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Scientific Cognition as Model-Based Reasoning

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ABSTRACT. Recent work on model-based reasoning (MBR) in science has focused on scientific discoveries and conceptual change. This paper argues that model-based reasoning may provide a framework to explain the reasoning in every scientific context at the level of cognitive mechanisms, and attempts to account for normal science and scientific explanation within a model-based framework (model-based reasoning thesis).

1 Introduction

The view of Scientific Cognition in terms of *model-based reasoning* (MBR) has increasingly occupied the literature of the last two decades, and the accounts of mental modeling have provided a crucial understanding of the cognitive basis of scientific reasoning. This kind of approach to scientific cognition is mainly a direct reaction to the received view, especially related to the problems of the nature and structure of theories and to the syntactic account of scientific reasoning, as well as a reaction to Kuhn's theory of scientific revolution as *Gestalt* shift. Consequently, it is natural for this approach to focus on the problems of the nature of theories and of their generation and on the changes of conceptual structures in the contexts of discovery and development. Given the general claim that scientific cognition can be studied in terms of model-based reasoning, it seems to us that it is also particularly interesting to use the conceptual framework of MBR to capture details of scientific practices as considered in other traditions, including those involved in the context of justification developed by logical positivists, Kuhn's normal science, and even Lakatos' degenerative research programs.

In this paper, we will consider scientific cognition as a kind of model–based reasoning claiming that this can provide a new framework for the explanations of reasoning practices of every scientific context at the level of cognitive mechanisms. We will make a distinction between the singular problem of mental models and the plural one of model-based framework of science: the singular problem is not concerned with specific forms (including structures and formats) of models on which reasoning operates; on the

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contrary, the plural problem is related to specific forms of mental models. Based on this distinction, we claim that model–based reasoning is a semantic process implemented by cognitive operations on instantiated models in working memory. [1] After having provided an analysis of the case of Maxwell's electromagnetic theory with the aim to illustrate that scientific discoveries and revolutionary changes share the same kind of model–based processes with other reasoning practices (say, in normal science), this paper will provide a tentative account for model–based practices in normal science and in explanations, to favor the construction of a whole model–based framework for science.

2 Scientific cognition as model–based reasoning thesis

> ... [T]he cognitive sciences might come to play the sort of role that formal logic played for logical empiricism or that history of science played for the historical school within the philosophy of science. This development might permit the philosophy of science as a whole finally to move *beyond* [Italic emphasis by the authors of this paper] the division between "logical" and "historical" approaches that has characterized the field since the 1960s [Giere, 1992, p. xv].

It is this "*beyond*" that suggests that scientific cognition as MBR Thesis can be taken as a general claim, independent of any traditional demarcations of scientific contexts. In addition, the continuum hypothesis held between science and ordinary cognition also provides an underlying support to the thesis as a universal claim. "While there is currently little direct evidence on the issue of continuity" [Brewer, 1999, p. 492], a lot of important research work and theories developed recently in the fields of science studies (e.g., that of Dunbar, Gentner, Giere, Gooding, Magnani, Nersessian, Thagard, Tweney), developmental psychology (e.g., that of Carey, Gopkin, Keil, Perner, and Wellman) and science education (e.g., that of Chi, McClosky, and Clement) shows that the continuum assumption has been a fruitful working hypothesis. In this case, the former itself can be considered as an indirectly empirical support to the hypothesis of continuity. On the other hand, according to Johnson–Laird's mental model theory (MMT) of ordinary human reasoning, endowed with an extensive experimental confirmation[2], ordinary reasoning too is the kind of model–based reasoning.

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[1] Nersessian's definition of mental modeling is: "Mental modeling, a semantic process thought to utilize perceptual mechanisms in inference, is hypothesized by many cognitive scientists to be a fundamental form of human reasoning" [Nersessian, 2003, p. 197].

[2] The theory has been tested by a lot of experimentation involved in various reasoning tasks, including reasoning with logical connectives, reasoning with quantifiers, modal or

Following the continuum hypothesis, it is natural to claim that scientific reasoning is merely an extension of ordinary human reasoning; namely, the former is a refinement and complication of ordinary cognitive strategies. Hence, there are no reasons for us to believe that model-based reasoning is a salient feature *only* of some scientific contexts (say, discovery and conceptual change). In other words, the continuum hypothesis suggests that the processes of model–based reasoning can constitute a unified cognitive basis underlying both ordinary and scientific reasoning–practices, looking for reasonable explanations of scientific practices at the level of cognitive mechanisms.

