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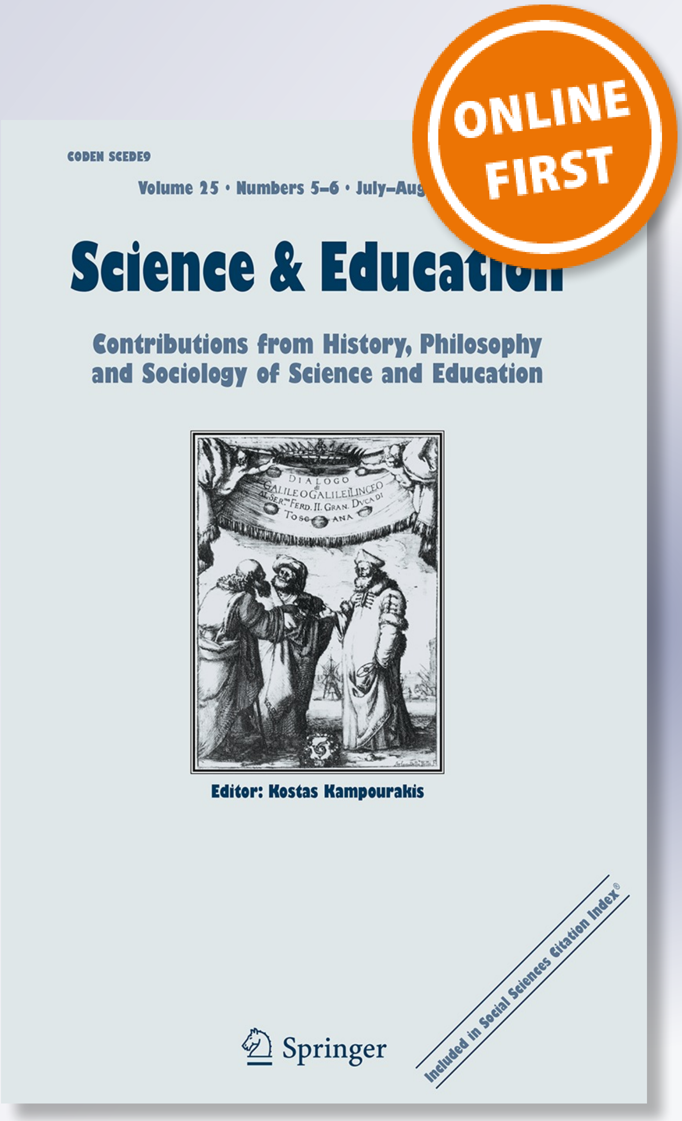
Science & Education
Contributions from History, Philosophy
and Sociology of Science and
Mathematics

ISSN 0926-7220

Sci & Educ
DOI 10.1007/s11191-016-9845-3



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ARTICLE

Meta-Theoretical Contributions to the Constitution of a Model-Based Didactics of Science

Yefrin Ariza[1,2,3] · **Pablo Lorenzano**[1,3] · **Agustín Adúriz-Bravo**[2,3]

Abstract There is nowadays consensus in the community of didactics of science (i.e. science education understood as an academic discipline) regarding the need to include the philosophy of science in didactical research, science teacher education, curriculum design, and the practice of science education in all educational levels. Some authors have identified an ever-increasing use of the concept of 'theoretical model', stemming from the so-called semantic view of scientific theories. However, it can be recognised that, in didactics of science, there are over-simplified transpositions of the idea of model (and of other meta-theoretical ideas). In this sense, contemporary philosophy of science is often blurred or distorted in the science education literature. In this paper, we address the discussion around some meta-theoretical concepts that are introduced into didactics of science due to their perceived educational value. We argue for the existence of a 'semantic family', and we characterise four different versions of semantic views existing within the family. In particular, we seek to contribute to establishing a model-based didactics of science mainly supported in this semantic family.

1 Introduction

During the last 30 years, significant progress has been made regarding the introduction of *meta-scientific* concepts (i.e. concepts to think *about* science) in our understanding of science education. Those concepts have been taken mainly from the philosophy of science,

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understood as the meta-science *par excellence* (e.g. Adúriz-Bravo 2013; Izquierdo-Aymerich and Adúriz-Bravo 2003; Matthews 1994). The ‘rapprochement’ between the philosophy of science and didactics of science (Matthews 1994) primarily relates to a marked movement in our discipline from classical philosophical positions (e.g. logical positivism, critical rationalism, and the received view) to ‘historicist’ positions—especially represented by Thomas Kuhn (1962/1970), Imre Lakatos (1971, 1978), and Stephen Toulmin (1972)—in order to provide meta-theoretical foundations for science teaching, curriculum design, teacher education, and didactical research.

However, advances in recent and contemporary philosophy of science seem to have been excluded from most of didactics of science. Concretely, the movement occurred in the philosophy of science regarding the analysis of scientific theories from syntactic/axiomatic conceptions, via historicist conceptions, towards semantic conceptions is not paralleled in science education. Science education is still resorting to meta-scientific production that is over 45 years old and has been significantly improved.

This tendency might be reverting in recent years. In the latest academic production on science education[1], there are incorporations of some of the contributions of the so-called *semantic view of scientific theories* (particularly some aspects of Ronald Giere’s proposals and, to a lesser extent, of Bas van Fraassen’s ideas). The meta-scientific content of this view—especially the construct of ‘theoretical model’—has been the target of various reflections that constitute an emerging line of research and innovation gaining space in the literature on science education (cf. Erduran and Duschl 2004; Gilbert and Boulter 2000; Khine and Saleh 2011). Additionally, the emergence of what could be considered a ‘model-based’ didactics of science has been pointed out by several authors in the discipline (e.g. Adúriz-Bravo 2013; Chamizo 2010, 2013; Develaki 2007; Izquierdo-Aymerich and Adúriz-Bravo 2003; Oh and Oh 2011; Passmore et al. 2014). This so far very timid integration of semantic perspectives can be extended and modified so as to include other proposals—besides that of Ron Giere’s, which dominates the literature—in current didactical research.

The aim of this article is to present, for didacticians of science, some elements of recent philosophy of science related to the analysis of theories and models, and particularly the semantic view—with its different variants, approaches or versions that can be conceived of as ‘members’ of one big *family*, which can be called the ‘semantic family’ (Lorenzano 2013). Subsequently, and with further developments, this aim would be continued in the introduction of intellectual tools of the semantic family in the practice of science education in the classrooms and in science teacher training. In order to do so, it is necessary to overcome the difficulties caused by science education researchers’ and science teachers’ lack of acquaintance with post-Kuhnian developments in the philosophy of science (Ariza et al. 2010).

The work reported here intends to deepen the idea of the presence of a set of distinctive features within the current semantic view of scientific theories and to argue for the existence of a semantic family in which those features are specified in distinct forms. We want to provide elements that allow recognising and distinguishing the main approaches within

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[1] We use the expression ‘science education’ to refer to the practice of educating in science, whereas we call ‘didactics of science’ the academic discipline that reflects and investigates upon such practice (cf., Adúriz-Bravo and Izquierdo-Aymerich 2005). In accordance with this, we call ‘science educators’ the practitioners of science education; ‘didacticians of science’ would then be the academic researchers in our discipline. Equivalent expressions are standard in the main languages in continental Europe (e.g. French: didactique des sciences/didacticiens; German: Didaktik der Naturwissenschaften/Didaktiker; Spanish: didáctica de las ciencias/didactas).

this family. The spirit is then to contribute to the establishment of a model-based didactics of science (Adúriz-Bravo 2013; Ariza 2015) supported in contemporary philosophy of science, and especially in that semantic family, which is considered by some authors as one of the most robust proposals to understand science, its processes, its products, and its changes over time.[2]

We therefore agree with the more general contention that it would be important to introduce semantic characterisations of scientific theories into science teacher training and into science education through all educational levels, following scholars within the community of the philosophy of science who believe that the semantic family is a widespread and strongly established meta-theoretical research programme, with solid foundations and providing a richer framework for reflection than its predecessors, and even other contemporary schools of the philosophy of science (cf., Estany 1993; French and Ladyman 1999; Moulines 2008).

In this article, the main features of each of the diverse proposals that integrate the semantic family will be explicated by using their major works; however, it is clear that in the context of disciplines *outside the philosophy of science*—and such is the case of didactics of science—those works are almost unknown, and so are the discussions about the existence of a semantic family. In this sense, the characterisation of the main similarities and differences among the proposals that constitute this family is indeed an original contribution in the case of science education.

An approach to classical semantic views in order to expand the theoretical framework for a hypothetical model-based didactics of science (as it is intended in our work) could help strengthen lines of didactical research that use recent achievements from the philosophy of science as support. In particular, it could help in clarifying the various relationships between the philosophy of science and didactics of science through a comprehensive analysis, or—as it is called here—a 'road map', guiding our approach to contemporary philosophy of science in a simple and formative way, avoiding ambiguities and respecting as far as possible the subtleties of meta-theoretical reflection.

