

METHODS OF CONCEPTUAL CHANGE IN SCIENCE: IMAGISTIC AND ANALOGICAL REASONING

Nancy J. Nersessian

1. *How to study conceptual change?*

With the "revolutionary" changes in physical theory early in the 20th century came the recognition that conceptual change is a crucial component of major changes of theory. Various philosophers, Poincare, Hempel, Feyerabend, and Kuhn among them, have been concerned with the problem of how to characterize conceptual change in science. Two main views have emerged. Logical positivism characterized conceptual change in science as continuous and cumulative. Kuhn and Feyerabend have characterized it as discontinuous and non-cumulative.

The positivist characterization had its origin in *a priori* considerations of what scientific knowledge must be like in order to count as knowledge. Kuhn and Feyerabend claimed that their characterization came from examination of the actual history of science. The contradiction between how philosophers thought empirical knowledge must change and how the paradigm of such knowledge - science - seemed in fact to change created a crisis in philosophy of science as yet unresolved. Central to the crisis is the question of what constitutes proper philosophical methods of analysis. The major issue has been whether to approach conceptual change by treating scientific conceptual structures as languages and transferring conclusions from studies of the nature and necessities of language *per se* to scientific languages (See, e.g., Putnam, 1975) or to begin from descriptive accounts of the actual linguistic practices through which scientists have brought about changes in the conceptual structures of science and construct a theory from these (See, e.g., Shapere, 1988).

The problem with the former approach is that scientific conceptual structures may be - and many have argued, are - different in important respects from natural languages. While the latter approach has the advantage that philosophical theories will be firmly rooted in an understanding of actual practices in science, its problem is that it is not possible to construct a

general theory of conceptual change from individual case studies alone, no matter how salient. I have argued for a different approach to constructing a theory of conceptual change in science: a "cognitive-historical" method (Nersessian, 1987). This approach combines analyses of specific cases of conceptual change with analytical tools and theories of the cognitive sciences; in particular, cognitive psychology and artificial intelligence where it interfaces with psychology.

First, a theory of conceptual change in science must use the history of the development and change of actual scientific theories as a data base. It is only through fine-structure analyses of actual conceptual changes in science that we can discern the nature of the problems a satisfactory account of conceptual change needs to solve. In analyzing the history of science we find that conceptual change is more complex than either of the most influential characterizations has portrayed: it is both continuous and discontinuous; cumulative and non-cumulative. Numerous historical studies establish that, in agreement with Kuhn and Feyerabend, new conceptual structures are not simply extensions of previous structures; the concepts of two different theories can neither be combined nor be translated into a common structure. However, these studies also show that, in agreement with logical positivists, new conceptual structures derive in part - and in a way not yet understood - from existing structures. There is significant continuity between successive representations of a domain. Thus, a more suitable characterization of conceptual change in science is that it is *continuous, but not simply cumulative*. At times of major conceptual change the scientific community does experience what Kuhn has aptly called a "*Gestalt* switch", but the new *Gestalt* is connected with previous conceptual structures through analyzable reasoning processes. Understanding these processes will enable us to see what role existing conceptual structures play in constructing new, and sometimes radically different, structures.

In emphasizing the endpoints, or products, of a conceptual change, e.g., Newtonian mechanics and relativistic mechanics, the change of *Gestalt* is made to appear artificially discontinuous. However, conceptual change is an extended process. From fine-structure analyses of the periods of transition, the more complex characterization emerges. The difficult task for the philosopher of science is to provide an explanatory account of the continuity and discontinuity found in actual conceptual changes in science. A critical dimension of this task is to formulate an understanding of how new conceptual structures are constructed.

The cognitive part of the method has as its working hy-

pothesis that scientific conceptual structures are *representations* of the external world constructed by the minds of scientists and, as such, have much in common with what cognitive psychologists call "mental models". Understanding how humans construct representations, generally, can be brought to bear on the question of how conceptual structures emerge and change in science because the cognitive mechanisms at work in changing scientific conceptual systems are fundamentally the same as those we employ in "ordinary" contexts. Thus, a full understanding of conceptual change as it occurs in science requires bringing our account in line with the reasoning processes and the nature of representations used by cognitive beings. The problems encountered in characterizing and explaining the dynamics of concept formation and change in science, thus, need to be examined in light of pertinent results, interpretations, and debates in the sciences of cognition.

The goal of the cognitive-historical method is to be able, eventually, to reconstruct scientific reasoning using cognitive theories. However, the fit between cognitive theories and scientific reasoning is, at present, still quite problematic. The cognitive sciences have not advanced to the stage where we can even consider wholesale importation of analyses and methods to scientific cases to be reliable. Specifically, any adequate theory of cognition must take data from analyses of scientific reasoning into account in its formulation, and this has not yet been done to any significant extent. Thus, in its present stage, 'cognitive-historical' analysis of conceptual change in science requires feeding the historical data back into the cognitive theories being used to help interpret the data. Case studies of conceptual change in science provide a data base for testing to what extent theories of cognitive processes can be applied to scientific reasoning and for indicating in what ways these theories may need revision and extension to accommodate the new data. The method is blatantly, but not viciously, circular: it is a bootstrap procedure.

The advantage of employing a cognitive-historical method will allow us to go beyond the historical data in theorizing about conceptual change, while not committing the serious injustices of past reconstructive approaches. In summary, to paraphrase Putnam (1975), traditional philosophical accounts of conceptual change in science have left out actual scientific practices and the human beings who invent them. To rectify this deficiency, a new methodological approach is needed, one which incorporates the dimension of discovery - the history of science and the science of cognition - into the philosophical analysis of the

conceptual structures of scientific theories. This methodological approach is a multidisciplinary enterprise in which all of the disciplines stand to benefit from the interaction.