As Giere writes, "[. . .] adopting a model-based framework makes it possible to employ resources in cognitive psychology to understand the structure of scientific theories in ways that may illuminate the role of theories in the ongoing pursuit of scientific knowledge" [Giere, 1999, p. 99].If we consider the flourishing current development of cognitive studies in the area of model–based reasoning in science, we should have to take this suggestion seriously. In the last two decades, indeed, many authors contributed a lot to the development of the thesis, and much of their work appeared in several important books (e.g., [Magnani *et al.*, 1999; Magnani and Nersessian, 2002; Giere, 1992; Carruthers *et al.*, 2002; Gorman *et al.*, 2005] and some special journal issues (e.g., *Foundation of Science* 5(2), 9(3); *Philosophica* 61(1), 62(2); and *Mind and Society* 2(4), 3(5)). However, much of research on the thesis is restricted to scientific practices *only within* the context of discovery. This over-concentration of this kind of research would bring potential problems. For example, overlooking and undervaluing the legacies of the traditional philosophy of science instead of reconsidering its central topics in terms of cognitive analyses, and misunderstanding the role of model–based reasoning in science thus creating the illusion that scientific creativity and the generation of novel conceptual structures own their peculiar cognitive processes or mechanisms fundamentally different from those of other scientific practices. This would reproduce the distinction between justification and discovery, instead of developing a unified model–based framework for all kinds of reasoning practices in science.

It seems there are some confusion and inconsistencies within the current model–based framework. Among them, the most common one in the current literature is the use of the concept "mental model", which is so popular that we are not surprised that there are few responses to Brewer's challenge and clarification[3] [Brewer, 1999; Brewer, 2003]. A salient case of this confusion

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probabilistic reasoning, relational reasoning, everyday inferences and arguments, counterfactual reasoning, reasoning by psychotic individuals, etc.

[3] We agree with Brewer's clarification. But it seems that there never is a linguistic

is the mix of Johnson–Laird's concept [Johnson-Laird, 1980; Johnson-Laird, 1983] with Gentner *et al.*'s term [Gentner and Stevens, 1983] under the same label of "mental model".[4]

To avoid potential conceptual confusion in the current literature, the first question we have to answer is about the real status of the models involved in the processes of reasoning. It is obvious that both external physical and internal mental models often play an important role in the processes of reasoning. While the manipulations of external physical models would cause the changes of corresponding mental models (see [Dogan and Nersessian, 2005]), it is the latter that is responsible for the mental operations of reasoning. Hence we are sure that the models employed to account for cognitive operations of reasoning are the knowledge structures constructed with mental representations. Moreover, we are also sure that certain kinds of scientific reasoning operate on many kinds of knowledge structures other than Johnson–Laird's mental models. Hence, it is not appropriate to appeal for some specific form of mental representations in defining the term of "model–based reasoning", since mental models in question are constructed with different contents (kinds and levels of information), structures, and formats of internal representations and thus may take many forms.[5] For example, we learn of some forms such as images, prototypes, frames, schema, mental models, perceptual symbols, and theories from the field of psychology.

Based on the above considerations, we suggest a distinction between the singular problem of mental models and the plural one regarding the model–based framework of science. On the one hand, it is a singular problem just because this problem of mental models is not concerned with their specific forms (including structures and formats); that is, the singular problem is a question of what is the nature of mental models in general – in this sense, we call them "generalized mental models", in order not to be confused with both of Johnson-Laird's and Gentner's concepts. Mental models in the singular problem only refer to internal mental representations functioning in reasoning and in the generation of new mental representations; thus,

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reform in cognitive science though we have had Brewer's proposals [Brewer, 1999].

[4] It is important to note that Johnson–Laird's mental models are kinds of knowledge structures constructed temporarily in working memory at the organizational level of schema, and that Gentner *et al.*'s mental models refer to a class of knowledge structures in long–term memory. These are, according to Brewer, "the subclass of theories which use causal/mechanical explanatory frameworks" [Brewer, 1999, p. 500]. To distinguish between them, Brewer suggests the term "mental model" still for Gentner's concept and "episodic model" or "constructed schemata" for Johnson–Laird's concept [Brewer, 1999]; also see [Brewer, 2003] for an overview on mental models).