At the same time, we aim at initiating research that enables the 'structuralist meta-theory' (understood as *one* variant in the semantic family) to approach the field of didactics of science. Nowadays, within this meta-scientific school there is no developed line of research on its influence in science teaching or on the possible implications that its constructs for meta-theoretical analysis, as well as the large amount of theories reconstructed with structuralist instruments, may have.[3] Thus, our work would also constitute, in a broad sense, the expansion of the scope of research in meta-theoretical structuralism towards didactics of science.

Under all these considerations, the first part of this article is a brief presentation of the semantic view of scientific theories, which we portray as an epistemological turn in the philosophy of science of the 1970s (Sect. 2). Then, we present an outline of what we call the 'semantic family' (Sect. 3); the outline aims to represent the main features of all of the

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[2] In the last 35 years, there is an ever-increasing amount of philosophical work on scientific models. In this article, we centre our attention on the literature that considers models as an essential component of scientific theories, namely the already mentioned semantic view or family. We are of course aware that there exist very rich recent developments on models that analyse them without a reference to theories—as being 'independent' of theories, 'autonomous', or 'mediators' between reality and theories. For such views, which would demand a whole paper of their own, see e.g. Cartwright et al. (1995), Morgan and Morrison (1999), Morrison (1999) and Weisberg (2013).

[3] However, it is only fair to make clear that just very few—if any—philosophical schools of science take as a case of study their influence on science teaching.

different 'varieties' within the family. In Sect. 4, we make explicit the distinctions between four of those varieties (Suppe's, Giere's, van Fraassen's, and meta-theoretical structuralism) through a presentation of each of them; we propose a didactical schematisation of those four approaches that could be useful for readers to get familiarised with this meta-theoretical family. Sections 5 and 6 recapitulate and introduce some final considerations.

2 The Semantic View of Scientific Theories

The strong conviction of the semantic view of scientific theories is that concepts relative to models are much more fruitful for the philosophical analysis of theories, their nature and function, than concepts relative to linguistic propositions (such as laws). The semantic view's focus on models as non-linguistic entities rather than on the linguistic formulation of theories frontally contrasts the 'syntactic' character of classical analyses on theories performed by logical positivists and their followers. The so-called received view on scientific theories, dominant by mid-twentieth century, conceived them a set of phrases or sentences ('propositions'). From a strictly syntactic point of view, philosophers reduced, at least in principle, a theory to a distinct subset of propositions, the *axioms*, and to the class of their logical consequences. This led to inconsistencies in philosophers' depictions of theories that eventually brought about the abandonment of the syntactic approach, making way for a semantic conception of scientific theories in the 1970s (Suppe 1974).

The origin of this semantic conception can be traced back to the work made in the first half of the twentieth century by Hermann Weyl (1927, 1928), J. von Neumann (1932) and Birkhoff and von Neumann (1936), related to the foundations of quantum physics. Along the same line of those seminal contributions, and after World War 2, there was work done by E. W. Beth (1948a, b, 1949, 1960)—developing Weyl's analyses—on the same field of physics, plus the fundamental writings of Suppes (1957, 1962, 1969, 1970, 2002; McKinsey et al. 1953) reconstructing physical theories through using the set-theoretical methods he learned from J. C. C. McKinsey and Alfred Tarski. All these scholars started a new way of reconstructing scientific theories that is now known as the *semantic*, *modellistic*, or *model-theoretic* approach, conception, or view.

In the "Afterword" to the second edition of his *Structure of Scientific Theories*, Fred Suppe claimed that "[t]he semantic conception of theories […] is the only serious contender to emerge as a replacement for the Received View analysis of theories" (Suppe 1977, p. 709). Twelve years later, he reaffirmed such contention: "The semantic conception of theories today probably is the philosophical analysis of the nature of theories most widely held among philosophers of science" (Suppe 1989, p. 3). And at the beginning of the twenty-first century, Frigg wrote that "[o]ver the last four decades the semantic view of theories has become the orthodox view on models and theories" (Frigg 2006, p. 51).

This new conception on the nature, structure, and use of scientific theories was developed in specific ways by several authors. Those particular developments gave rise to different approaches, variants or versions, such as the model-based proposal by Ronald N. Giere (1979, 1983, 1985, 1988, 1994), the state-space approach of Bas van Fraassen (1970, 1972, 1974, 1976, 1980, 1987, 1989, 1997, 2008), the phase-space approach of Frederick Suppe (1967, 1972, 1989), and the structuralist view of theories of J. D. Sneed and his followers (Sneed 1971; Stegmüller 1973, 1979, 1986; Balzer et al. 1987; Balzer and Moulines 1996; Balzer et al. 2000), just to mention some of them.[4] But, despite the notable differences between these various semantic views, they all share some common important elements that make it possible to include them in one big family, the *semantic family*.

'Members' of the semantic family consider that the most fundamental component for the identity of a theory is a *class* (set, population, collection, family) *of models*. A theory can be characterised in the first place for defining/determining the class, set, population, collection, or family of its models: to present/identify a theory means mostly presenting/identifying the characteristic models as a family. Besides, the semantic view understands that the models of the theory are proposed in order to *account for* a certain part of the world: their aim is to account for particular empirical systems, data, phenomena, or experiences corresponding to certain aspects of 'reality'.

A scientific theory, according to a semantic conception, defines the models with the intention that they should *adequately* represent the phenomena, or 'reality', and this intention is made explicit by a linguistic or propositional act, by stating a *claim*—the so-called empirical claim. This claim states that between the empirical systems that we want to account for and the models determined by the laws of the theory there is an ascertainable relationship. Thus, we have the three components that, according to semanticists, are basic for the identification of a scientific theory (but of course these components are not necessarily *the only relevant ones* for each and every specific semantic approach): 1. the class, set, population, collection, or family of models; 2. the empirical systems, data, phenomena, experiences, or parts of the 'real world' that theories intend to account for, interpret, explain, and predict; and 3. the relationship claimed to hold between empirical systems and models. Those three elements will constitute the crucial components of our explicative scheme in the next section.

3 Introducing the Semantic Family in Model-Based Didactics of Science

In our opinion, ignorance, misconceptions, or naïve conceptualisations of the semantic family of theories in its different versions (mainly Giere's, Suppe's and van Fraassen's, and meta-theoretical structuralism) in didactics of science have become major obstacles for the effective introduction of recent philosophy of science into the different areas of reflection and innovation on science teaching. In addition, the space recently gained by some semantic conceptions in science education does not seem to be considering contributions from the structuralist view on theories.

We have begun to elaborate a response to this diagnosed situation, pointing at the difficulties of introducing innovative philosophical content in the academic community of didactics of science, part of whose practitioners have relatively poor background in philosophy of science (cf., Ariza et al. 2010). We have proposed a 'road map' to introduce the philosophy of science in science teaching that includes characterising the semantic family and its different approaches. This road map would in turn provide grounds for establishing what we have called a model-based didactics of science. This effort to *clarify* what now

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[4] Other versions are: the *partial structures* approach of N. C. A. Da Costa, S. French, J. Ladyman and O. Bueno (Da Costa and French 1990, 2003; Bueno 1997; French and Ladyman 1999), the approach proposed by R. Torretti (1990), and many 'European versions' of the semantic view, such as those of M.L. Dalla Chiara and G. Toraldo di Francia (1973), M. Przełecki (1969) and R. Wójcicki (1976), G. Ludwig (1970, 1978), and E. Scheibe (1997, 1999, 2001).

makes up the semantic family contains a particular aspect: it is initiated in the philosophy of science and then imported into didactics of science.

In the philosophy of science, there exist a manifold of mappings with open triangular structures (e.g. Giere 1979, 1988) intending to show the connections between *world*, *models* and *theories* from a semantic perspective (and thus opposing the analytic dogma that scientific propositions directly refer to the real world). However, it requires some degree of specialisation in meta-theoretical analyses to understand (and 'draw') such mappings for the different approaches within the semantic family. Such specialisation has not been reached by many didacticians of science and science teachers.

Accordingly, we propose, as a didactical tool, a much simpler scheme for the mapping (our 'triangle' in Fig. 1). In our scheme:

1. We strongly highlight the formal similarities between each semantic proposal on the nature of scientific theories. This allows us to identify all of them as part of a single meta-theoretical 'family'.
2. We make apparent the fact that, even when coinciding in a core characterisation of scientific theories, there are major differences in how the various proposals understand and conceptualise the object 'theory'. This leads to our distinction of 'approaches' within the family.

