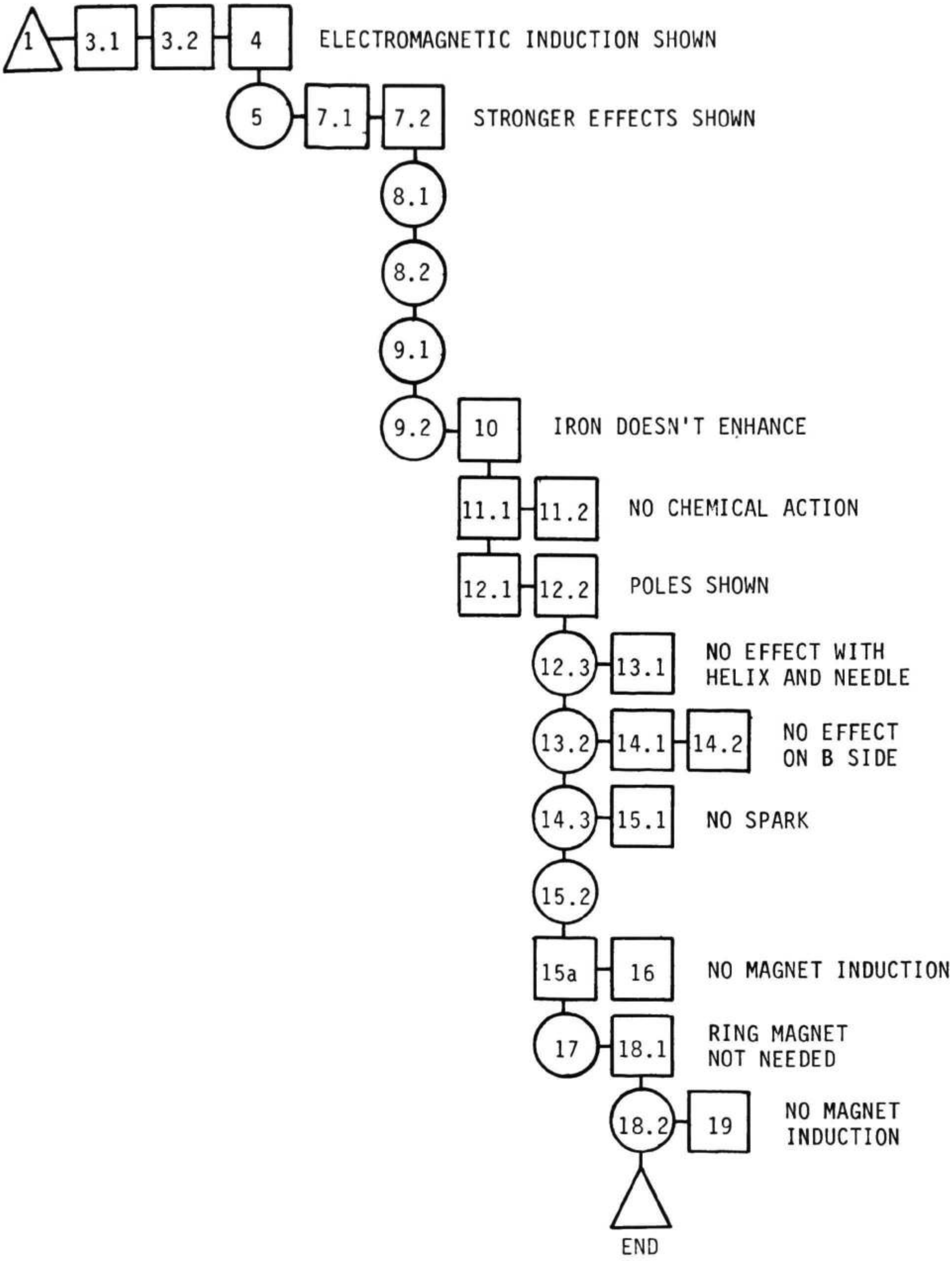

PROBLEM BEHAVIOR GRAPH FOR AUGUST 29 AND 30, 1831