2. *Heuristic procedures and conceptual change*

My intention here is to illustrate the cognitive-historical method through an examination of the roles of imagistic and of analogical reasoning in the creation of new scientific concepts; in particular, the concept of electromagnetic field. Thus, the aim of this paper is not to present something completely new, but to draw upon and elaborate previous results (Nersessian 1984, 1987, 1988) in order to instruct its readers in the method and, hopefully, persuade them of its fecundity.

A major task of a theory of conceptual change is to understand the methods through which new scientific concepts are constructed. Philosophers of such disparate views as Reichenbach and Feyerabend have claimed that scientific concepts do not emerge through a reasoned process. For Kuhn, the process of how the new *Gestalt* comes into being is left a mystery. However, examination of actual cases of concept formation in science, establish that concepts do not emerge fully grown from the heads of scientists, but *are constructed in attempts to solve to specific problems by utilizing specific procedures*. Central among these procedures are analogical reasoning, imagistic reasoning, and idealization, such as thought experiment and limiting case analysis. These heuristic procedures constitute a substantial portion of scientific method. While they have not received much attention from the philosophical community, they provide the key to explaining how it is possible to have continuous, non-cumulative development of conceptual structures in science. Understanding how these procedures function will enable us to discern how new conceptual structures build importantly upon existing structures while at the same time genuine novelty is created.

Where does the widespread belief that new concepts are not the result of reasoned processes come from? One source of it is the general belief that no "logic of discovery" - either deductive or inductive algorithms for generating scientific knowledge - is possible. But, to confine scientific method to constructing valid arguments is unnecessarily restrictive. To do so rules heuristic procedures out of the analysis by fiat, even though there is a lot of evidence that such procedures figure centrally in the

“discovery” process. Another source of the belief is to be found in the stories - some apocryphal, some true - of discovery through sudden “flashes of insight”, such as Kekulean dreams and Archimedean eureka-experiences. But most sudden insights are *prepared* insights and it is likely that even these will yield to cognitive analysis as well (See, e.g., Langley & Jones, 1986).

Another problem philosophers have in countenancing the import of heuristic methods is that such strategies, even if used correctly, can lead to no answer or a wrong answer. It is true that the ultimate acceptability of a representation is determined not merely by its method of construction, but by other criteria, such as the adequacy of the consequences that can be drawn from it. However, developing criteria for evaluating heuristic strategies as “good” or “bad”, will enable us to show why it is rational to believe inferences resulting from good heuristics are worth testing, holding conditionally if testing is not feasible, etc.

There are numerous cases in the history of science where analogy has played a central role in the construction of a new scientific concept: Newton’s analogy between projectiles and the moon (‘universal gravitation’), Darwin’s analogy between selective breeding and reproduction in nature (‘natural selection’), and the Rutherford-Bohr analogy between the structure of the solar system and that of the configuration of sub-atomic particles (‘atom’) are among the more widely known. One of the most important, and controversial, cases in the history of science is Maxwell’s use of analogy in formulating the electromagnetic field concept. While no current cognitive theory is comprehensive enough to handle all the complexity of the Maxwell case, what we will see here is that what is known about analogical problem solving supports my position that the specific analogy generated the key elements in the solution to the problem of finding a field representation for electric and magnetic forces.

There is also a small, but growing body of literature that documents the prominence of imagistic reasoning in the construction of a new scientific representations, especially in the early phases (See, e.g., Gooding, 1985; Miller, 1984; Nersessian, 1984, 1988). Imagistic representations are often used in analogical reasoning in science, and most likely this is so in ordinary problem solving as well. However, very little research has been done on the role of imagistic reasoning in problem solving. Thus, although imagistic reasoning in scientific concept formation will be discussed, the bulk of the analysis is of analogical reasoning. I will offer some support for the hypothesis that imagistic reasoning is a form of analogical reasoning.