The terms used in our scheme should be considered 'unspecified' (i.e. without a fixed interpretation) and not referring exclusively to one of the semantic approaches. The 'effort of interpretation' of this main scheme of the semantic family results in a systematic presentation of each semantic approach. These latter are deployed from the main scheme if we accept that there are differences between:

1. The ways in which each approach characterises the notion of scientific model;
2. The ways in which they identify the class of models;
3. The ways in which they characterise the empirical systems, or 'pieces of reality', for which theories are intended to account;
4. The ways in which models are associated with empirical systems; and
5. The constituents or components of a scientific theory as a whole.[5]

4 Four *Approaches* Within the Semantic Family

In this section, we concentrate in four versions, variants or approaches within the semantic family that we deem the most interesting to understand the nature of scientific theories in science education: the frameworks proposed by Giere, van Fraassen, Suppe and Sneedian structuralists. Each approach—together with its corresponding scheme—is presented with a brief theoretical account that precedes it, so it can be interpreted in the light of its meta-theoretical reference. We present our succinct descriptions of the approaches without going into technicalities, suiting the presentation to didacticians of science (for the details, readers should refer to the fundamental works of each approach).

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[5] The components of theories (i.e. constituting elements that give them their identity) are boldfaced in the 'specified' schemes of Sect. 4.

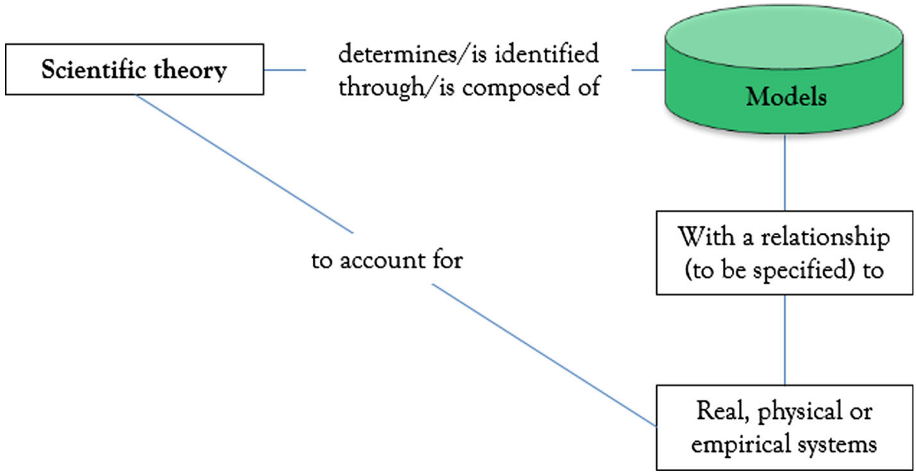

Fig. 1 Our basic or central scheme, valid for the whole *semantic family*

4.1 Ronald Giere, Models and *Theoretical Hypotheses*

Ron Giere develops his own version of the semantic view of scientific theories within the framework of a wider meta-scientific programme aiming at analysing the different elements of science from a *cognitive* perspective (cf., especially, Giere 1988; also his classical textbook on scientific argumentation, Giere 1979, its later editions, and Giere 1983, 1985, 1988, 1994).

Giere understands scientific theories as means for defining abstract models, whose application to certain real systems is explicitly postulated:

> My preferred suggestion, then, is to understand a theory as comprising two components: (1) a population of models, and (2) various hypotheses linking those models with systems in the real world. (Giere 1988, p. 85)

The first component of the theory is a population, or *family*, of models:

> The situation in nuclear physics nicely illustrates my early characterization of a scientific theory as being a family of models. There is no single 'Schrödinger model' of the nucleus. Rather, there is a family of models whose members are all characterized by the general form of the Schrödinger equation, but differ in the types, and the details, of the included interaction potentials. (Giere 1988, p. 184)

According to Giere, a *theoretical model*, or simply a *model*, of a theory is an *abstract entity*, a mental (internal, abstract, non-linguistic, often imagistic) representation of reality (Giere 1988, p. 81). The laws and equations that are presented in science textbooks *define* those entities. The equation $md^2s/dt^2 = -kx$ defines what a simple harmonic oscillator *is*; the equation $md^2s/dt^2 = -(mg/l)x$ defines a more specific kind of simple harmonic oscillator, namely the pendulum without friction. Thus, "the model is defined as something that exactly satisfies the equations" (Giere 1988, p. 79). Oscillators and pendulums are, therefore, just models defined by the equations above, and as such they "are *socially* constructed entities […] [that] have no reality beyond that given to them by the community of physicists" (Giere 1988, p. 78, emphasis in the original).

Such models are connected to reality through the second component of scientific theories, namely *theoretical hypotheses*: "Unlike a model, a theoretical hypothesis is, in my account, a *linguistic entity*, namely a statement asserting some sort of relationship between a model and a designated real system (or class of real systems)" (Giere 1988, p. 80, emphasis in the original). The relationship asserted by the theoretical hypothesis is not one of identity, because systems are real, physical entities, whereas models are abstract entities, but one of *similarity*. In order to be precise enough, the similarity relationship must be qualified; it has to be specified to given *respects* and *degrees*:

> A theoretical hypothesis asserts the existence of a similarity between a specified theoretical model and a designated real system. But since anything is similar to anything else in some way or other, the claim of similarity must be limited (at least implicitly) to a specified set of respects and degrees (Giere 1988, p. 93).

As a linguistic entity, a theoretical hypothesis (*unlike* models) can be true or false:

> To claim a hypothesis is true is to claim no more or less than that an indicated type and degree of similarity exists between a model and a real system. (Giere 1988, p. 81)

Another problem explored by Giere is the difficulty of identifying theories. For him,

> a scientific theory turns out not to be a well-defined entity. That is, no necessary and sufficient conditions determine which models or which hypotheses are part of the theory. This is most obvious in the case of hypotheses. (Giere 1988, p. 86)

In the case of the models that identify a theory, they would be those that keep a *family resemblance* between them (defined by the laws of the theory). But even though the resemblance is undeniable, it does not consist for Giere in anything *structurally* identifiable in the models. The only possible determination is—according to him—in sociological terms:

> […] a model must bear a "family resemblance" to some family of models already in the theory. That such family resemblances among models exist is undeniable. On the other hand, nothing in the structure of any models themselves could determine that the resemblance is sufficient for membership in the family. That question, it seems, is solely a matter to be decided by the judgements of members of the scientific community at the time. This is not to say that there is an objective resemblance to be judged correctly or not. It is to say that the collective judgments of scientists *determine* whether the resemblance is sufficient. This is one respect in which theories are not only constructed, but socially constructed as well. (Giere 1988, p. 86)

The approach proposed by Ronald Giere can be schematised as in Fig. 2.

4.2 Bas van Fraassen and the *State-Space Approach*

Inspired by the work of Evert Willem Beth (1948a, b, 1949, 1960) on quantum mechanics—who in turn developed previous ideas by Hermann Weyl (1927, 1928)—Bas van Fraassen published a series of writings (van Fraassen 1970, 1972, 1974, 1976, 1980, 1987, 1989, 1997, 2008) in which he presents and develops his own version of the semantic conception of theories, namely, the so-called *state-space approach*.

For him,

> To present a theory is to specify a family of structures, its *models*; and secondly, to specify certain parts of those models (the *empirical substructures*) as candidates for the direct representation of observable phenomena. (van Fraassen 1980, p. 64)

With respect to the first part (presenting a theory), van Fraassen conceives models of a physical theory as mathematical structures that represent the behaviour of physical systems, while "[a] physical system is conceived of as capable of a certain set of *states*,

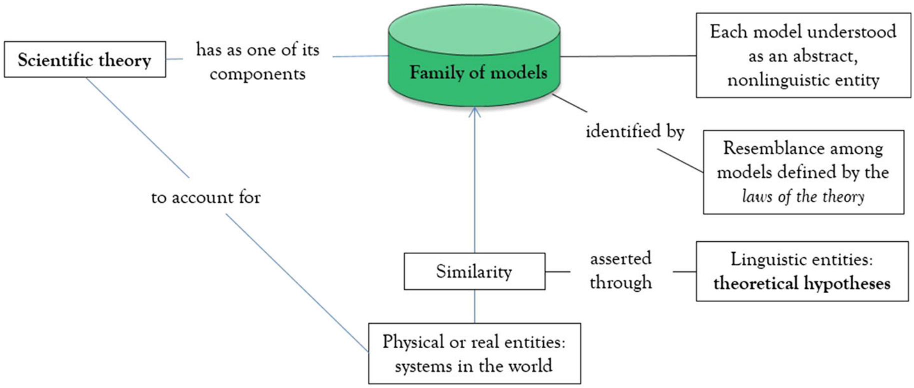

Fig. 2 Ronald Giere's approach

and these states are represented by elements of a certain mathematical space, the *state-space*" (van Fraassen 1970, p. 328, emphasis in the original). A model of the theory is a mathematical structure that satisfies the *equations*, *principles* or *laws* of the theory—or, as van Fraassen (1989, p. 223) also calls them, "laws of the model"—and represents a physical system. It can be depicted by a *trajectory* in (through) the state space—if the laws are of *succession*, i.e. if they say how the state of the physical system is related to possible states at other times—or by a *region* in the state space—if the laws are of *coexistence* or of *interaction*, i.e. if they say how the state of the physical system is related to other possible states or results from the interactions of two physical systems (van Fraassen 1970, pp. 330–333).