[5] [Brewer, 1999; Brewer, 2003] and [Nersessian, 2002a] discussed alternative forms of mental models.

they are characterized not by their particular forms, but by their internal status and their general cognitive functions in representing reality and in reasoning processes. Mental models in the generalized sense cover all forms of knowledge structures involved in processes of reasoning, and should be used in arguments for model–based reasoning as a semantic process. Mental models in the "plural" sense, on the other hand, related to the kinds of specific forms of mental models, deal with a variety of classes both of mental models and of reasoning.

In addition, it seems that model–based reasoning in specific cognitive tasks operates on some specific and integrated structures in working memory (WM) – we call them "instantiated models" – instead of operating directly on knowledge structures in long–term memory (LTM). Working memory plays a central role in integrating both retrieved information from long–term memory and/or perceptual information into instantiated models and in generating new mental representations based on instantiated models. In this way, working memory acts as a kind of *assembling* apparatus, considering that more common and more realistic kinds of reasoning are those based on multi–models with multi–forms of mental representations. It is in working memory that many forms of mental representations, including perceptual and imaginary ones, are combined together in an integrated model functioning in a process of reasoning. In her studies on Maxwell's vortex–idle wheel model, Nersessian writes: "The practices of analogical modeling, visual modeling, and thought experimenting (simulative modeling) are frequently used together in a problem-solving episode" [Nersessian, 2002a, p. 137]. That is, several forms of mental representations involved in those modeling processes come together and generate an integrated model for a reasoning task. Constituent forms or models are not just supervening things or epiphenomena: a mental image of the wheel in Maxwell's case is helpful to generating an external representation, such as drawings [Nersessian, 2002a, p. 138].

In the working memory assembling (WMA) model of mental representations, we divide mental models generated in WM by information in long–term memory into three kinds: theoretical models (including those of Gentner's mental models), schematic models (such as Johnson–Laird's mental models), and imagery models (e.g., images in Kosslyn's account). Following the generations of these three kinds of models, an integration of kinds of mental models with different formats happens in working memory for a variety of cognitive tasks.

The picture characterized above might be helpful to reduce the confusion in the current literature and to make the model–based framework a more reliable tool able to account for the reasoning practices of other contexts of science and not only for discovery and conceptual development. In the following section, a case analysis will show that revolutionary changes share the same model–based processes with reasoning practices of normal science.

3 Maxwell's electromagnetic theory: the continuity between normal science and scientific revolution and the continuity of scientific revolution

Nersessian [2002a] says that model–based reasoning is a central characteristic of scientific reasoning during scientific revolution and theory innovations. She uses the cognitive–historical approach to study the development of Maxwell's electromagnetic theory, and points out that model–based reasoning causes conceptual changes in science. Indeed some processes of model–based reasoning, such as analogical modeling and visual modeling, can draw and check the constraints of the current conceptual system in terms of the constraints derived from the target, and generate new constraints which thus are integrated in a new revised conceptual system. It is the process of "generic abstraction" that completes the tasks of drawing and integrating constraints derived from many sources, and thus that causes the genuine creativity in science. It seems clear that Nersessian's analysis of model–based reasoning focuses on the contributions of these processes of reasoning to conceptual and theoretical innovations, and provides a new perspective on the understanding of scientific revolutions, considered as continuous and non–accumulative process.

Maxwell and even other physical scientists before Einstein's rejection of the concept "ether", as [Nersessian, 2002b] points out, still believed that electromagnetic phenomena are mechanical phenomena of ether by nature, and that a complete explanation of electromagnetic field has to involve a mechanical theory of ether. Also, Maxwell insisted that the electromagnetic theory was not yet a complete theory, but he believed that there would be a mechanical theory of ether in the future that would meet with his electromagnetic theory. It is obvious that Maxwell's theory still belongs to Newton's conceptual framework at a large extent; thus his "conceptual innovation" is not a conceptual change and innovation in Kuhn's sense (revolution). The significance of Maxwell's work, however, is that his concept of "electromagnetic field" brings new constraints that conflict with those implied in the conceptual system of Newton' mechanics. It is this conflict, as we know, that was resolved by Einstein's radical revision of the conceptual foundations of Newton's mechanics, which eventually establishes electromagnetic phenomena as a realistic domain different from that of mechanical phenomena. It is this last shift of the concept of "electromagnetic field" that is a genuine conceptual innovation in the sense of scientific revolution.