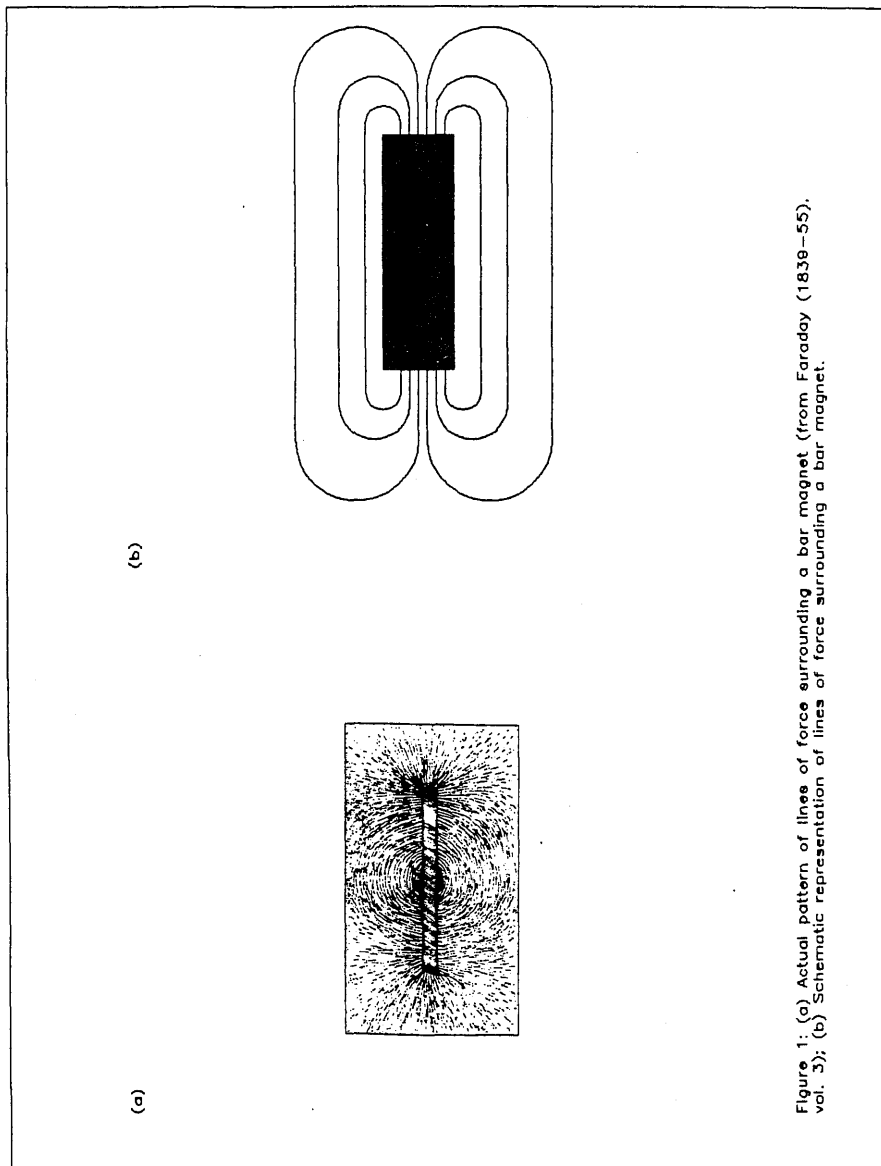


Figure 1: (a) Actual pattern of lines of force surrounding a bar magnet (from Faraday (1839-55), vol. 3); (b) Schematic representation of lines of force surrounding a bar magnet.

3. Imagery and analogy in the construction of the field concept

The concept of the electromagnetic field had its origins in vague speculations that there might be physical processes in the regions surrounding bodies and charges and that these processes might account for what seem to be the actions of one body upon one another at some distance from it. Faraday was the first to attempt to construct a unified field representation for electric and magnetic actions. His concept is primarily qualitative, and reasoning from imagistic representations figures predominantly in its construction. He created a "field" representation for electric and magnetic actions by reasoning from a representation of the "lines of force" that are formed when iron filings are sprinkled around a magnetic source (See, Figure 1). Many line-like features are incorporated into his field concept. He characterized the lines as "expanding", "collapsing", "bending", "vibrating", "turning corners", and "being cut". Ultimately, for Faraday, all the forces of nature are unified and interconvertible through various motions of the lines of force, and matter, itself, is nothing but point centers of converging lines of force. As further evidence of the centrality of this imagistic representation in his construction of the field concept we can see its influence on the only quantitative relationship he formulated: that between the number of lines cut and the intensity of the induced force. This relationship is incorrect because "number of" lines is an integer, while "field intensity" is a continuous function. With our hindsight, this "mistake" can be traced directly to the fact that the imagistic representation makes the lines appear discrete, while they actually spiral indefinitely in a closed volume.

Near the end of his research Faraday introduced another imagistic representation that was to play a key role in Maxwell's construction of a quantitative field concept. He represented the interconvertibility of electricity and magnetism by curves interlocking at right angles to one another (See, Figure 2(a)). This image represented the "oneness of condition of that which is apparently two powers or forms of power" (Faraday, 1839-55, 3, paragraph 3268). We can see that it is an abstraction from the "lines of force" representation: magnetic lines repel laterally, which has the same effect as a longitudinal expansion of electric current lines, and contract longitudinally, which has the same effect as a lateral attraction of electric current lines (See, Figure 2(b)). These reciprocal dynamical relations, as represented by the "*mutually embracing curves*" (Maxwell, 1890, 1, p.194n; Maxwell's italics) were expressed quantitatively by