Relating to the second element for the presentation of a theory, we find a difference between van Fraassen's initial views on the phenomena and their relationship to models and his more recent ones. According to his former views, which we can find until 1997, "concrete observable entities (the appearances or phenomena) can be isomorphic to abstract ones (substructures of models)" (van Fraassen 2008, p. 386). Such substructures of models were conceived of as "the empirical structures in the world [that] are the parts which are at once *actual* and *observable*" (van Fraassen 1989, p. 228). The postulated relationship between the appearances or phenomena and models was one of *isomorphism* or of *embeddability*, as he also calls it (van Fraassen 1989, p. 228). And in such isomorphism or embeddability lies the empirical adequacy of the theory: "A theory is *empirically adequate* exactly if all appearances are isomorphic to empirical substructures in at least one of its models" (van Fraassen 1976, p. 631); the notion of empirical adequacy "consists in the embeddability of all these parts [which are at once *actual* and *observable*] in some single model of the world allowed by the theory" (van Fraassen 1989, p. 228, emphasis added).

If a theory is empirically adequate, we may say—using the classic expression—that it "saves the phenomena" (van Fraassen 1976, 1980, p. 4). And because of that, we can *accept* the theory. But, in line with van Fraassen's special form of anti-realism, we must distinguish between accepting a theory (as empirically adequate) and *believing* the theory, i.e. believing it to be true. These are not the same: "Empiricism has always been a main philosophical guide in the study of nature. But empiricism requires theories only to give a true account *of what is observable*" (van Fraassen 1980, p. 3, original emphasis). Van Fraassen thus talks about 'constructive empiricism':

> I use the adjective 'constructive' to indicate my view that scientific activity is one of construction rather than discovery: construction of models that must be adequate to the phenomena, and not discovery of truth concerning the unobservable. (van Fraassen 1980, p. 5)

The only belief involved in accepting a scientific theory is the belief in its empirical adequacy, whereas the acceptance of a theory does not commit us to belief in its truth, in the truth of *all* of it (and not just in its observable part), in particular in the reality of anything at all that was either unobservable or not actual (see van Fraassen 1980, p. 197).

Since 1997, van Fraassen begins to modify his earlier views on phenomena and their relationship to models: "in *The Scientific Image* […] I define empirical adequacy using unquestioningly the idea that concrete observable entities (the appearances or phenomena) can be isomorphic to abstract ones (substructures of models)" (van Fraassen 2008, p. 386). But only a mathematical structure can be isomorphic to substructures of models or can be embedded in another mathematical structure:

> For a phenomenon to be embeddable in a model, that means that it is isomorphic to a part of that model. So the two, the phenomenon and the relevant model part must have the same structure. Therefore, the phenomenon must have a structure. (van Fraassen 2008, p. 247)

To solve this problem, van Fraassen (2008) makes use of the concept—borrowed from Suppes (1962)—of *data model*. Now, according to him, "a scientific theory will first of all represent the phenomena by means of mathematical structures, and then show how those structures fit into larger ones, the theoretical models" (van Fraassen 2008, p. 240). These mathematical structures that represent phenomena are the data models. Thus, the embedding relationship is not anymore a relationship between a phenomenon and a theoretical model, but one between the data model, which represents the phenomenon, and the theoretical model. It consists in a *matching*, as he also calls it now, "of two mathematical structures, namely the theoretical model and the data model" (van Fraassen 2008, p. 240).

Van Fraassen's revised position emphasises the importance of mathematical structures not only as a way of conceiving theoretical models, but as a way of representing phenomena as well. According to van Fraassen, *all we know through science is structure* (cf.,

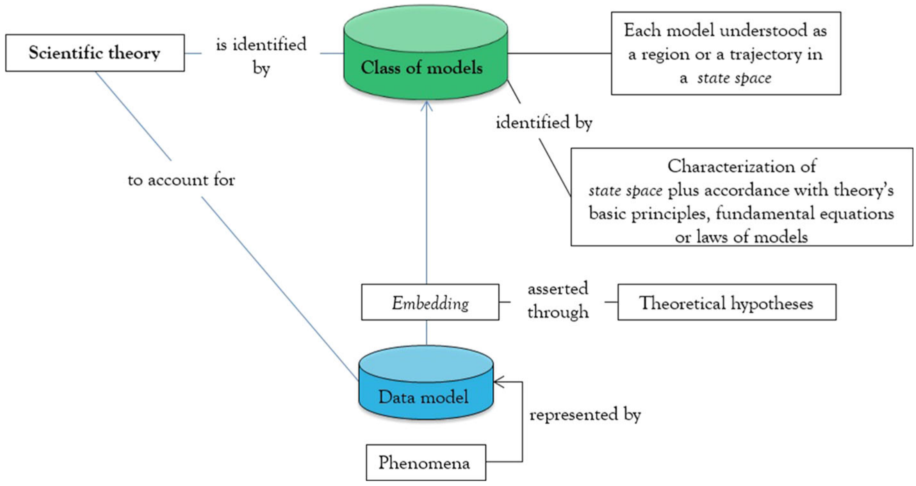

Fig. 3 Bas van Fraassen's approach

van Fraassen 2008, p. 238); he re-labels his view as ‘empiricist structuralism’. The main components of van Fraassen’s proposal can be schematised as in Fig. 3.

4.3 Frederick Suppe and the *Phase-Space Approach*

Fred Suppe initiated in his doctoral thesis (Suppe 1967) a proposal that he continued to develop and expand during the ’70s and ’80s (Suppe 1972, 1989). His proposal was influenced by Johann von Neumann’s and Garrett Birkhoff’s (von Neumann 1932; Birkhoff and von Neumann 1936) work on the foundations of quantum mechanics, and by Patrick Suppes’s work on models of data (Suppes 1962).

A theory, according to Suppe, is a *relational system:*

> consisting of a domain containing all (logically) possible states of all (logically) possible physical systems for the theory together with various attributes defined over that domain. These attributes, in effect, are the *laws* of the theory. (Suppe 1989, p. 84, emphasis in the original)

The first component of a relational system—logically possible states of logically possible physical systems for the theory—is the so-called *phase space*. The second component—the relations established by the laws, in *any* formulation of such laws—determines the possible models of the theory: “[…] laws are relations which determine possible sequences of state occurrences over time that a system within the law’s intended scope may assume” (Suppe 1989, p. 155).

The relational system contains what Suppe calls the *causally possible physical systems*, which are the theoretical models of the theory:

> When such a space [the phase space] […] has such configurations imposed on it corresponding to the attributes of the theory [i.e., the laws of the theory], we say the space is a phase space model of the theory. (Suppe 1989, p. 106)

Thus, similar to van Fraassen, models can be represented by *trajectories* through the *phase space*—if the laws are of *succession*—or by *subspaces* in the *phase space*—if the laws are of *coexistence* or of *interaction* (Suppe 1989, pp. 84–85, 155–162).

Through determining causally possible physical systems (i.e. models), the theory seeks to explain certain selected aspects of the phenomena that Suppe calls the ‘intended scope of a theory’ (Suppe 1989, p. 82). This domain of application is constituted by physical systems that act as ‘hard data’ for the theory:

> […] the observation reports or “hard” data to which the theory is applied are partial description of the behavior of some physical system, the physical system being an abstract replica of the phenomena from which the data were collected. [T]heories have “hard” data reports as their primary subject matter rather than observation reports […] the need for an observational/theoretical dichotomy disappears […]. Replacing it is the distinction between nonproblematic “hard” data about physical systems and boundary conditions, and so on, and the more problematic theoretically obtained assertions about these systems. (Suppe 1989, pp. 68–69, 71)

Suppe’s concept of intended scope of a theory commits his own “version of the semantic conception to an anti-nominalism (to a view that some classes correspond to real divisions of nature and other do not) that van Fraassen would reject” (Suppe 1989, p. 98). Then, according to him, “[a] theory has as its intended scope a natural kind class of phenomenal systems” (Suppe 1989, p. 97).

