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Models in Science and Mental Models in Scientists and Nonscientists

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Abstract *This paper examines the form of mental representation of scientific theories in scientists and nonscientists. It concludes that images and schemas are not the appropriate form of mental representation for scientific theories but that mental models and perceptual symbols do seem appropriate for representing physical/mechanical phenomena. These forms of mental representation are postulated to have an analogical relation with the world and it is this relationship that gives them strong explanatory power. It is argued that the construct of naïve theories as used in developmental psychology may be the appropriate form of mental representation for non physical/mechanical domains. The paper adopts a strong form of psychologism in the philosophy of science and argues that model-based approaches to scientific theories are more appropriate forms of representation for scientific theories than the formalist approaches that dominate current philosophy of science.*

Keywords *Mental models, scientific theories, representation, model-based theories, perceptual symbols, naïve theories, formal models, images, schemas, explanation.*

In the early part of the last century there was a heated debate between proponents of model-based theories and proponents of mathematics-based theories. In both physics and in the philosophy of science the formal mathematical approach won. In this paper I argue that the victory of the formal approach has distorted our view of the role of models in science and their role in the cognitive processes of nonscientists. Before I begin the initial arguments I want to establish some basic vocabulary that I will be using:

- a model-based theory is a conceptual framework that provides an explanation for a set of phenomena by postulating a structural relation to another more familiar conceptual framework;
- mechanical model-based theories are the sub-class of model-based theories where the familiar conceptual framework providing the explanation is restricted to causal/mechanical constructs;
- a mathematics-based theory is a conceptual framework that describes a set of phenomena by postulating a set of formal entities and abstract relations which are associated with the phenomena to be described.

In this paper I will examine: (a) the form of mental representation of scientific theories; (b) the representation of scientific theories themselves; (c) the implications of representation for understanding scientific theories and for science instruction; and (d) the role of representation in scientific discovery. I will look at each of these issues for scientists and for nonscientists. The comparisons of scientists and nonscientists provide converging evidence on some of these topics. It seems likely that scientists have the same basic cognitive architecture as nonscientists, with some possible differences due to selection and special training. There is not too much communication between the literature on scientists and on nonscientists, so comparing the two groups should enrich our understanding of both groups.

1. Mental representation of scientific theories in nonscientists

There is a large literature (e.g., Driver, Guesne & Tiberghien, 1985; Driver & Easley, 1978; Pfundt & Duit, 1991) showing that nonscientists try to make sense of the observable phenomena of the physical world just as scientists do. This leads directly to the issue of how knowledge about these domains is represented in the minds of nonscientists. I take a domain specificity approach and assume that there are different mental representations for different domains. Thus one needs different forms of representation for the causal/mechanical domain (e.g., falling and colliding objects), another for nonmechanical physical domains (e.g., natural selection), and yet another for abstract domains (e.g., mathematics).

1.1 Images

Even though in dealing with many domains of science (e.g., mechanics, observational astronomy) it is obvious that one would get strong reports of imagery, it does not seem to me that static images are conceptually rich enough to be the mental representations for naïve theories of these domains. A static mental image of a robin or of the sun just does not seem to be the kind of conceptual framework to provide explanations of natural phenomena in they way that a mental representation of the natural world should be able to do.

1.2 Schemas

Another possible candidate representation for scientific knowledge is schemas. Schemas were introduced into psychology by Sir Frederic Bartlett (1932) to account for knowledge-based effects in human memory (cf. Brewer, 2000). These ideas were developed in later work and in an important paper, Rumelhart (1980) argued that schemas were the mental representations for generic knowledge. In examining these issues Glenn Nakamura and I concluded that "Schemas are the unconscious mental structures and processes that underlie the molar aspects of human knowledge and skill. They contain abstract generic knowledge that has been organized to form qualitative new structures" (Brewer & Nakamura, 1984, pp. 140-1). Schemas have been used by cognitive psychologists to deal with generic knowledge such as "the sun rises in the east" or "birds that feed on flowers have thin beaks." Given this, it seems to me that schemas are also not quite the right form of representation for naïve theories of the natural world. However, if one accepts the standard distinction in the philosophy of science between *laws* as empirical generalizations and *theories* as structures that provide explanations (e.g., Hempel, 1966; Nagel, 1961) then schemas seem very appropriate as the form of mental representation for the low level empirical generalizations about the world that are formed by nonscientists.