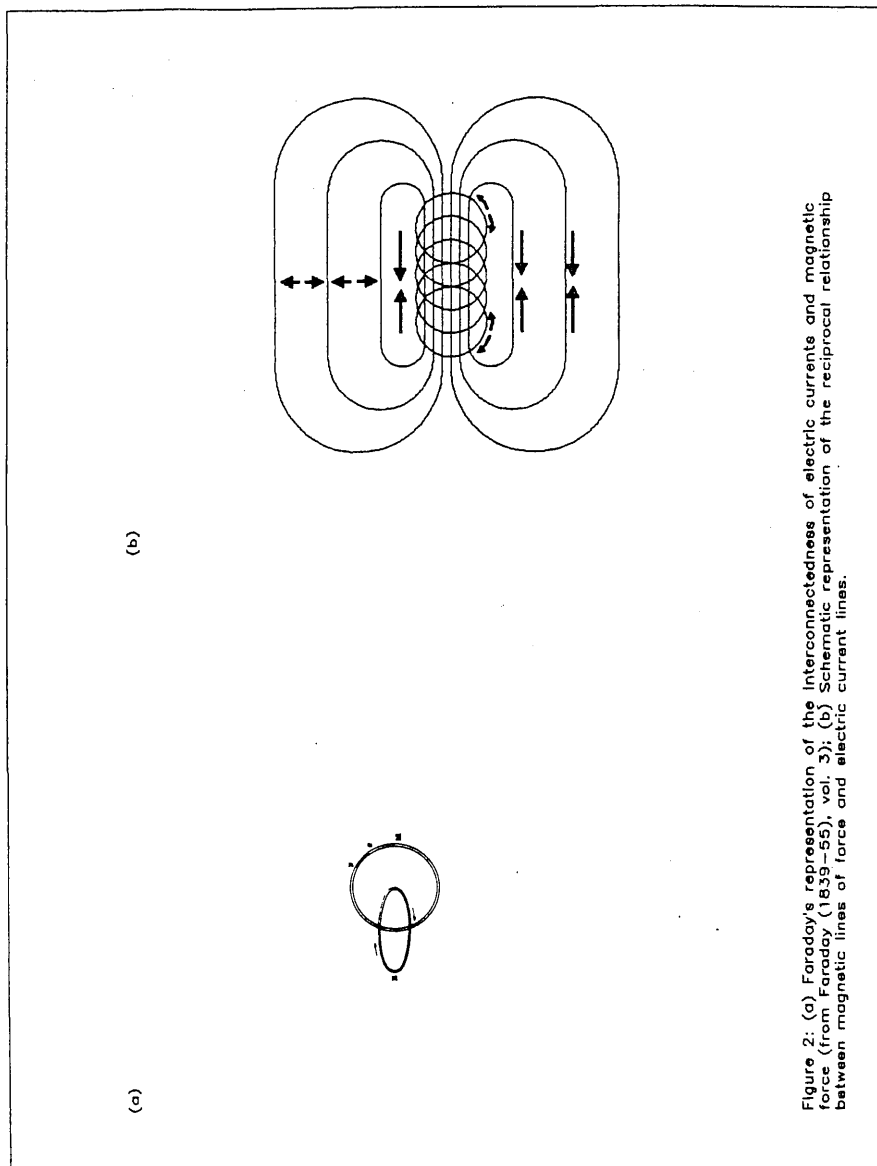


Figure 2: (a) Faraday's representation of the interconnectedness of electric currents and magnetic force (from Faraday (1839-55), vol. 3); (b) Schematic representation of the reciprocal relationship between magnetic lines of force and electric current lines.

Maxwell in his first paper on electromagnetism (Maxwell, 1890, 1, pp.155-229). Without going into detail, the direct relationship between the image and the mathematical representation he formulated can be seen in his complicated use of two fields each - one for "intensity", a longitudinal measure of power, and one for "quantity", a lateral measure of power - for the electric and magnetic forces, where only one is needed for each. These quantities and intensities remain in Maxwell's quantitative representation of the electromagnetic field throughout his work. In later work, the image provided a means for representing the propagation of electromagnetic actions through the aether. We start with an electric and a magnetic field, then summations of the quantities and intensities associated within these are propagated through the aether in "chains" of interlocking curves (Extend Figure 2(a) into a chain). As Wise has noted in his excellent analysis of Maxwell's use of this image, the "mutual embrace now became productive of offspring" (Wise, 1979, p.1316).

Maxwell combined imagistic reasoning with quantitative reasoning in what he called "the method of physical analogy". A physical analogy provides both a set of mathematical relationships and a pictorial representation of those relationships, drawn from a sufficiently analyzed source domain, to be applied in constructing a representation of a target domain about which there is partial knowledge. Using this method enabled Maxwell to exploit the powerful representational capabilities of continuum mechanics in constructing a quantitative field representation of electric and magnetic forces. Maxwell's use of the method is most interesting, and controversial, in his second paper on electromagnetism (Maxwell, 1890, 1, 451-513), where he derived the electromagnetic field equations. As noted earlier, this second analogy and its role in Maxwell's derivation of the field equations is one of the most important cases in the history of science. It has been discussed extensively in the literature and is the subject of continuing controversy (Berkson, 1974; Bromberg, 1968; Chalmers, 1986; Duhem, 1902; Hesse, 1973; Nersessian, 1984). My own view is that those who attribute a minimal role or no role to the analogy in the derivation of the field equations do so because of an inadequate appreciation of how analogical reasoning functions in problem solving.

Maxwell's goal was to formulate a unified representation of electric and magnetic actions. His analogy expressed potential stresses and strains in a mechanical electromagnetic medium (aether) in terms of well-formulated relationships between known mechanical phenomena. The initial formulation of the analogy was