With this characterisation, a theory is *empirically true* if the data coincide with the models of the theory, if the physical systems within the intended scope coincide with the causally possible physical systems determined by the theory (perhaps with some idealisations), i.e. if there is a mapping relationship between the models and real systems, or, better, between the causally possible physical systems (specific models of the theory, which are *counterfactual descriptions*) and particular empirical systems (hard data) of its intended scope:

> Theories are asserted to stand in some mapping relationship *M* to real systems within the scope of the theory. […] *M* would be a homomorphism. On Suppe's *quasi-realistic* version, *M* would be a counterfactual relationship specifying how the real systems would behave were they isolated from influence by variables not in *T*. (Suppe 1998, p. 349, original emphasis)

Suppe agrees with van Fraassen in that accepting a theory does not necessarily require the acceptance of its truth, of the truth of *all of it*, but he does not agree with van Fraassen's reasons. This difference is what allows him to defend, against van Fraassen, a kind of realism that he calls 'quasi-realism'. He claims that theories

> do not offer literal descriptions of how the real world behaves. [T]heories provide a *counterfactual description* how the world *would be if* neglected parameters *did not* influence the phenomena the theory purports to describe. But typically, neglected parameters at least sometimes do influence the phenomena, and so the characterizations offered by theories are not literally true, but at best counterfactually true, of the phenomena within their scopes. This is the quasi-realist construal of theories I have long advocated. (Suppe 1989, pp. 348–349, emphasis in the original)

A theory would not be 'literally' true, because it does not literally describe the real world, but it just describes the world through the selected parameters, and thus a theory may be at best 'counterfactually' true. The proposal of Frederick Suppe can be schematised as in Fig. 4.

4.4 Meta-Theoretical Structuralism

This version of the semantic family originates in Joseph Sneed's book *The Logical Structure of Mathematical Physics* (Sneed 1971). Sneed's work is further developed in Europe in the '70s and '80s, mainly by Wolfgang Stegmüller (1973, 1979) and his disciples C. Ulises Moulines (1975, 1982) and Wolfgang Balzer (1978, 1982, 1985). This approach was initially labelled the 'emended Ramsey view', or simply 'Sneedian programme' (or 'Sneedism'); later it was called 'non-statement view', and nowadays it is

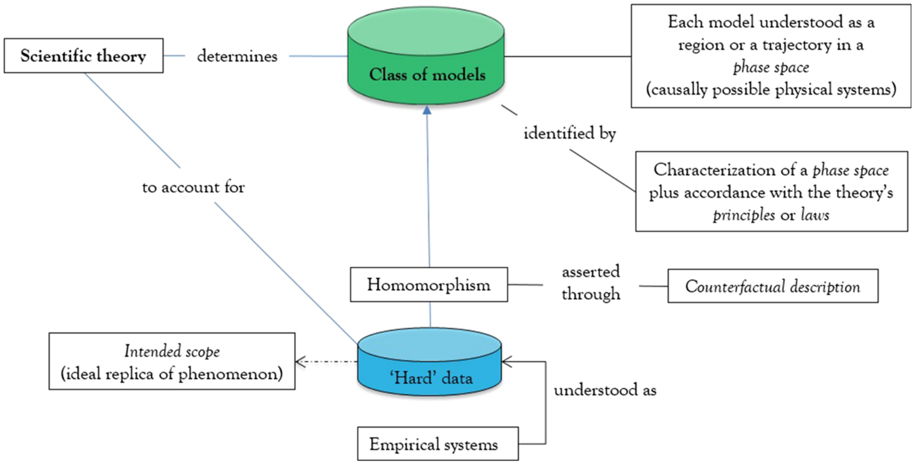

Fig. 4 Frederick Suppe's approach

usually known as 'structuralist view of theories', *structuralism*, or—in order to distinguish it from other structuralisms—'meta-theoretical structuralism', 'meta-scientific structuralism', 'Sneedian structuralism'.[6] The most important results of the foundational period of structuralism are systematically presented in the book by Balzer, Moulines and Sneed, published in 1987, *An Architectonic for Science: The Structuralist Program*. Since then, the structuralist programme continues its growth and development through the efforts of many supporters, not only in continental Europe (mostly in Germany, but also in the Netherlands and Finland), but also in Spanish-speaking countries in Europe and Latin America, such as Spain, Mexico, Colombia, and Argentina, as well (see Diederich et al. 1989, 1994; Abreu et al. 2013).[7]

Sneed's proposal follows the teachings of his doctoral supervisor, Patrick Suppes, in accepting the fundamental semantic thesis that is more suitable for theories to be identified through their models than with a set of axioms. In trying to be as precise as possible, Sneed prefers the use of (elementary) set theory—whenever possible—as the most important formal tool for meta-theoretical analysis. However, this formal tool is not essential for the main tenets and procedures of the structuralist representation of science (other formal tools, such as logic, model theory, category theory, and topology, as well as informal ways of analysis, are also used). In the standard expositions of meta-theoretical structuralism, models are conceived of as *set-theoretical structures* (or models in the sense of *formal semantics*), and their *class* is identified by defining (or introducing) a *set-theoretical predicate*, just as in Suppes.

In addition, on the one hand, Sneed accepts Ernest W. Adams (1955, 1959) proposal of including a component of pragmatic nature into the explication of the concept of an empirical theory, namely the intended models (or intended interpretations), and reconceptualises these as *intended applications*. They constitute the phenomena or systems to which a theory is intended to be applied and for which it has been devised. On the other hand, according to structuralism, there are other components of an empirical theory besides these two—the class of (actual) models M and the domain of intended applications I. Such additional components are the following: 1. the class of *potential models* of the theory M_p; 2. the class of *partial potential models* M_{pp}; 3. the so-called *constraints* C; and 4. the *inter-theoretical links* L.

In order to characterise the structuralist basic notions, we need to take into account two distinctions: the distinction between two kinds of 'conditions of definition' (or 'axioms', as they are also called) of a set-theoretical predicate, and the distinction between the T-theoretical/T-non-theoretical terms (or concepts) of a theory T. According to the first distinction, the two kinds of conditions of definition of a set-theoretical predicate are: 1. those that constitute the 'frame conditions' of the theory and that "do not say anything about the world (or are not expected to do so) but just settle the formal properties" (Moulines 2002, p. 5) of the theory's concepts and 2. those that constitute the 'substantial laws' of the theory and that "do say something about the world by means of the concepts previously determined" (Moulines 2002, p. 5). According to the second distinction, which replaces the traditional, positivistic theoretical/observational distinction, it is possible to establish, in (almost) any analysed theory, two kinds of terms or concepts: the terms that

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[6] In addition, in some Anglo-Saxon circles the labels 'German structuralism' or 'German structuralist school' are also used.

[7] The reader who would like to have access to an extensive and technically precise presentation of the programme should consult the above-mentioned book by Balzer et al. (1987). For those who want to have a briefer and more informal presentation, we recommend Moulines (2002).

are specific or distinctive to the theory in question and that are introduced by the theory T—the so-called T-theoretical terms or concepts—and those terms that are already available and constitute its relative empirical basis for testing—the so-called T-non-theoretical terms or concepts, which are usually theoretical for other presupposed theories T', T'', etc. The structuralist view provides a precise criterion to T-theoreticity, which can be informally characterised as follows: a term or concept used by T is T-theoretical if and only if its extension cannot be determined without presupposing the laws of T, i.e. if and only if *every* method of determination of the concept's extension uses some law of T. Otherwise, the term or concept used by T is T-non-theoretical.

Now, we are in position to characterise the structuralist basic notions:

1. The class of *potential models* of the theory M_p is the total class of entities (i.e. of structures) that satisfy the 'frame conditions' that just settle the formal properties of the theory's concepts, but not necessarily the 'substantial laws' of the theory as well;
2. The class of (actual) *models* of the theory M is the total class of entities (i.e. of structures) that satisfy the 'frame conditions' and, in addition, the 'substantial laws' of the theory;
3. The class of *partial potential models* M_{pp} are obtained by 'cutting off' the T-theoretical concepts from the potential models M_p;
4. The *constraints* C characterise connections or relations between different applications or models of the same theory;
5. The *inter-theoretical links* L characterise the theory's 'essential' connections to other theories;
6. The domain of *intended applications* of a theory I, even when it is a kind of entity strongly depending on pragmatic and historical factors that, by their very nature, are not formalisable, is conceptually determined through concepts already available, i.e. through T-non-theoretical concepts; thus, each intended application may be conceived as an empirical (i.e. T-non-theoretical) system represented by means of a structure of the type of the partial potential models M_{pp}.

All these components constitute the simplest kind of set-theoretical structure that can be identified with, or can be regarded as a formal explication or reconstruction of, a theory (in an informal, intuitive sense). This set-theoretical structure is called a *theory-element,*[8] and can be identified, in a first approximation, with an ordered pair consisting of the '(formal) *core*' K—composed by the ordered classes of potential models, actual models, partial potential models, constraints and links, i.e. $K = \langle M_p, M, M_{pp}, C, L \rangle$—and the theory's 'domain of intended applications' I. Thus, we have that $T = \langle K, I \rangle$.

