Between Logic and Science, or How Is Possible an *Exact* Philosophy of the *Real* Science?

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"Attention to logic made it possible to formulate rigorous criteria of adequacy for any proposed solutions."
(Bas C. van Fraassen)

While logic has sometimes tended to lead to oversimplification and abstraction, it has also made it possible to refine philosophical problems pertaining to science so as to give them rigor and precision, and in some cases, to solve them definitively.

—Bas C. van Fraassen

What I do not understand is why most philosophers of science believe that problems of the philosophy of science can be solved by logic. Their interminable arguments, documented by whole issues of the journal **Philosophy of Science**, *shows that this is not the best way to reach a solution. An empirical approach . . . seems to be a better way.*

—E. Mayr

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The Relevance Problem: Stegmüller's Dilemma of the Contemporary Philosophy of Science

The formal philosophy of science was considered the most important contribution to the philosophical analysis of science produced in the first part of the 20th century. Conceived as the new "logic of science" in the works of the main representatives of the Vienna Circle and of other centers of "scientific philosophy" (Berlin, Lvov–Warsaw, Uppsala etc.), this kind of philosophical investigation of science intended to produce structural representations of the most important scientific theories and at the same time to offer secure foundations to the advanced sciences (mathematics and natural sciences, in the first place). This double function of the formal study of science was inspired by the new form of (mathematical) logic constructed by Frege, Russell and Whitehead et al., and by the scientific structuralism of the first part of the last century as illustrated by Hilbert's style of axiomatic program of the axiomatization of physics. As was sustained by D. Shapere, this philosophical movement was also inspired by the "developments of fundamental importance in science, particularly the advent of relativity and quantum theories," by which in the way of implications, "not only the classical scientific theories, but also the classical philosophies which attempted to interpret science, its methods, and its goals, seems to have been refuted" (Shapere 2004, 41).

As an embodiment of the classical ideal of knowledge certainty and secure foundations, this kind of exact philosophy of science has as its main objective the representation of scientific inference, the structure and functions of theories, of their mutual relations and of the relations between theoretical constructs and experience in the formal manner using exclusively the instruments offered by the so-called "canonic language of science," the first-order logic (such logical reconstruction is usually termed "standard formalization of theories").

The formal study of science pursued in the standard fashion, illustrated by the classical model of the "logic of science" (Carnap et al.), intended to be at the same time descriptively relevant and explanatorily adequate; it tried to be a faithful representation of the constructive and inferential procedures of science and at the same time to offer a fundamental framework as a medium for foundational research of the actual knowledge claims of all theoretical constructs. In this sense, as W. Stegmüller said, the formal philosophy of empirical sciences tried to imitate the "big brother," the metamathematics formulated by David Hilbert.

The standard program of the logical reconstruction of science was not confronted with such metatheoretical results as Gödel's incompleteness theorems, which undermined Hilbert's program in the foundations of mathematics. So it cannot be said to be internally inconsistent or technically defective. It was confronted with different kinds of objections and critiques.

In the first place we must note the very interesting idea expressed, for example, by J. van Benthem: in fact, in this kind of research the contacts between logic and (the philosophy of) science were, "on the whole, rather superficial—going no deeper than elementary logic. The Carnap–Suppes–Sneed tradition is a favorable exception; but, there as well, advanced applications of logic remain isolated examples: occasionally, one encounters Padoa's Method (1901), Beth's Theorem (1953) or Craig's Theorem (1953). Highlights of modern logic, like Cohen's forcing technique or nonstandard model theory, have found no application at all. Moreover, the technical work which is being done often seems to lack contact with actual science" (logic included, we can say) (van Benthem 1982, 432). In the same direction, D. Pearce and V. Rantala claimed not only the minimal use in the formal philosophy of science of the technical results of contemporary logic, but, and this is more important, the lack of contacts with the real level of abstraction of contemporary logic research as exemplified by the general logic and abstract theory of models (Pearce and Rantala 1983).