The interesting facts related to the shift is that the result of Michelson–Morley experiment had no impact on Einstein in the generative process of his theory of relativity, and that instead the experimental result of the constancy of the velocity of light – a predication derived from Maxwell's theory – and the elegancy of Maxwell's theory impressed Einstein. Therefore, when facing the conflict between Maxwell's theory and the mechanical theory, Einstein chose the former and renovated Newton's mechanics. Informed by this historical case model-based reasoning provides undoubtedly the possibility of genuine scientific creations: we maintain that it is not only characteristic of scientific reasoning in the processes of revolutionary changes. The case of Maxwell's theory does show that model-based reasoning is a basic cognitive process of scientific practices of reasoning in the stage of normal science too: this that becomes one of indicators to the continuity between normal science and scientific revolution.

The above analysis suggests that the general claim maintaining that scientific cognition consists in model–based reasoning seems more important from a perspective of cognition than only emphasizing on model–based reasoning as the basic cognitive process or mechanism of scientific discovery and/or conceptual change in science. The next section will instead characterize scientific practices of normal science within the conceptual framework of scientific cognition as model–based reasoning, a perspective which has received little attention in the current literature on model–based reasoning in science. In section five, we will discuss a central topic of the standard philosophy of science, scientific explanation, based on our perspective on model–based reasoning.

4 Reasoning practices in normal science

Following Nersessian's account of mental modeling, we consider modeling constraints as an aspect important for understanding scientific cognition. Thus we set out the characterization of the core of normal science, namely Kuhn's concept of "paradigm", in light of modeling constraints. Here our working hypothesis suggests that knowledge background and paradigms have to be considered as modeling constraints in scientific reasoning. This suggestion is consistent with Nersessian's idea of concepts as modeling constraints and Giere's conception of scientific theories as incomplete models.

Nersessian points out that it is necessary to understand concepts of scientific theories on the basis of modeling constraints. In addition, [Giere, 1999] claims that scientific laws are not really statements about the world but *part* of characterization of theoretical models, such that only combining them with a specific problem context one has a model that can be compared with a real system. It is obvious that one has to understand scientific laws and theories in terms of theoretical models but not in terms of modeling constraints if laws and theories are merely linguistic descriptions of incomplete theoretical models. Thus, we use modeling constraints to understand a theoretical framework or paradigm that is presupposed for scientific practices in normal science: a paradigm is a set of modeling constraints. The constraints provided by a paradigm can be divided into two main kinds: explicit constraints which constitute a disciplinary matrix, and implicit/tacit constraints which consist in exemplars. According to this viewpoint, the practices of puzzle–solving in a normal science are the processes of model-based reasoning within one fixed set of constraints. Consequently, there are three important aspects in our analysis of the concept of paradigm as a set of modeling constraints: a disciplinary matrix as explicit constraints; exemplars as implicit/tacit constraints; and puzzle–solving as model–based reasoning.

The claims mentioned above merit investigation in two directions. On the one hand, the empirical support for them derived from cognitive psychology shows that the processes of model–based reasoning in ordinary tasks can be used to understand the remarkable features of scientific practices in normal science. This is a kind of indirect but substantive evidence for the continuum hypothesis as an indispensable component of the conceptual framework of scientific cognition as model–based reasoning. In other words, this makes it clear that (at least) the two kinds of cognition, ordinary and scientific, are continuous. On the other hand, that empirical evidence in turn provides a support for the model–based view of theories developed by [Giere, 1999], along the line of semantic approaches to the nature of scientific theories. The latter would become (Nersessian [1992; 2002a; 2002b]) a conceptual framework employed in an analysis of cognitive features of scientific practices and even common human knowledge.