The *empirical claims* made by means of scientific theories are of the following kind: that a given domain of intended applications I may actually be approximately *subsumed* or *embedded* under the laws, constraints, and links of the theory. This claim simply makes explicit an intention already implicitly contained in the pair $\langle K, I \rangle$. It is true that if we identify them in this way, theories are strictly speaking neither true nor false. Theories are in a one-to-one correspondence with entities that are certainly susceptible of being true or false: their claims. Therefore, although we cannot primarily ascribe truth value to theories, we can say that a theory is 'derivatively true' if and only if all of its claims are true. If there is any interesting sense in which theories are not falsifiable, it is not because they are

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[8] The concept of theory-element may be seen as a precision and elaboration of a Kuhnian idea: "A theory consists, among other things, of verbal and symbolic generalizations *together with* examples of their function in use" (Kuhn 1969, p. 501, emphasis in the original).

entities to which the predicates true or false cannot be ascribed. Those predicates cannot be ascribed primarily, but they certainly can be ascribed derivatively, and this is enough for the important sense of falsifying: if the empirical claim is false, the theory becomes 'falsified' in the sense that not everything can remain the same. Typically, in any 'really existing' theory, the 'exact version' of the so-called *central empirical claim* of the theory—that the whole domain of intended applications I may actually be (exactly) subsumed (or embedded) under K—will be strictly false. What usually happens is that either there is a subclass of intended applications for which the empirical claim is true, or that the central empirical claim is false but *approximately true*.[9] The basic structuralist conception of a theory may be schematised as in Fig. 5.

It is important to note that Fig. 5 provides the most basic scheme of a theory, since it includes only the class of actual models M and the domain of intended applications I. But, as we previously mentioned, according to structuralism there are other components of an empirical theory (M_p, M_{pp}, C, and L).

On the one hand, the class of actual models M has a relationship of inclusion within the class of potential models of the theory M_p. On the other hand, the theoretical/non-theoretical distinction made relative to each theory induces the distinction between the class of potential models and that of partial potential models, and allows characterising the empirical, i.e. T-non-theoretical, independent, basis of testing, and the domain of intended applications. The class of partial potential models M_{pp} are obtained, as we already stated, by cutting off the T-theoretical concepts from the potential models M_p. This 'cutting off' can be schematised as follows (Fig. 6).

Finally, the intended applications I have a relationship of inclusion within the class of partial potential models of the theory, M_{pp}.

The rest of the components in the characterisation of a theory are less apparent but equally essential, and it could be claimed that they go unnoticed for other approaches within the semantic family. Those components are the constrains C, which represent intra-theoretical relationships, i.e. relationships between models of the same theory, and the inter-theoretical links L, which represent relations of the models of a theory with other theories (Fig. 7).

As we see, the basic or central scheme for the semantic family, when specified for the structuralist approach, becomes richer, since what we now should depict in one of the boxes is not just the class of models, but the whole (formal) core of the theory (understood as a theory-element), which includes in addition other types of models as well as the connections between different models of the theory-element and from these to other theories. Figure 8 provides a more complete version of a schematic representation of a theory-element.

The simplest cases of scientific theories may actually be reconstructed as *one* theory-element, but normally single theories in the intuitive sense have to be conceived of as *aggregates* of several (sometimes a great number of) theory-elements. These aggregates are called 'theory-nets'. They consist of a hierarchically ordered array of theory-elements

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[9] It is worth noting that meta-theoretical structuralism *per se* is *neutral* with respect to the issue of scientific realism (see Sneed 1983; Stegmüller 1986)—understood either in terms of the 'true description' (or approximately true description) of the 'real world' given by a theory or of the 'reality' of the *denotata* of the T-theoretical terms of a theory—although there are supporters of this approach that have stated the problem within this framework and argued for, as well as against, scientific realism.

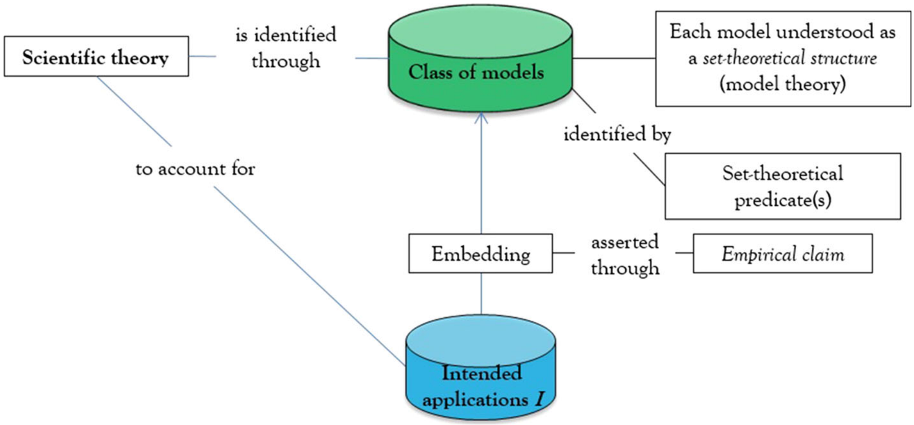

Fig. 5 Basic scheme of a theory in the structuralist approach

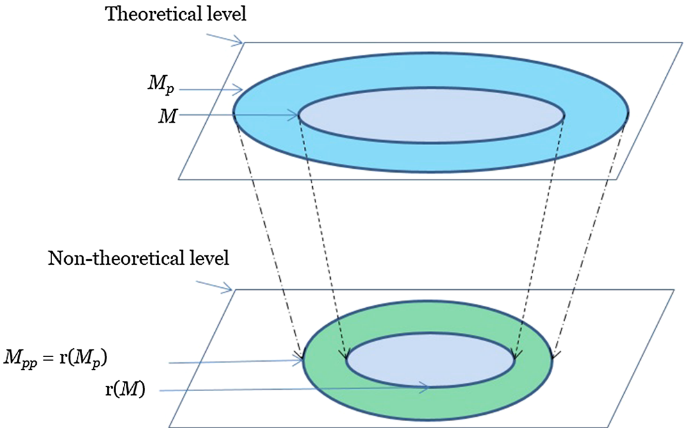

Fig. 6 Scheme of partial potential models M_{pp}, obtained by cutting off the T-theoretical concepts from the potential models M_p

related by a particular kind of inter-theoretical relation called *specialisation*—which is reflexive, anti-symmetric and transitive.[10] Thus,

> […] a theory-net is a partially ordered set of theory-elements with a basic element on the "top", from which the rest of the theory-elements come out by a process of successive restrictions of the class of

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[10] The concept of a theory-net may be seen, again, as a precision and elaboration of another Kuhnian idea, namely the 'general principle plus specification relation' idea: "[…] generalizations [like $f = ma$] are not so much generalizations as generalisation sketches, schematic forms whose detailed symbolic expression varies from one application to the next. For the problem of free fall, $f = ma$ becomes $mg = md^2s/dt^2$. For the simple pendulum, it becomes $mg\sin\theta = -md^2s/dt^2$. For coupled harmonic oscillators it becomes two equations, the first of which may be written $m_1d^2s_1/dt^2 + k_1s_1 = k_2(d + s_2 - s_1)$. More interesting mechanical problems, for example the motion of a gyroscope, would display still greater disparity between $f = ma$ and the actual symbolic generalization to which logic and mathematics are applied" (Kuhn 1969, p. 465).

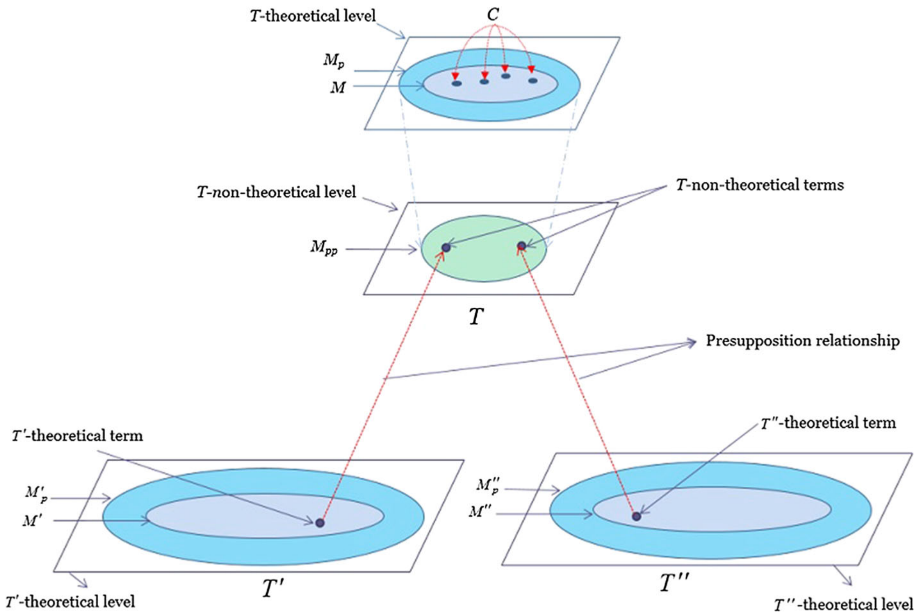

Fig. 7 Representation of *constrains C* and *inter-theoretical links L* (*red lines*). (Color figure online)