1.3 Mental models

An obvious candidate for the representation of scientific knowledge in nonscientists is the concept of mental model. This however, becomes a bit complex because the term "mental model" is used in current cognitive psychology with (at least) two somewhat different meanings. One usage derives from a book on mental models edited by Gentner and Stevens in 1983. The researchers in this tradition have not tended to give an explicit account of what they mean by mental model, but it is fairly clear from their practice what they have in mind. For example, Collins (1985) stated that "Mental models are meant to imply a conceptual representation that is qualitative, and that you can run in your mind's eye and see what happens" (p. 80). The work in this tradition is almost exclusively directed at the causal/mechanical domain (cf. Stevens & Gentner, 1983, p. 2). Overall, I think we can see the construct of mental models as used in this tradition as a good candidate for the mental representation of mechanical/causal domains.

The other use of the term "mental models" derives from the work of Johnson-Laird (1983). Johnson-Laird proposed that "A model *represents* a state of affairs and accordingly its structure is not arbitrary like that of a propositional representation, but plays a direct representational or analogical role. Its structure mirrors the relevant aspects of the corresponding state of affairs in the world" (Johnson-Laird, 1980, p. 98). In practice, Johnson-Laird has used the construct of mental model to deal with the mental representations of unfamiliar spatial arrays (e.g., the layout of an unfamiliar town) and with solving of logic problems. However, it seems clear that mental models as he uses the term could also be used to represent many aspects of the natural world.

While neither group of mental model researchers thinks that mental models can be represented by static mental images, both groups are aware that mental models give rise to mental imagery. Thus Collins (1985, p. 80) and de Kleer & Brown (1981, p. 286) state that mental models can be "run in the mind's eye." Johnson-Laird (1983) states that "images correspond to *views* of models" (p. 157).

1.4 Perceptual symbols

Barsalou (1999) has proposed a new system of representation that he calls perceptual symbols. He proposes that attention works to extract perceptual components from experience. He then suggests that the perceptual symbols are integrated into frame-like structures and that the frame structures give rise to processes such as predication and recursion. In essence, Barsalou's representations are an attempt to combine the nonarbitrary (analogical) nature of perceptual representations with the symbolic/generative character of frames to produce a generative nonarbitrary form of representation. I have noted (Brewer, 1999a) that Barsalou's perceptual symbols are a natural form of representation for the causal/mechanical domain.

Barsalou has taken two radically different approaches as to how to interpret these representations as mental (?) constructs. In his earlier work (Barsalou et al., 1993) he considered them to be consciously experienced entities, but in his recent work he states that they are "neural states." (Given that we have no neurological evidence about the "configurations of neurons" that underlie perceptual symbols, I think this can best be taken at the current time as a assertion by Barsalou that they are not consciously experienced entities.) Barsalou asserts that the extracted perceptual components can be used to represent *all* forms of knowledge, including the most abstract forms of thought. I have argued (Brewer, 1999a) that this aspect of his approach is unlikely to be correct. Nevertheless, I think perceptual symbols provide the most detailed account available in cognitive psychology of a form of representation appropriate for the causal/mechanical domain.

1.5 Naïve theories

Given that we have several forms of mental representations which seem appropriate for the causal/mechanical domain, how are we going to represent nonmechanical causal domains? In developmental psychology there is a research tradition that posits naïve theories as a form of representation. This tradition began with the work of Karmiloff-Smith and Inhelder (1975) and Carey (1985) on young children's understanding of the natural world. It has been articulated in the recent work of Wellman, Gopnik, and Meltzoff on children's representations of the minds of other people (Gopnik & Meltzoff, 1997; Gopnik & Wellman, 1992; Wellman, 1990). The researchers in this tradition have basically argued that children are like little scientists and that they develop naïve theories of their world. These researchers have developed their ideas about the nature of a naïve theory from philosophy of science. However, Schwitzgebel (1999) has pointed out that neither earlier positivist accounts of theories nor more recent semantic accounts of theories seem like the right kind of representations for psychological accounts of naïve theories. So these researchers have ignored the detailed proposals in the philosophy of science and have taken just the basic structure of standard accounts of theories and then gone on to postulate that naïve theories are mental structures that contain theoretical entities (usually nonobservable), relations among the theoretical entities, and relations between the theoretical entities and some phenomena. Since many of these researchers were attempting to develop a theory-based account of how children come to understand that other individuals have minds, they clearly wanted an account general enough to extend beyond the domain of physical/mechanical phenomena.