The continuum hypothesis, if taken for granted, should be also taken as a reason why we expect that (at least) some of basic features of ordinary reasoning would be present in scientific reasoning. According to the mental model theory of ordinary human reasoning put forward by [Johnson-Laird, 1980] and developed by him and his followers and proponents, human reasoning is a process of model–based reasoning in nature. The findings of psychological experiments indicate that mental models play an indispensable role in ordinary human reasoning, and that there are several common characteristics of the use of mental models, such as

1. A mental model represents one possibility satisfying constraint of modeling, but captures what is common to all the possibilities.

2. With regards to modeling constraints, mental models do not represent what is false, but what is true.
3. Procedures of model-based reasoning rely on counter-examples (alternative models) to refute invalid inferences.
4. The greater the number of models that a task needs, the poorer the performance is.[6]

Let's interpret the above features taking advantage of the problem of relational reasoning.

According to Johnson-Laird and Byrne, human beings' reasoning relies on the construction and manipulation of mental models and can be characterized as a three–step procedure:

- They imagine a state of affairs in which the premises are true; in other words, they construct a mental model of the premises.
- They come up with a putative conclusion compatible with this model.
- They try to falsify this conclusion by constructing alternative models of the premises. If there are no such models, then the conclusion is a valid inference from the premises.

In the following problem of relation reasoning (Problem 1), for example, the premises are:

1. A is to the right of B
2. C is to the left of B
3. D is in front of C
4. E is in front of A

The subject is asked to answer the spatial relation between D and E.

Problem 1 is compatible with the model:

C B A

D   E

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[6] Among the characteristics of the use of mental models discussed by Johnson-Laird [1983; 1999; 2001] Byrne and Johnson Laird [1989], these four features are very useful for our characterization of scientific reasoning.

Based on this model, the subject would draw an initial conclusion: D is to the left of E. No other models are compatible with the premises. Thus, Problem 1 is called as the "problem of one-model".

Problem 2:

1. B is to the right of A
2. C is to the left of B
3. D is in front of C
4. E is in front of B

The problem is compatible with one model:

C A B

D   E

Based on the above model, the subject would draw an initial conclusion: D is to the left of E. After further searches for models, the subject would find out that the below model

A C B

  D E

is also compatible with the premises and supports the same conclusion.

According to the theory of mental model, Problem 2 should be more difficult than Problem 1 because it is harder to deal with two models than with one model. This claim is confirmed by experiments.

The model–based reasoning in the ordinary inferential tasks such as the one described above permits to draw and to integrate the constraints derived from the premises in virtue of mental models – if the premises in question are taken as the linguistic descriptions of modeling constraints. If the claim that model–based reasoning is a fundamental process underlying both ordinary and scientific reasoning is true, it is possible to account for scientific practices of normal science in light of the key features of model–based reasoning revealed by cognitive psychology. First, as mentioned above, a mental model in the sense of the mental model theory captures what is common to all the possibilities even though it represents only one possibility satisfying modeling constraints. In the practices of normal science, the central function of exemplars is to represent the modeling constraints involved in a paradigm in a cognitively manageable way, such that scientists develop other models through the processes of inference by similarities.

In particular, the tacit constraints derived from exemplars are necessary to the practices of problem–solving in normal science and make them processes of similarity–grouping since the similarity to an exemplar ensures that the necessary tacit constraints are satisfied by the processes of model–based reasoning.

Second, mental models represent what is true relative to modeling constraints, and thus may lead to systematic errors. Similar situations would happen in reasoning practices of normal science (for example, the historical cases of the particle theory, when it was used to explain phenomena of light such as reflection, refraction, and Newton ring). Of course, it is has to be noted that, due to the function of generic abstraction, new constraints can emerge in the processes of model–based reasoning, even those that suggest us to reject the old entrenched constraints, as shown in Nersessian's analysis of the Maxwell's case [Nersessian, 2002b]. Moreover, this second feature of mental models is responsible for the conventionality of normal science and accounts for the fact that the practices of puzzle–solving would (at least usually) not challenge the fundamental theoretical hypotheses or principles of a paradigm.

Third, the procedures of model–based reasoning in ordinary inferential tasks rely entirely on alternative models to refute invalid inferences. The subject would confirm the inference from the initial models in the case that there are no incompatible alternative models or that he/she could not discover alternative models. This may be the reason why a genuine valid refutation against an existent hypothesis/model in reasoning practices of normal science is that of putting forward incompatible alternative hypotheses/models. That is, the presence or construction of competing theories is a prerequisite or an essential way to frustrate an existing theory; on the contrary, the fact that there are no alternative hypotheses/models which could be developed is a strong argument for an existent hypothesis/ model.