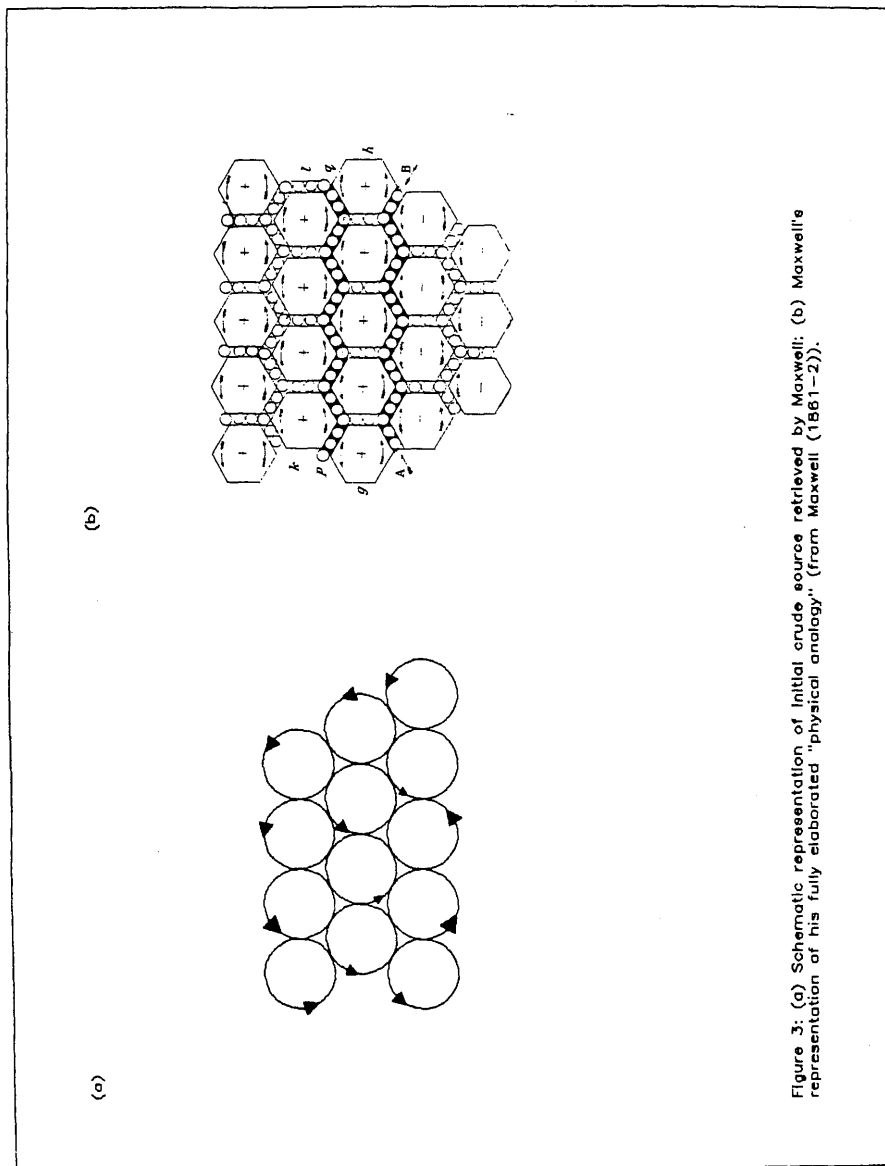


Figure 3: (a) Schematic representation of Initial crude source retrieved by Maxwell; (b) Maxwell's representation of his fully elaborated "physical analogy", (from Maxwell (1861-2)).

designed to take into account both the physical facts that electric and magnetic actions take place at right angles to one another and that the plane of polarized light is rotated by magnetic action and Faraday's speculative notions that there is tension along the lines of force and a lateral repulsion between them. A mechanical analogy consistent with these four constraints is that of a fluid medium, composed of vortices, under stress (See, Figure 3(a)). This allowed Maxwell to construct a mathematical representation for magnetic induction. He then moved to the problem of how to construe the relationship between electric current and magnetism. This required a modification of the analogy. Since contiguous parts of the vortices must be going in opposite directions, mechanical consistency requires the introduction of "idle wheels" to keep the rotation going. Maxwell enhanced the source of the analogy by representing these idle wheels by small spherical particles, surrounding the vortices and revolving in the direction opposite to their motion, with a tangential pressure between the particles and the vortices (See, Figure 3(b)). The dynamical relationships expressed between the particles and the vortices are those between a current and magnetism. Finally, in the analysis of electrostatic induction, the source is modified once again by treating the entire medium as an elastic solid. This part of the analysis provided Maxwell with the key element of his representation - the "displacement current" - from which a testable consequence followed: Electromagnetic actions are transmitted at approximately the speed of light.

Note that the imagistic representation of the source of the analogy functions more abstractly here than was the case with Faraday. As part of a "physical analogy" it serves only to make the salient relationships in the structure "vizualizable". For example, only the dynamical relationships between the spherical particles and the vortices are assumed to hold between an electric current and magnetism, no other features of the particles map over. If this interpretation is correct, any imagistic representation that embodied these specific relationships would do. This interpretation does make sense of Maxwell's repeated cautions that the pictorial representation he used should not be taken literally, i.e., as an hypothesis about the real structure of the aether. Although Maxwell believed that there was, indeed, vortex motion in the aether, Figure 3(b) did not represent the actual structure of the aether.

4. *Cognitive analysis of analogical problem solving*

Analogical problem solving has been the subject of much recent work in cognitive psychology and artificial intelligence. Problems solved by analogical reasoning involve "transfer of knowledge" from one domain to another or within domains, and understanding the transfer process is essential to the development of expert systems and to understanding the psychology of learning. In this section I want to present relevant aspects of cognitive theories of analogical reasoning that have an implementation and to point out some results from psychological studies that seem pertinent to an examination of the role of analogical reasoning in concept formation in science.

At present there are three major computational theories of analogical problem solving: "structure mapping" (Gentner, in press), "constraint satisfaction" (Holyoak and Thagard, in press) and "derivational analogy" (Carbonell, 1986). All are based on psychological studies of analogical problem solving. Although the state of these theories is somewhat fluid, fixed points of agreement and disagreement can be extracted from them. They all agree, first, that a complete theory must give an account of the processes of retrieval, mapping, transfer, and learning and, second, that there are three kinds of constraints that operate on these processes: syntactic, semantic, and pragmatic. Their disagreement is, primarily, over which constraints operate on which processes. The major disagreement is between the theory of Gentner, as implemented in the "structure mapping engine" (SME) and that of Holyoak and Thagard, as implemented in "analogical mapping by constraint satisfaction" (ACME). It is not possible to give an extensive analysis of the theories or of the controversy within the confines of this paper. It suffices to say that the main disagreement is over whether pragmatic constraints play a role in the selection and mapping processes.

Although something will be said about retrieval, we will concentrate primarily on the mapping process. Here the theories agree that the ingredients of "good", i.e., productive, problem solving are:

- (1) mapping systems of relations, especially causal
- (2) maintaining structural consistency in the mapping
- (3) striving for isomorphic mapping
- (4) creating a shared abstraction, or "schema" that will further problem solving;

while they disagree on:

- (5) using the goals and constraints of the target domain to

direct the mapping process.