1.6 Explanation

Many of the discussions of scientific theories by scientists and by philosophers of science have emphasized that one of the roles of theories is to provide explanations of natural phenomena. Thus it is interesting to examine the ability of the forms of mental representation just discussed to provide explanations. It seems that, for the most part, static images and schemas are not the type of conceptual structures that provide explanations. However, mental models certainly do. For example, Williams, Holland and Stevens (1983) explicitly make the point that mental models "can also be used to produce explanations or justifications" (p. 135). Proponents of naïve theories have made explanation a core component of their account of naïve theories in children. For example, in an early important discussion of these issues Carey (1985) argued that "Explanation is at the core of theories. It is explanatory mechanisms that distinguish theories from other types of conceptual structures" (p. 201). In a similar vein Perner (1991) stated that a theory "must provide a *causal explanatory framework* to account for phenomena in its domain" (p. 241). Thus clearly the proponents of both mental models and naïve theories see the ability to provide explanations of natural phenomena as one of the characteristics of these forms of mental representation.

1.7 Models and the world

Theorists who have favored mental models have been fairly clear about postulating that there is some relatively close relationship between the hypothesized mental models and the world. One of the influences on modern mental model theories was the early work of Kenneth Craik. Craik (1943) stated that "human thought has a definite function; it provides a convenient small-scale model of a process so that we can, for instance, design a bridge in our minds and know that it will bear a train passing over it" (p. 59). Johnson-Laird (1980) has been very explicit about this issue with his assertion that the structure of a mental model "mirrors the relevant aspects of the corresponding state of affairs in the world" (p. 98). A powerful advantage to this approach is that it is able to give a motivated account of how mental models could contribute to success in reasoning about the world.

1.8 Conclusions

This analysis of psychological accounts of the form of representation of the natural world in nonscientists suggests that neither static images nor schemas are structurally rich enough to account for the understanding of most domains. Schemas however, are a plausible candidate for the representation of the low level empirical generalizations referred to as laws in the philosophy of science. Mental models and perceptual symbols seem to provide plausible accounts of mental representation of mechanical/causal domains. Naïve theories seem possible accounts of the representation of nonmechanical domains.

What about purely formal accounts of physical phenomena? In discussions of the mental representations of nonscientists, this does not seem to be a relevant issue. Nonscientists are not exposed in explicit form to these accounts until late adolescence and, even then, only a small minority learn these approaches, so it is not obviously relevant for a general account of the mental representation of nonscientists. Many psychologists have wanted to postulate formal psychological representations in some implicit form, but since there is, at present, little evidence to support these approaches, it appears that we do not need to deal with formal representations of the physical world for nonscientists.

2. Mental representation of scientific theories in scientists

There has been little empirical study of the mental representations used by working scientists. However, there are many anecdotal accounts by scientists and they raise some interesting issues.

Duhem, in *The aim and structure of physical theory* (1914/1991) made some very strong psychological claims about mental representation in scientists. Based on an older faculty psychology he argued that certain physicists thought in formal abstract forms. He stated that for these individuals "the faculty of conceiving abstract ideas and reasoning from them is more developed than the faculty of imagining concrete objects" (p. 56). He contrasted these "deep but narrow" French minds with the "ample but weak" British minds. Duhem claimed for the British mind "the objects to which it is directed must be those falling within the purview of the senses, they must be tangible or visible" (p. 56). He stated that these minds are "ill prepared to abstract and deduce" (p. 56) and must "create a visible and palpable image of the abstract laws that his mind cannot grasp without the aid of [a] model" (p. 74). Given our current understanding of the mind I think we can reject Duhem's dichotomous faculty approach and assume that all scientists have a similar set of basic cognitive equipment though we might temper this with the possibility that differential backgrounds might lead to expertise differences in different scientists.

2.1 Imagery

Many scientists have provided accounts that imagery plays an important role in their scientific thinking (cf. Shepard, 1978; Root-Bernstein, 1985). For example Campbell (1913) described an attempt by J.J. Thomson to develop a theory of quantum effects and praised it as "the only attempt that has been made to visualize the mechanism" (p. 251). However, a number of writers have used arguments similar to those I made for the case of nonscientists to criticize the view that scientific theories can be represented in purely imagistic form. McAllister (1996) states "to portray a visualization as a model is to trivialize the latter notion" (p. 52). Mellor (1968) notes that "Much hostility to the use of the concepts of model and analogy in explicating theoretical explanation stems from the belief that such use requires scientists to express their theories in these crudely picturesque ways" (p. 283).