Finally, the greater the number of models that a task needs, the poorer the performance is. In fact, the number of mental models involved in a task is inversely proportional to the amount of modeling constraints. Kuhn expounds how the "would-be" researchers acquire capacities to do research work in a specific discipline through the inferential training similar to that of exemplar–exercises in textbooks. The cognitive process similar to learning based on exercises in textbooks is required for the training of researchers even though the two processes are fundamentally different in the sense that a question involved in exercises usually has a single definite resolution (model), but researchers in actual scientific practices have to find out a variety of unknown constraints of modeling.

5 Model-based explanations in science

Explanation is one of the most typical and important functions of scientific theories, and the covering–law model of scientific explanation is one of the most valuable historical legacies of logical positivist philosophy of science. From the recent literature, a novel idea emerges: many forms of mental representations can be used to produce explanations and thus lead to the feelings of understanding (see [Brewer, 1999] for a short review; and [Brewer *et al.*, 1998] for a psychological account of explanation). Accordingly, it is possible to develop a psychological account that expounds the cognitive basis of scientific explanation within the conceptual framework of model–based reasoning.

Scientific explanation as model–based reasoning is a kind of goal–guided cognitive process. Goals, derived from specific cognitive tasks, play an important role in determining what kinds of modeling-constraints need to be abstracted from an explanandum and which levels of explanations should be reached. We divide the complex forms of mental representations of scientific knowledge into three suitable levels: instance, schema, and theory, which can produce three basic levels of explanations respectively. In fact, most discussions on the representational forms of conceptual structures in the current cognitive–historical analyses of science focus on schematic models and theoretical models (e.g., mental models discussed in [Gentner and Stevens, 1983]. Schematic models provide explanations at the law-like level, as Brewer says: "schemata are the forms of mental representation that are appropriate to account for laws in the psychology of science and for the large class of empirical generalizations in nonscientists" (p. 496).

According to the model of explanation as model–based reasoning, there are four basic steps of cognitive operations in a process of model–based explanation: (1) generic abstraction; (2) ascription of feature constraints; (3) generation of instantiated models in working memory; and (4) the feelings of understanding. Usually, an explanation begins at the stage of generic abstraction, in which two kinds of constraints on modeling a phenomenon or conceptual construct (e.g., Boyle's law) are temporarily fixed. One is a set of feature constraints that characterize the phenomenon or construct; another is a set of variables (and/or a set of constants) that describe the initial and boundary conditions of the explanandum. In contrast to the mental modeling way of generating a new conceptual structure (see [Nersessian, 2002a, p. 152], the following step is not to construct an initial model for target, but to search for a suitable relation of ascription under some representational forms of knowledge stored in long–term memory. It should be noted that this process is often involved in a selection of one ascription in light of specific cognitive goals and background knowledge. At the third stage of explanation by model–based reasoning, an instantiated model is generated through the information stored in long–term memory and thanks to the constraints that describe the initial and boundary conditions of the explanandum. Finally, the agent who undertakes the explanation undergoes the experience of understanding the explanandum through an internal process of mapping.

Therefore, explanation is a semantic process of understanding based on mental models, in which tacit or implicit constraints are often used to construct instantiated models. This is the fundamental reason why it is impossible in principle to construct a logical structure which links the explanandum with the explanans. In other words, instantiated models are not the explanans in Hempel's models of scientific explanation even though such kinds of explicit knowledge contained in the explanans are necessary constraints which are used to construct instantiated models. Thus, information stored in long–term memory that covers the explanandum cannot produce an explanation if it does not support the construction of an instantiated model.

6 Conclusion

Cognitive approaches are not a kind of panacea that can save the philosophy of science and make it be perfectly recovered from the illness of logicism and historicism. While they are able to overcome some shortcomings of the traditional philosophy of science and to open new areas and research, cognitive studies of science have their own limitations. The proposal of this paper was an extension of Giere's model–based view of theories and of Nersessian's mental modeling account, which defend a model–based framework for the explanations of scientific practices at the level of cognitive mechanisms.

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