In ACME, structural, semantic, and pragmatic constraints all operate in the mapping process. With SME, semantic constraints are assimilated with structural through the restriction that corresponding relations must be identical, and pragmatic constraints operate only before and after the mapping process. What the difference amounts to is that SME produces unconstrained generation of all possible inferences, which are then assessed with respect to the pragmatic constraints; while ACME uses implicit and explicit knowledge about the purposes of the analogy to constrain the generation of inferences. SME and ACME differ on retrieval in that SME focuses on structural similarities between elements of the source and target, while ACME considers goals and constraints as well.

Which, if any, of the theories is correct in its assumptions will be determined by how well the implementations solve problems analogically and by further examination of human analogical problem solving. The analogy used by Maxwell is too complex to be generated by either system, but analysis of it can provide some insight into the role of pragmatic considerations in analogical mapping and, thus, have some bearing on the controversy.

Some findings from psychological studies that have not yet been worked into computational theories of analogical reasoning are also germane to the issues of this paper. First, since, in problem solving, novices tend to focus on surface features, while experts focus on more abstract relational information (Chi, Feltovich, and Glaser, 1981), one would expect expertise to effect the mapping process. Second, in the investigation of analogies used as mental models of a domain, the question has been raised as to whether the choice of a specific analogy has significant effects on problem solutions, i.e., would the use of a different analogy produce a different solution? It has been demonstrated that inferences made in problem-solving depend significantly upon the particular analogy in terms of which the domain is represented. For example, in one study where subjects constructed a mental model of electricity in terms of either an analogy with flowing water or with moving objects, specific inferences, in some cases erroneous, could be traced directly to the analogy (Gentner and Gentner, 1983). This result supports the view that analogies do not serve merely as guides to thinking, while some deductive or inductive logical analysis is central to solving the problem, but that analogies are an integral part of the reasoning process; i.e., they are "generative".

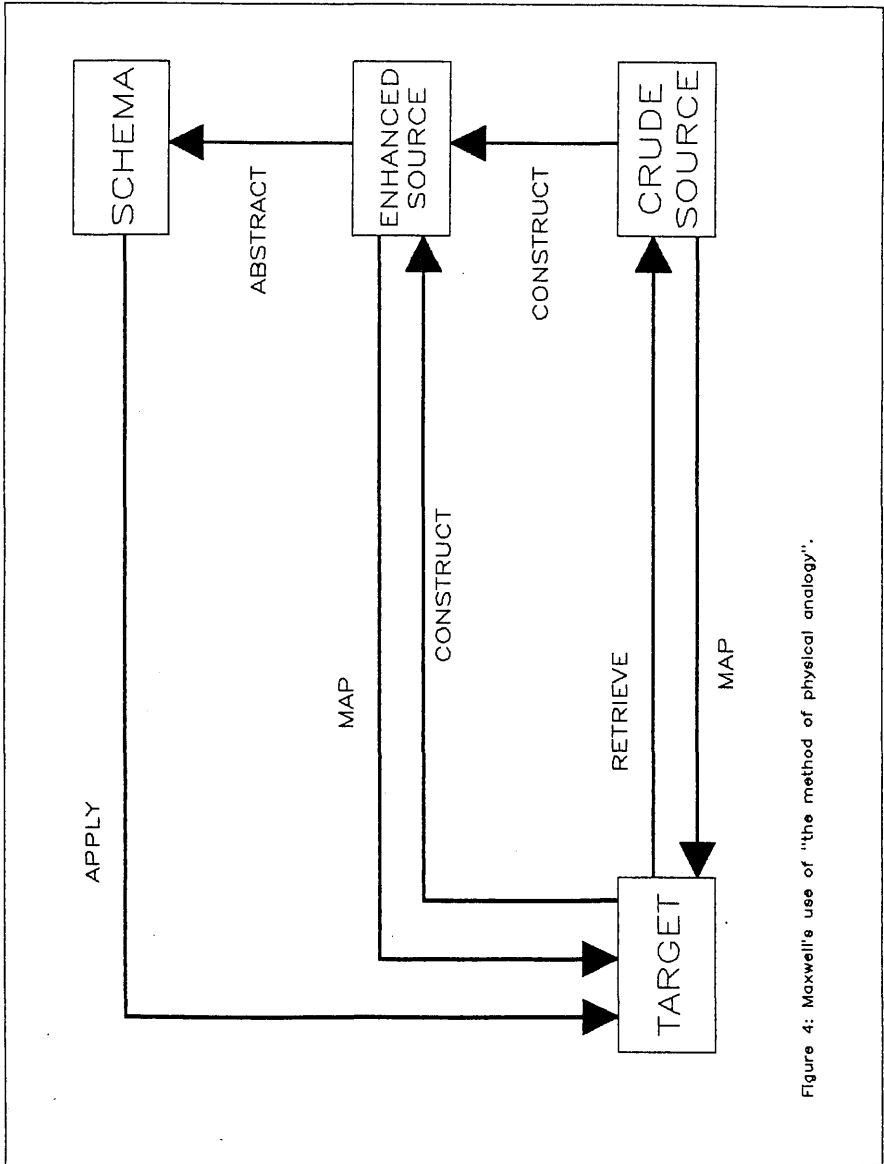


Figure 4: Maxwell's use of "the method of physical analogy".

5. *Analogical reasoning in concept formation in science*

Use of analogy in ordinary problem solving and in scientific problem solving differ mainly in that the scientific problems are more complex, often less well-defined, and, of course, the solution is not known to anyone. Despite such differences, cognitive analyses of both kinds of problem solving support the claim that "the component processes, which when assembled make the mosaic of scientific discovery, are not qualitatively distinct from the processes that have been observed in simpler problem-solving situations" (Simon, Langley, Bradshaw, 1981, p.2).