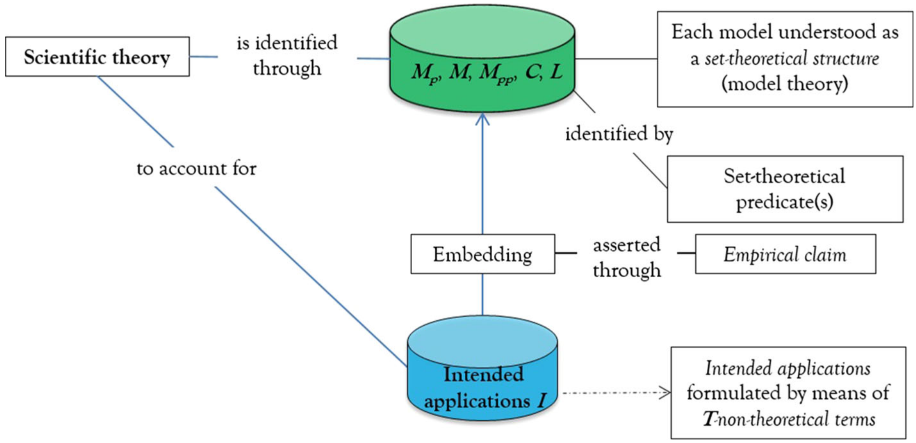

Fig. 8 More complete scheme of the structuralist approach

> actual models (and constraints and links) and of the range of intended applications. What gives its unity to the theory-net is the basic element. (Moulines 2002, p. 8)

A theory-net is then the standard structuralist conception of a theory from a static or *synchronic* point of view. The synchronic structure of a theory may be represented as a net *N* (Fig. 9), where the nodes are given by the different theory-elements, and the links represent different relations of specialisation.

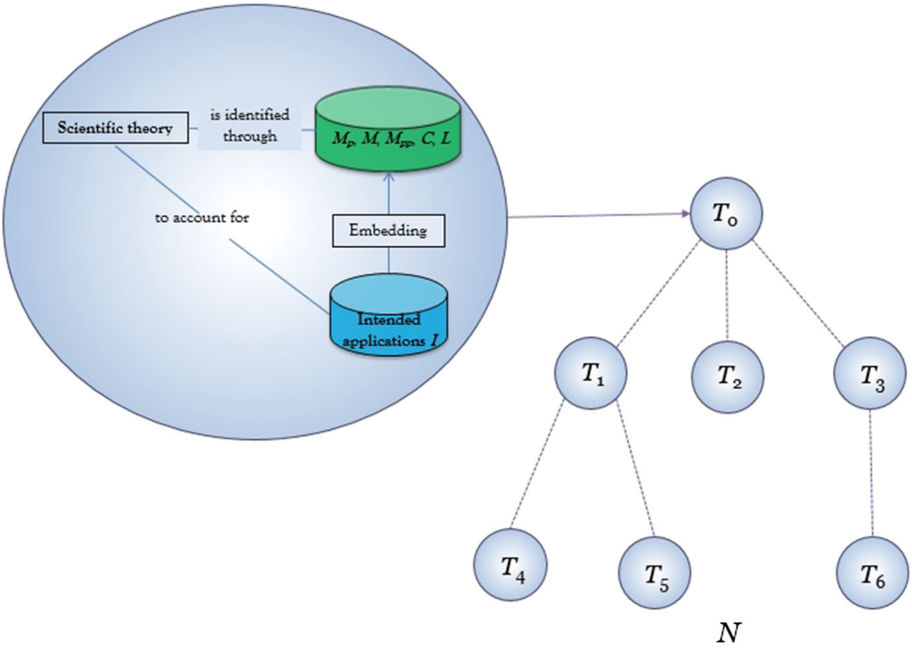

Fig. 9 Schematic representation of a *theory-net N*

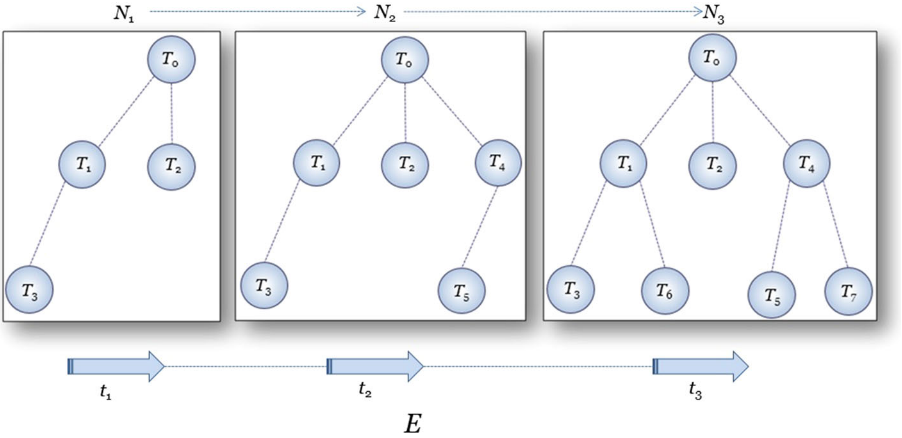

Fig. 10 Schematic representation of a *theory-evolution E*

But a theory can also be conceived of as a kind of entity with a history of development over time. A theory in the *diachronic* sense is not just a theory-net, which exists in the same form through history, but a *changing* theory-net, which grows and/or shrinks over time. Such an entity is called a *theory-evolution.*[11] It is basically a sequence of theory-nets

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[11] Once again, the concept of a theory-evolution may be seen as a precision of some other Kuhnian idea, namely that of normal science.

satisfying two conditions: at the level of cores, it is required for every new theory-net in the sequence that all its theory-elements are specialisations of some theory-elements of the previous theory-net; at the level of intended applications, it is required that the domains of the new theory-net have at least some partial overlapping with the domains of the previous

Table 1 Comparative overview of the specific tenets of the four approaches of the semantic family analysed in this paper

	Giere's approach	van Fraassen's approach	Suppe's approach	Sneedian structuralism approach
1. Notion of model	An abstract entity, a mental (internal, abstract, and non-linguistic) representation of reality	A mathematical structure	Causally possible physical systems (counterfactual descriptions)	A mathematical structure
2. Identification of the class of models	By laws and equations	By (trajectories or regions in) a state space	By (trajectories or regions in) a phase space	By a set-theoretical predicate
3. Characterisation of the empirical systems	Real systems	Data models that represent the phenomena	Empirical systems (hard data)	Intended applications represented by means of *T*-non-theoretical concepts
4. Relationship between models and empirical systems	Similarity	Embedding	Homomorphism	Embedding
5. Components of a theory	A family of models and theoretical hypotheses	A class of models and theoretical hypotheses	The theoretical models: relational systems consisting of all (logically) possible states of all (logically) possible physical systems for the theory, together with the laws of the theory	Understood as a theory-element: the core (consisting of the classes of potential models, models, partial potential models, constraints, and inter-theoretical links), and the domain of intended applications Understood as a theory-net: a hierarchically ordered array of theory-elements related to specialisation Understood as a theory-evolution: a sequence of theory-nets fulfilling additional requirements

theory-net (Balzer et al. 1987, pp. 218–219). A schematic representation of a theory-evolution *E* is shown in Fig. 10.

5 A Brief Overview of the Four Approaches of the Semantic Family

In our account of meta-theoretical semanticism, we acknowledge that the basic, irreducible aspects of the semantic family are not denied in any of the four approaches; on the contrary, each of these approaches starts from the same central structure, preserving it in the development of its specific proposal. However, every semantic approach differs in the way it characterises some structural elements of the theories. In Table 1, we present a synthesis of the specific tenets of the four approaches of the semantic family that we have analysed in this paper.

The identification of similarities and differences between the four semantic approaches that we have selected for our article suggests, in our opinion, that the structuralist 'tools' are an interesting option when we intend to introduce meta-theoretical treatments, or more generally meta-scientific content, in didactics of science. Our position is mainly founded on the following salient features of the structuralist programme:

1. With respect to the analysis performed in the classical phase of the philosophy of science, meta-theoretical structuralism recovers much of the formalist ideal characterising such phase, refines it, and incorporates other 'formal resources' that seem very suggestive for the elucidation of the internal structure of theories (mainly naïve set-theory).
2. Regarding the historicist analysis from the 'new philosophy of science', meta-theoretical structuralism recovers and refines some major historicist notions (e.g. incommensurability), tuning them with the basic study on the nature of theories.
3. Among the semantic approaches, structuralism is probably the one that provides the most detailed analysis of the structure of theories, both of their synchronic and diachronic components, although this may entail a price to be paid: "This is the complex picture of science structuralism offers. A quite complicated picture, indeed. Too complicated!—some may exclaim" (Moulines 2002, p. 9). However, we should not get it wrong by 'blaming the messenger': "the fault of this complication (if this is a fault at all) does not lie in the picturing but rather in the object depicted. After all, the structure of theoretical science *is* a quite complicated affair" (Moulines 2002, p. 9, emphasis in the original).[12]
4. Structuralism is also the semantic approach that has analysed and reconstructed the greatest number of particular theories, ranging from physics and chemistry through biology, neurophysiology and psychology to sociology, economics, administration sciences, linguistics and literary theory.[13]

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[12] Some authors have recognised the rich development of the structuralist programme. Nancy Cartwright suggests that, in comparison with other semantic approaches, "the German structuralists undoubtedly offer the most satisfactory, detailed and well-illustrated account of the structure of scientific theories on offer" (Cartwright 2008, p. 65). Sebastian Enqvist makes a similar point by claiming that "[t]he structuralist model of theories is impressive in two respects: first, it presents a very detailed analysis of what may be called the deep structure of an empirical theory. Second, it has been shown that a range of actual scientific theories can be reconstructed as theory nets" (Enqvist 2011, p. 107).