2.2 Schemas

In keeping with the arguments I made earlier for nonscientists, it would seem that schemas provide a good candidate for the mental representation of the empirical regularities and law-like phenomena in scientific work.

2.3 Mechanical mental models

A number of scientists have made strong claims for the important role of introspectable mental models as a form of mental representation. Perhaps the most famous is the statement of Lord Kelvin in his Baltimore lectures. He stated "I never satisfy myself until I can make a mechanical model of a thing. If I can make a mechanical model I can understand it. As long as I cannot make a mechanical model all the way through I cannot understand" (Thomson, 1884, pp. 270-1). J. J. Thomson stated that in mechanical model-based theories "an attempt is made to form an idea of something concrete, a model, for example, which will supply us with a mental picture of what may be taking place in the physical phenomena under consideration" (1930, pp. 15-6).

2.4 Non-naive theories

In addition to the mental models for mechanical domains it is necessary to assume the presence of nonmechanical model-like conceptual structures. Something of this type is required to give an account of the expert scientist's mental representation of a nonmechanical domain such as evolutionary theory.

2.5 Mental representations for formal entities

A number of writers have made the argument that modern physics requires formal non-model-based mental representations. For example, Suppe (1977) criticized Nagle's support for such models and stated that "If such iconic models must be in terms of familiar conceptual or visualizable materials, then Nagel surely is wrong" (p. 98). He goes on to give modern quantum theory as a counter example. Feynman, who reported that he frequently used mental models in his work (1985), noted that when faced with the construct of electric and magnetic fields he could not form an appropriate model. He stated, "How do *I* imagine the electric and magnetic field? What do *I* actually see?... I have no picture of this electromagnetic field that is in any sense accurate. I have known about the electromagnetic field a long time....When I start describing the magnetic field moving through space, I speak of the E- and B fields and wave my arms and you may imagine that I can see them. ... I cannot really make a picture that is even nearly like the true waves" (Feynman,1964, pp. 20-9 to 20-10). On the other hand it is interesting to note that Feynman also reported that he had a striking ability to convert some formal problems into a model-based format and then solve them using model-based reasoning (1985, pp. 84-7; pp. 243-5). Nevertheless, it seems clear that certain domains of theoretical physics require some form of mental representation for purely formal entities.

2.6 Conclusion

The conclusions to be drawn from the self-reports of working scientists seem similar to those from the study of the mental representations of nonscientists. It does not appear as if static images provide enough structure to be the form of mental representation for most scientific theories. However, there is strong support for representing physical/causal domains with imagistic mental models. On one issue there is a contrast with the conclusions from nonscientists. It is clear that some scientists function with formal representations of physical theories and so it will be necessary to have some form of mental representation for those forms of scientific theories (cf. Brewer, 1999b).

3. Representation, by psychologists, of the naïve scientific theories of nonscientists

The issue of how the psychologist, as theorist, represents the knowledge of nonscientists is a very confused issue in current cognitive psychology. There have been many proposals for representing this knowledge: propositions (e.g., Anderson & Bower, 1973), semantic nets (e.g., Collins & Quillian, 1969), schemas (e.g., Rumelhart, 1980), mental models (e.g., Johnson-Laird, 1980), naïve theories (e.g., Gopnik & Wellman, 1992) and perceptual symbols (e.g., Barsalou, 1999). Few of the theorists in this area make it clear if they are making a proposal about the form of the representation in the mind of the people they are studying or if they are making a proposal about the form of representation that they, as *scientists*, are using to study these individuals. Theorists in this area often shift back and forth between these two different positions. For example, in Rumelhart's classic paper on the nature of schema (1980) he defines a schema as "a data structure for representing the generic concepts stored in memory" (p. 34). This strongly suggests that he was intending schemas to be a representational tool to be used by the psychologist. However, in other pages of the same chapter he says things such as "Schemata are employed in the process of interpreting sensory data" (p. 33-4) or "memory traces are assumed to be very much like schemata themselves" (p. 53). These quotes sound as if he is referring to characteristics of the minds of the people he is studying. While it is rarely discussed overtly, it seems to me that many theorists in information processing psychology are instrumentalists. Thus, for these theorists the ambiguity is not a problem; regardless of exactly how they phrase things, these theorists believe that the representations they are proposing are simply hypotheses designed to predict the data.