The processes of analogical reasoning through which Maxwell constructed a dynamical field representation for electric and magnetic actions are, briefly, as follows (See, Figure 4). Maxwell's over-all goal was to produce a unified mathematical representation of the production and transmission of electric and magnetic forces. Such a representation should at least demonstrate the possibility that mechanical, i.e., Newtonian, stresses and strains in the aether could produce observed electric and magnetic phenomena, and thereby incorporate electromagnetism into Newtonian mechanics. The obvious source domain lay within continuum mechanics, for in this domain continuous-action phenomena, such as heat, fluid flow, and elasticity, had been given mechanical analysis. Applying the forms of representation used in continuum mechanics to electromagnetism would enable Maxwell to express potential stresses and strains in the electromagnetic medium in terms of well-formulated relationships known to hold for mechanical phenomena.

Maxwell retrieved a crude source (See, Figure 3(a)) from this domain by applying the set of four constraints - listed above in Section 3 - in the selection process. That source is a fluid medium composed of vortices and under stress. He then proceeded to explore a possible isomorphism between some of the quantitative relationships known to hold for the source phenomena and the corresponding relationships assumed to hold for the target phenomena. Electromagnetic quantities, such as magnetic permeability and electric capacity, were identified with mechanical properties of the medium (mass and elasticity, respectively) the presumed stresses and strains, i.e., the structural relations, in a mechanical electromagnetic medium are identified with known mechanical stresses and strains in a fluid medium. The mappings are one-to-one and mainly of systems of causal relationships.

Breaking the over-all goal down into subgoals of the prob-

lem, viz., representing magnetic induction, electricity, electromagnetic induction, and electrostatic induction, determined what parts of the analogy to use and how to make modifications to the source, such as the addition of "electric particles" (See, Figure 3(b)), during the problem-solving process. Thus, both selection and mapping depend on the goals and constraints of the target domain. Finally, as a result of the mapping process, a common abstraction ("schema") between the laws of mechanical continua and electromagnetism was constructed. The relationships common to both the base and target domains are those of "connected system", i.e., a general dynamical system. Once constructed, the schema could be used directly to generate a mathematical representation of the electromagnetic field, and this is precisely what Maxwell did in his third paper on the subject (Maxwell, 1890, 1, 526-97).

Our examination of Maxwell's application of "the method of physical analogy" reveals that the four agreed-upon features of a productive analogy proposed by cognitive theories are present. Additionally, both the retrieval and mapping processes depended upon the goals and constraints of the problem. This lends support to the Holyoak and Thagard analysis. The analogy was clearly generative: The previously unknown relationship between electrostatics and magnetism was derived from the fact of the elasticity of the source medium, as was the inference that the velocity of propagation of vibrations in the electromagnetic medium is nearly the speed of light. The construction and application of the schema also demonstrate the generative role of the analogy. Contrary to what some have claimed, Maxwell did not know how to apply general dynamics to electromagnetism until after he had abstracted the schema from the complete analogy.

Although Maxwell had attained his goal, his field concept remained incomplete since the actual mechanical processes in the electromagnetic medium were never specified, though he fully expected they would be. In fact, they are unspecifiable. Maxwell's construction, as history was to show, differs significantly from what he had intended. His goal was to fit electromagnetism into the Newtonian framework. However, as was worked out between Maxwell and Einstein, "dynamical" is a broader notion than "mechanical". That is Newtonian mechanics and general dynamics are not co-extensive; relativistic mechanics, e.g., is also an instance of a general dynamical system. The relationships expressed in the electromagnetic field equations are those of a dynamical system, but it is non-mechanical (i.e., non-Newtonian). (For a discussion of the differences between

“mechanical” and “dynamical”, see, Nersessian, 1984, pp. 86-91.)

While this case fits well with what are thought to be good analogical problem-solving techniques, it also points to an area in need of investigation. None of the current computational theories even addresses the kind of “on-line” enhancement of the source that is central in this case. Yet, such one would expect such re-representation to be common in ordinary problem solving as well.

6. Imagistic reasoning in concept formation in science

We saw that imagery figured prominently in the construction of the field concept. The function of imagery in problem solving has not yet received much attention from cognitive scientists. So, what can be said here is limited. Nevertheless, I would like to draw together some strains in the literature and to make a proposal for opening a line of investigation. What is called “the imagery debate” in cognitive science is over whether imagistic reasoning (manipulating pictures) is different in kind from computational reasoning (manipulating symbols). The historical material presented here can shed no light on this debate. However, even those who maintain that imagery is just epiphenomenal concede that using imagistic reasoning may make stored information easier to manipulate. Johnson-Laird (1983) has suggested a compromise position: There may be different levels of cognitive processing, and while the bottom level may use only symbol manipulation, higher levels may use various sorts of representations. Imagery could, thus, play a significant role in problem solving, while at the same time not increasing computational power. One recent line of investigation provides some insight into the functioning of certain kinds of imagistic representations in problem solving. Simon and Larkin (1985) establish that translating sentential representations of problems into diagrammatic representations facilitates problem solving. They suggest that this is because much of the information needed to make an inference is clustered in a single location. Diagrammatic representations support a large number of perceptual inferences, which humans find easy to make.

We saw that the imagistic representation of the lines of force played a more prominent role in Faraday’s thought than in Maxwell’s. We also saw that the specific nature of the image was more important in the early, qualitative, phase of construction of the field representation of electric and magnetic actions. With

Maxwell's physical analogy, it was only important that the picture represent the specific relationships under investigation, and thus an equivalent representation of those relationships might have been equally productive.

Combining the historical case and the cognitive material on imagery and on analogy, I want, first, to suggest that imagistic reasoning is a form of analogical reasoning and, second, that the chief value of using an imagistic representation is that it makes structural relations immediately evident, while the main drawback is that, lacking adequate constraints, too many of the features specific to the image may be incorporated into the new representation.