[13] See, for example, the three "Bibliographies of Structuralism" (Diederich et al. 1989, 1994; Abreu et al. 2013), as well as Balzer et al. (2000).

5. When compared to other proposals available in semantic philosophy of science, it can be safely said that meta-theoretical structuralism has reached interesting results dealing with many of the classic philosophical problems (representation, correspondence, truth, theory testing, evolution of theories, etc.).

6 Final Remarks

As we have stated, the semantic family is considered as an interesting and promising approach to understand science, its processes, its products and its changes over time by a substantive part of the meta-scientific community (Estany 1993; French and Ladyman 1999; Frigg 2006). In addition, authors positioning themselves in model-based didactics of science (Adúriz-Bravo 2013; Chamizo 2010, 2013; Develaki 2007; Izquierdo-Aymerich and Adúriz-Bravo 2003; Oh and Oh 2011; Passmore et al. 2014) regard the semantic conception of theories as a good candidate to operate as 'epistemological foundations' for our discipline. A semantic approach would be useful to understand the nature and use of school scientific content by analogy with scientists' theories.

Although some analyses have been conducted on the differences, similarities, convergences, and divergences of what we here recognise as 'approaches' from the semantic family (e.g. Diederich 1996; Lorenzano 2013), these discussions were not produced with a didactical purpose, and consequently they have not been connected to the field of science education with clarity and simplicity. It would be important to consider more fruitful dialogue between the two communities—philosophers of science and didacticians of science—in order to promote linkages that could prove powerful for meta-theoretical analysis of science teaching. With this paper, we think we have contributed to this aim.

Even though our work is still in progress, the initial proposal contained in this paper could be useful to researchers in didactics of science and, to a lesser extent, to science teachers. To all those who adhere to the idea of a model-based didactics of science, our presentation helps in getting familiarised with an updated presentation of this extremely active meta-theoretical school. Our work aims to represent the fundamental advances in the semantic family at the same time *as simply and as correctly as possible*:

1. It uses terms that are substantively linked in one way or another to all the different semantic approaches. Those terms are kept general and flexible so that they can be 'shared' by all the members within the semantic family, but at the same time they are rigorous enough not to go beyond the boundaries of the family.
2. The targeted combination of 'simplicity' and 'rigour' allows our account of the semantic family to be approached by the didactical community (researchers in the first place and then perhaps teachers).
3. That account constitutes a movement *from* philosophy of science *towards* didactics of science, and this may make it an interesting 'didactical artefact' well founded on an epistemological basis.

We of course recognise that our proposal is in its very early stages. Model-based didactics of science is slowly consolidating, and contributions of many researchers concerned with the introduction of current notions from the philosophy of science are beginning to increase. However, the lack of widespread consensus and the variety of available theoretical frameworks (among other things) bring forth lack of stabilisation of shared meta-theoretical foundations on which to establish guiding principles for the new didactics of science. Undoubtedly, more work needs to be done along this line.

Among the semantic approaches that we have discussed above, structuralist meta-theory is in our opinion an interesting option, supported by the promising results of the analysis of several empirical theories. Further development of model-based didactics of science with specific proposals for science teaching, using not just an updated overview of the semantic family in general, but also of the structuralist meta-theory in particular, is a task that exceeds the scope of this article but, at the same time, sets an exciting line of enquiry and argumentation to explore. Thus, we may point out some possible advances to be made, along the following lines:

1. *Didactical reconstruction of the basic notions of structuralist meta-theory.* Structuralist notions such as intended applications, inter-theoretical links, and constraints can be introduced in science teacher education, but this should not be done in a direct way. The main objective would be the education of science teachers *in the philosophy of science*, and not the preparation of prospective philosophers of science.[14] In this sense, structuralist notions should be *transposed* so that they can be linked to the actual needs that science teachers have for meta-theoretical analysis. This means that structuralism could be introduced into the teaching of science *so that it remains consistent with the meta-theoretical requirements that teachers face in their practice*, for instance, a deep understanding of the 'mechanics' of the theories that they are teaching.
2. *Use of reconstructed theories, and of the conclusions arising from theory reconstructions.* One advantage of resorting to meta-theoretical structuralism is that they have analysed a significant number of theories (not comparable with any of the other approaches, which tend to exemplify their meta-theoretical proposals with a rather limited range of stereotypical theories, for example classical mechanics). In this sense, one of the ways forward is the treatment of a bunch of theories reconstructed by meta-theoretical structuralism in order to make them accessible and appealing to science teachers. This would entail reducing the load of the (sometimes) very formal reconstruction, but without losing the sophistication of its elucidation. While this 'didacticised' meta-theoretical treatment should not betray the essence of structuralist meta-theory, new ways of access should be ensured for our discipline: by this, we mean finding consistent *re-presentations* of the original analyses suitable for non-specialists. We firmly believe that pre- and in-service education of science teachers in the philosophy of science could be initiated though the meta-theoretical treatment of theories that would really feature in their (future or actual) teaching practices. It has been usual practice the presentation of standard meta-theoretical models using as paradigmatic cases the theories that were most influential in the period of 1850–1940, theories especially coming from physics. While this could be considered a first step, we are proposing didactically appropriate meta-theoretical analyses of a wider variety of theories, matching both the existing curricula and the disciplinary interests of teachers.
3. *Planning and implementation of collaborative efforts between the philosophy of science and didactics of science aimed at diffusing the semantic approaches among*

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[14] This approach can also be part of the meta-theoretical training of other professionals, for example in the formation of philosophers of science and general philosophers, or in other degrees that include contents of the philosophy of science in their curricula. It would then be necessary to adapt it to match the needs of each audience.

science teachers. In didactics of science, there are several strategies to teach core meta-theoretical constructs and ideas, which include the canonical 'tenets' of the nature of science (cf., McComas et al. 1998), the so-called questions of the nature of science (cf., Clough 2008), and the 'key ideas' of the nature of science (Adúriz-Bravo 2001, 2005). Regarding tenets, the fact that such proposal rests on the need to reach disciplinary consensus—according to many authors, hard if not impossible to achieve—on what the structuring principles of the nature of science are has generated serious criticism. Questions, on the other hand, seem to be too abstract for effective meta-theoretical education of science teachers: they raise the big problems of the philosophy of science, but they provide no concrete solutions that are 'teachable'. In the line of fostering what we call *meta-scientific activity* among science teachers, we believe that the construct of key ideas (cf., Adúriz-Bravo 2001, 2005) could be applied to structuralist analysis so as to introduce meta-theoretical content related to the elucidation of the nature of scientific theories. In the last decade, we have been constructing, implementing, and evaluating activities that use the notion of key ideas of the nature of science to introduce the fundamentals of some of the semantic approaches; lately, we have been aiming at the diffusion of meta-theoretical structuralism among teachers.

We are also starting a review of the state of the art of model-based didactics of science so as to identify therein the most fertile zones in which the semantic family in general, and meta-theoretical structuralism, in particular, can be of value. This review could also open up to even more recent philosophical developments on the nature of models (e.g. Morgan and Morrison 1999; Weisberg 2013). Conversely, and as a fruit of the collaboration between philosophers and didacticians, a new line of research within the semantic family may arise, namely that of elucidating the structure of theories that are taught and learnt.

We believe that what we have presented here is a necessary step towards the education of science teachers in some particular aspects of the philosophy of science, but there is still a laborious way to go in order to generate more synergies. A 'renewal' in the lively intellectual exchanges that exist between the philosophy of science and didactics of science is particularly difficult in the case of the semantic family, which is highly sophisticated and formulated in a rather obscure jargon. It is therefore necessary to perform a set of *transpositional operations* (Adúriz-Bravo 2011), i.e. we need to transform philosophical knowledge into simple and rigorous teaching objects. We need to aim at a convergence of the specialised languages of the philosophy of science and didactics of science, with an additional effort to approach these two languages to the discourse shared by science teachers.

Acknowledgments Research reported in this article was supported by Research Grants FFI2012-37354/CONSOLIDER INGENIO CSD2009-0056 (Spain), FFI2013-41415-P (Spain), PICT-2014-1741 and PICT-2013-0503 (ANPCyT, Argentina), and PIP 112-201101-01135 (CONICET, Argentina).

Conflict of interest The authors declare that they have no conflict of interest.

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