3.1 Models and the world

In the physical sciences, scientists who favor models have had a tendency to be realists. They believe that air really is composed of molecules, that the earth really does go around the sun, that there really are genes. There is probably the same pull for mental model theorists in psychology. However, this leads to real ontological problems for these theorists – in psychology, *what* should such a model-based theorist be a realist about? I have already mentioned a good example of this difficulty in discussing Barsalou's perceptual symbols. He feels the realist tug and in his earlier work (1993) hypothesized that perceptual symbols were consciously experienced images. However, in his more recent work (1999) he has hypothesized that they are neural states. In addition to conscious states and neural states, cognitive theorists have also suggested unconscious cognitive states as an ontological possibility. For example, recall the definition of schema that Glenn Nakamura and I gave: "Schemas are the unconscious mental structures and processes that underlie the molar aspects of human knowledge and skill" (Brewer & Nakamura, 1984, p. 140). Clearly the special characteristics of the domain of cognitive psychology have made it hard for the theorists to find a consistent ontological position.

In the physical sciences model-based theorists have tended to argue that their models have some structural relation with the phenomena that the theory is about. Frequently the theorists talk about this relation in terms of an analogy. In cognitive psychology, model-based theorists have made the same move. For example, recall the definition of mental models by Johnson-Laird that I quoted earlier; he states that "a model *represents* a state of affairs and accordingly its structure is not arbitrary like that of a propositional representation, but plays a direct representational or analogical role. Its structure mirrors the relevant aspects of the corresponding state of affairs in the world" (1980, p. 98). Barsalou states that "Because perceptual symbols are modal, they are also analogical. The structure of a perceptual symbol corresponds at least somewhat, to the perceptual state that produced it" (1999, p. 578). These arguments, when taken in conjunction with the ambiguity of which form of representation the theorists are talking about, lead to an interesting puzzle: Is the analogy between the mental states of the individual being studied and the physical world or between the theorist's representations and the mental states being studied or between all three at once. Overall, I think it is clear that the issue of how psychologists represent the naïve scientific theories of nonscientists is still a work in progress.

4. Representation, by psychologists, of the scientific theories of scientists

The field of the psychology of science is relatively underdeveloped. There have only been limited discussions by psychologists of science about how to represent the scientific knowledge of working scientists. For the most part, scholars in this area (cf. Brewer & Mishra, 1998; Gholson, Shadish, Neimeyer & Houts, 1989; Giere, 1992) show the same problems as the cognitive psychologists studying scientific knowledge in nonscientists. It is difficult to be sure if the investigators are talking about the representations in the minds of the scientists they are studying or if they are making a proposal about the form of representation they as psychologists of science are using to study scientists.

5. Representation of scientific theories

In addition to the psychologically oriented accounts of scientific theories given above, one can look at the more neutral issue of the forms of representation that scientists have used to represent the physical world. Much of the discussion of the role of models in scientific theories derives from a debate in the early 1900's about the nature of theories in physics.

5.1 Formal accounts

Duhem took a strong form of the formalist position and argued that "a physical theory is essentially a logical system. Perfectly rigorous deductions unite the hypotheses at the base of a theory to the consequences which are derivable from it"

(1914/1991, p. 78). Boltzmann (1899/1974) described theorists who take the formal approach as individuals who believe that "physics must...pursue the sole aim of writing down for each series of phenomena, without any hypothesis, model or mechanical explanation, equations from which the course of the phenomena can be quantitatively determined" (p. 95).

5.2 Mechanical model-based accounts

Mellor (1968) described the model approach to scientific theories as the postulation of "a *visualizable* model (roughly, discrete physical things in definite spatial relations, interacting only on contact)" (p. 283). Boltzmann (1902) characterized model-based theorists as those who believe "physical theory is merely a mental construction of mechanical models, the working of which we make plain to ourselves by the analogy of mechanisms we hold in our hands, and which have so much in common with natural phenomena as to help our comprehension of the latter" (p. 790). Lord Kelvin adopted a strong form of the mechanical model position. He stated, "It seems to me that the test of 'Do we or not understand a particular subject in physics?' is, 'Can we make a mechanical model of it?'" (Thomson, 1884, p. 132).