I suggest that the kind of imagistic reasoning discussed here is a form of analogical reasoning because the imagistic representation serves as the source from which a mapping is constructed between features of the image and the phenomena under investigation. When insufficient constraints are guiding the mapping between the image and the target phenomena, scientists reason in a way quite similar to that of novices in analogical problem solving. The imagistic source and the target phenomena are taken as nearly identical, as we saw with Faraday's reasoning from the lines of force. Imagistic representations, used without sufficient constraints, are clearly too generative. Our problem is the inverse of that of Simon and Larkin, i.e., the sentential representation has not been constructed. With insufficient constraints to guide the mapping process, the facts that the imagistic representation contains more information in it than is relevant to the problem to be solved and that perceptual inferences are made with ease combine to lead extraneous features of the image to be incorporated into the solution.

7. Conclusions

Not all concept formation in science is by analogical reasoning, but such reasoning has figured importantly in significant cases of conceptual change. Analogies used in concept formation are not just guides to thinking, but, as in ordinary problem solving, they are an integral part of the reasoning process. Concept formation by analogical reasoning is a process of abstraction from existing conceptual structures through increasing constraint satisfaction. New scientific representations of a domain are created through abstraction rather than by accretion. Our examination of the role of analogical reasoning in concept formation in science thus provides an explanation of the continuous

but not simply cumulative development of representations of a domain seen in the history of science.

Program in History of Science
Princeton University

ACKNOWLEDGEMENTS

Preparation of this paper was supported by National Science Foundation Scholars Award SES - 8821422.

REFERENCES

- Berkson, W. (1974). *Fields of Force: The Development of a World View from Faraday to Einstein*. New York: John Wiley and Sons.
- Bromberg, J. (1968). "Maxwell's Displacement Current and his Theory of Light." *Archive for the History of the Exact Sciences* 4: 218-234.
- Carbonell, J. (1986). "Derivational Analogy: A Theory of Reconstructive Problem Solving and Expertise Acquisition." in *Machine Learning: An Artificial Intelligence Approach*. (eds.) R. Michalski, J. Carbonell, and T. Mitchell. Los Altos: Morgan Kaufman. Pages 371-392.
- Chalmers, A.F. (1986). "The Heuristic Role of Maxwell's Mechanical Model of Electromagnetic Phenomena." *Studies in the History and Philosophy of Science* 17: 415-427.
- Chi, M.T.H., Feltovich, P.J., and Glaser, R. (1981). "Categorization and Representation of Physics Problems by Experts and Novices." *Cognitive Science* 5: 121-152.
- Duhem, P. (1902). *Les theories electriques de J. Clerk Maxwell*. Paris: A. Hermann & Cie.
- Faraday, M. (1839-55). *Experimental Researches in Electricity*. Reprinted, New York: Dover, 1965.
- Gentner, D. (in press). "The Mechanisms of Analogical Learning." in *Similarity and Analogical Reasoning*. (eds.) S. Vosniadou and A. Ortony. Cambridge: Cambridge University Press.
- Gentner, D. and Gentner, D.R. (1983). "Flowing Waters and Teeming Crowds: Mental Models of Electricity." in *Mental Models*. (eds.) D. Gentner and A. Stevens. Hillsdale, NJ: Lawrence Erlbaum Associates. Pages 99-130.
- Gooding, D. (1985). "In Nature's School': Faraday as Experimentalist." in *Faraday Rediscovered*. (eds.) D. Gooding and

- F.A.J.L. James. London: Macmillan. Pages 105-137.
- Hesse, M. (1973). "Logic of Discovery in Maxwell's Electromagnetic Theory." in *Foundations of Scientific Method: The 19th Century*. (eds.) R.N. Giere and R.S. Westfall. Bloomington: Indiana University Press.
- Holyoak, K. and Thagard, P. (in press). "Analogical Mapping by Constraint satisfaction: A Computational Theory." *Cognitive Science*.
- Johnson-Laird, P.N. (1983): *Mental Models*. Cambridge, MA: Harvard University Press.
- Langley, P. & Jones, R. (1986): "A Computational Model of Scientific Insight." University of California, Irvine, Computational Intelligence Project Technical Report 87-01.
- Maxwell, J.C. (1890). *The Scientific Papers of J.C. Maxwell*. (ed.) W.D. Niven. Cambridge: Cambridge University Press.
- Miller, A.I. (1984). *Imagery in Scientific Thought*. Boston: Birkhauser.
- Nersessian, N.J.(1984). *Faraday to Einstein: Constructing Meaning in Scientific Theories*. Dordrecht: Kluwer Academic Publishers.
- , (1987). "A Cognitive-Historical Approach to Meaning in Scientific Theories." in *The Process of Science: Contemporary Philosophical Approaches to Understanding Scientific Practice*. (ed.) N.J. Nersessian. Dordrecht: Kluwer Academic Publishers.
- , (1988). "Reasoning from Imagery and Analogy in Scientific Concept Formation." in *PSA 1988*. (eds.) A. Fine and J. Leplin. East Lansing, MI: Philosophy of Science Association.
- Putnam, H. (1975). "The meaning of 'meaning'." in *Philosophical Papers, Vol. 2*. Cambridge: Cambridge University Press. Pages 215-271.
- Simon, H.A., Langley, P.W., and Bradshaw, G.L. (1981). "Scientific Discovery as Problem Solving." *Synthese* 47: 1-27.
- Simon, H.A. and Larkin, J.H. (1987). "Why a Diagram is (Sometimes) Worth Ten Thousand Words." *Cognitive Science* 11: 65-100.
- Wise, N. (1979). "The Mutual Embrace of Electricity and Magnetism." *Science* 203: 1313-1318.