5.3 Explanation

Formal representations and model-based representations appear to contrast on the issue of explanation. There is strong agreement that model-based approaches exemplify what it means to explain a physical phenomenon. There is also moderate agreement that many formal approaches and theories of certain domains of modern physics do not provide explanations. Thus, in describing the theories of Kirchhoff, an early formalist, Boltzmann (1886/1974) states "Kirchhoff very clearly sets himself as a task merely to describe natural phenomena as simply and perspicuously as possible, renouncing all explanation" (p. 16). Buchdahl (1964) states that "the principles of relativity, like those of thermodynamics, 'do not explain' the laws to which they refer in the way that 'non-mathematical' theories like those of Faraday and Thomson do provide an explanation (involving as they do a possibility of visualizing the theoretical structures)" (p. 154). Buchdahl (1964) describes Norman Campbell's views on models and explanation as follows: "the 'intellectual satisfaction' involved in 'explanation' requires more than the establishment of 'merely formal connections between laws'; but 'that the theory enables the laws which it explains to be 'visualized'; it traces an analogy, more or less close, between the phenomena expressed by the laws and some other phenomena usually of a mechanical nature with which we are familiar in everyday experience" (pp. 159-60).

While modern physicists are quite pleased with the extraordinary success quantum theory has had in predicting physical phenomena the issue of explanation remains a problem for some. Thus Bell (1986, p. 51) states that quantum theory "does not really explain things; in fact the founding fathers of quantum mechanics rather prided themselves on giving up the idea of explanation." He states, "I'm quite convinced ... that quantum theory is only a temporary expedient" and asserts that "I do believe it's a good habit, to look for explanations." Bohm (1986) makes a similar argument. He states, "quantum mechanics does not explain anything; it merely gives a formula for certain results. And I'm trying to give an explanation" (p. 127); and he goes on to say, "models explain the thing in the sense that they show how it comes about; the explanation makes it intelligible" (p. 131).

Campbell (1920/1957) suggests a compromise solution. He states, "A strict mechanical analogy is not, for most men of science, the only source of intellectual satisfaction; such satisfaction can also be derived from simplicity and generality, from an explanation which is generalization as well as from an explanation which is a reduction to more familiar notions" (p. 157). Cushing (1991) takes a somewhat different approach. He suggests that we use the word "explanation" for formal approaches that succeed with a covering law approach. However, he goes on to argue that "*understanding* of physical processes must involve picturable physical mechanisms and processes that can be pictured" (p. 341). Thus, for Cushing, quantum mechanics can't be understood.

5.4 Models and the world

Model-based theorists have tended to be realists about their theoretical constructs. A realist interpretation gives a natural account of why models often succeed in predicting the data and why they have shown considerable power in leading to new discoveries. McMullin (1968) notes that a "good model has a surplus content which enables the theory based on it to survive challenge and extend in all sorts of unexpected ways ... The presence of this surplus content is our assurance that the model-structure has some sort of basis in the 'real world.' For what is 'reality' if not the reservoir from which such a surplus is drawn?" (p. 395). Hesse (1967) suggests that it is "natural to hold, as was naively held by almost all theorists before the nineteenth century, that when a theory is developed in terms of a model, the model is the description of the way the world is conceived by that theory" (p. 358). Suppe (1977) concludes a discussion of the value of models in science with the comment that model theorists "are correct in insisting that the theory cannot be just the partially interpreted formalism, and must include a model – the model being the theory – which, if the theory is true, stands in an iconic relation to its phenomena" (p. 101).

5.5 Decline of mechanical models in theoretical physics

While there might be some dissatisfaction with the loss of explanation, the history of modern theoretical physics shows that with the development of relativity theory and quantum mechanics the formalist position won. Einstein's autobiographical piece (1959) gives a poignant description of the decline of mechanical models in physics (see also Klein, 1972). Eddington describes the change that occurred in the first quarter of the 20th century as a change in physicists' "ideal of scientific explanation" (1928, p. 209).

5.6 Models in science

However, it seems to me that this change in the domain of mathematical physics obscures a much larger truth about the nature of scientific theories. First, until the rise of mathematical physics essentially all scientific theories had been model-based theories. Second, after the rise of mathematical physics, theories in most of the rest of the sciences have remained model-based. For example, outside of physics, the two largest conceptual revolutions in my lifetime have been molecular biology and plate tectonics – both very model-based theories. Clearly, over most of the history of science and across most of the sciences, scientific theories have been and continue to be model-based.

6. Understanding and instruction in nonscientists

Given that most sciences are model-based and that the deepest level of understanding about the natural world that one can expect in a nonscientist is to understand the model-based theories in a domain, it is seems to me obvious that much instruction in science education should focus on teaching model-based theories.

I do not know much about science instruction but the argument outlined above seems consistent with two lines of work in science education. There has been a group of researchers interested in conceptual change (e.g., Nussbaum & Novick, 1982; Posner, Strike, Hewson & Gertzog, 1982) who have focused on diagnosing children's naive theories and replacing them with less naïve theories. These researchers have worked almost exclusively with model-based approaches to representation. Another group (e.g., Clement, 2000; Gilbert & Boulter, 1998; Gobert & Buckley, 2000) has focused on the use of various model-based instructional techniques, including the use of actual physical models in different domains. It is not clear how much the basic research issues discussed in this paper can be used to direct applied instructional research, but these two lines of work certainly seem to fall within the framework discussed in this paper.

7. Understanding and instruction in scientists

In the history of science and the recent philosophy of science there has been much focus on the glamorous issue of scientific discovery. I believe that this focus distorts the reality of the work of the ordinary scientist. In the process of becoming a scientist and in the daily routine of most working scientists one of the major activities is trying to understand new scientific information.

A number of scientists have argued for a model-based approach to scientific understanding and instruction. Maxwell stated, "a truly scientific illustration is a method to enable the mind to grasp some conception or law in one branch of science, by placing before it a conception or a law in a different branch of science, and directing the mind to lay hold of that mathematical form which is common to the corresponding ideas in the two sciences ... the illustration is not only convenient for teaching science in a pleasant and easy manner, but the recognition of the formal analogy between the two systems of ideas leads to a knowledge of both, more profound than could be obtained by studying each system separately" (1890, p. 219). J.J. Thomson stated that "The majority of men can think to much greater advantage about concrete things than they can about abstractions like algebraic symbols; they see the possibilities that lurk in the model more clearly than those that are hidden in equations" (1930, p. 22).

Leatherdale has made an interesting claim about the connection between scientific discovery and scientific understanding. He states "that what brings conviction to the discoverer is also what will bring conviction to everyone else, so that the discoverer's analogical acts must in some essentials be repeated by those who seek to understand the purport of such discoveries or theories" (1974, p. 65). Note, however, the contrast here; the creative scientist has to generate the original insight, while the student can be lead to the insight through explicit texts and carefully directed teaching.

8. Scientific discovery by nonscientists

One, at first, might think the issue of scientific discovery is not appropriate for nonscientists who do not make a living by trying to discover new theories. However, that view would ignore the fact that there is a large literature (Pfundt & Duit, 1991) showing that children (without explicit instruction) develop their own naïve theories of the world. Thus young children make scientific discoveries at a pace that puts even the most outstanding scientists to shame.

Examination of children's discovered theories shows that they have a strong preference for naïve causal/mechanical models (e.g., Andersson, 1986; Reiner, Chi & Resnick, 1988; Vosniadou & Brewer, 1994). Children hypothesize that night is due to objects blocking the sun, they hypothesize that heat is a substance that moves through objects. It appears that discovery by nonscientists is strongly driven by model-based analogies.

9. Scientific discovery by scientists

Even among the strong critics of model-based theories there has been considerable agreement that in the history of science, model-based analogies have played a strong role in scientific discovery and in extending theories to cover new domains. Boltzmann (1892/1974) made the ironic comment that "Faraday's ideas were much less clear than the earlier hypotheses that had mathematical precision, and many a mathematician of the old school placed little value on Faraday's theories, without however reaching equally great discoveries by means of [their] own clearer notions" (p. 9). Nash (1963) notes that "the physical model or analogy that makes explanation makes also an instrument of discovery. For it is precisely 'by considering extensions of the analogy' that we arrive at the pregnant questions which, Hesse says, 'suggest extensions of the theory'" (p. 248).

10. Overall conclusions

It seems to me that the success of formal theories in mathematical physics and the focus on formal approaches to scientific theories in the philosophy of science have distorted our view of the role of models in science and in the psychology of science.

The arguments developed in this paper strongly suggest that most scientific theories are model-based and that both scientists and nonscientists prefer to represent these theories in terms of mental models.

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