One possible explanation for this reluctance of philosophers to use in the philosophical analysis and reconstruction of science the most profound and abstract results of contemporary logic was perhaps the fact (discussed by van Benthem) that, in comparison with the logic of the 19th century, which was directly connected with the inferential structure and methodological procedures present in the natural sciences (from Bolzano and Mill to Helmholtz and Hertz), starting with the works of Frege logic "underwent an agenda contraction towards the foundations of mathematics . . . The foundational turn made mathematics the paradigm for logical method (which it still is) and also the major field of investigation for these methods" (van Benthem 2012, 775–6). Although logical empiricists and their followers turned to the empirical sciences, their main concern remains with the formal-linguistic aspects of scientific theories, not with the actual scientific practices and the dynamic and evolution of knowledge.

This sort of philosophical analysis was contested by the historical school in the philosophy of science (Th. S. Kuhn, P. K. Feyerabend, N. R. Hanson, St. Toulmin), and by some internal critics, like P. Suppes, for whom "the formal language methodology of logic (was) irrelevant to scientific practice, where one goes for the relevant structures with any symbolism at hand, by-passing system-generated issues like first- versus higher-order languages that logicians delight in" (van Benthem 2012, 776).

The main objection to the formal philosophy of science addressed the representational claim. Roughly speaking, this kind of critique pretends that the formal models of the exact philosophy of science cannot adequately represent the structure, dynamics and methodological procedures of the actual science. As formulated by W. Stegmüller, the main difficulty of the formal philosophy of science consists of the fact that it was "caught in the middle": "rational reconstruction is extremely desirable, for many ends absolutely necessary, but it is not possible" (Stegmüller 1986, 20). This was called by Stegmüller "the dilemma of contemporary philosophy of science." In other words, the difficulty pointed out by Stegmüller is the following: if the philosophy of science is exact, it is of no relevance for the actual science; and if it tries to adequately represent the real science, it cannot be exact.

Stegmüller's dilemma represents an explicit recognition of a change concerning the general status of the philosophical study of science which has occurred in the second part of the last century. In was described (Krömer 2007, 6), for the special field of the foundational programs in the philosophy of mathematics, in a chapter of his book on the history and philosophy of category theory, with the very significant title "The Debate on the Relevance of Research in Foundations of Mathematics," in the following manner: "While the debate on the foundation at the beginning of the twentieth century was marked by the clash of different competing approaches, the debate in the second half of the century took an entirely different shape—it concerned namely first of all the question of whether the search for foundations is relevant at all" (ibid.). From a sociological point of view, in this debate were confronted two communities, one of so-called "working mathematicians" (or "working scientists") and the other of "non-working mathematicians" or of the philosophers of mathematics and science. As we shall argue, in both cases of the philosophy of science *tout court* and of the "mathematical philosophy" the solution to this "relevance debate" requires a completely new understanding of the creative role of philosophy *in* science.

This problem of the formal philosophy of science was presented sometimes as a direct incongruence between the objectives of the rational (logical) reconstruction of science and the theoretical and methodological practices of science. We can find such an attitude expressed by some reflective scientists of our time: E. Mayr, R. Feynman, St. Weinberg et al. In a similar direction some "systematic" philosophers of science admitted that logical reconstructions are too idealized and simplistic and cannot offer a correct account of the *mathematical* construction of science.

In his monograph on determinism, J. Earman contrasts "the formal-system approach," as illustrated by R. Montague's brilliant first-order logic formalization of "deterministic theories" (in fact, of a small part of classical mechanics) with the direct mathematical reconstruction of the very idea of determinism as an "internal form" of physical theories:

> *The formal-systems approach will not play much role in my discussion of substantive issues of determinism in modern physics. Most of the putative laws of physics take the form of differential equations for which questions of determinism principally involve existence and uniqueness properties of solutions, and these properties can be discussed with as much rigor as ever needed without having to resort to formal systems. If philosophers had spent less time trying to achieve for determinism the superficial "precision" afforded by formal symbolic notation and had spent more time studying the content of physical theories they might have confronted the truly fascinating substantive challenges that determinism must face in classical and relativistic physics*. (Earman 1986, 21)

For another philosopher of science for whom the formal techniques are very important analytic tools, B. C. van Fraassen, the standard formalization of scientific theories in terms of logical languages and the conceptual explanation of the key idea of laws in terms of "propositional" properties was also "orthogonal" to the actual theoretical activity in science:

> *When philosophers discuss laws of nature, they speak in terms of universality and necessity. Science too knows the terminology of laws, both in the title ("Ohm's law," "the law of conservation of energy"), and in generic classifications ("laws of motion," "conservation laws"). Scientists, however, do not speak of law in terms of universality and necessity, but in terms of symmetry, transformations, and invariance. You may open a scientific journal and read that some result was reached on the basis of consideration of symmetry—never that it was found through considerations of universality and necessity. Is the common terminology of laws still apt, or do we have here two discussions of relatively different subjects?* (van Fraassen 1989, 1)

The problem of the logical study of science was mainly presented as a tension between the logical models and different "faithful representations" of science, coming from within such fields of science studies as the history and sociology of science, or from the "experimental" philosophy of science.

All such kinds of (mediated) critiques must be confronted with some preliminary questions: What is the "real science" and where must we find it? What are the "correct" representations of science? Which individuation criteria must be used in order to define the objects of metatheoretical research? And last but not least, why, for example, the historical presentation of science is used as a counterexample to logical reconstruction, when even the most important proponent of such perspective (Th. S. Kuhn) admitted that his theory of science is also a kind of rational reconstruction. Kuhn accepted, in a letter to Stegmüller, that his account of science was not simply descriptive, a sort of first-level image of science, but a reconstruction: "*Structure* and my related articles . . . must classify not simply as reconstruction (like all history) but as *rational reconstruction* (and therefore not as history at all). They are, that is, always concerned with the general, historical matter being introduced only as evidence not for its own sake, in a manner long traditional in philosophy of science . . . Formalism is not itself rational reconstruction but a sometimes useful tool towards that end" (letter to Stegmüller, 20 January 1975, apud Damböck 2012). So a concept of science that can "emerge from the historical records of the research activity itself" (Kuhn 1970, 1) cannot by itself be considered a more (descriptively) adequate representation of the real science than the logical one, if it contains the same complex of interpretive and normative components as any rational reconstruction. "The theses suggested above," as Kuhn admitted in *The Structure of Scientific Revolutions*, "are, however, often interpretive and sometimes normative" (8).

In my opinion, the standard model of logical analysis of science was mainly abandoned not under the pressure of some external critiques but essentially as an unintended consequence of the transition in the philosophical study of science from the general philosophy of science to the special philosophy of science (or foundational studies related to particular theories). At this special level of research the standard formal-logical approach proved to be unable to elaborate detailed analyses of the most important scientific theories and to offer effective solutions to their logical and methodological problems, to construct serious research programs in the field of foundational research as a peculiar theoretical practice. Because of this failure, the second objective of the logical study of science, the foundational (or reductive) program has become very problematic.

A "Soft" Solution?

Confronted with such internal and external difficulties, the logical study of science has many possible ways for further development. The first consists in the enlargement of the set of admissible logical and methodological instruments, of the "technique" of rational reconstruction of science in general, together with a necessary "weakening" of the constraints or requirements which are determinative for the general status or the standard logical analysis, as for example the condition of first-order axiomatization of theories. (Ironically, it seems that this famous condition was stipulated later in the works of some commentators, and was not explicitly formulated in the original project of logical empiricists.) This option was present from the beginning, but it was not endorsed because of the fascination exercised upon the logical empiricist by Hilbert's metamathematics. It was explicitly sustained by K. R. Popper in his *Logik der Forschung* (1934), for which Popper selected as a leading thread a famous Kantian dictum: "I for my part hold the very opposite opinion, and I assert that whenever a dispute has raged for any length of time, especially in philosophy, there was, at the bottom of it, never a problem about mere words, but always a genuine problem about things." In the preface to the first English edition (1959), Popper wrote: "I do not deny that something which may be called 'logical analysis' can play a role in this process of clarifying and scrutinizing our problems and our proposed solutions; and I do not assert that the methods of 'logical analysis' are necessarily useless. My thesis is, rather, that these methods are far from being the only ones which a philosopher can use with advantage and that they are in no way characteristic of philosophy. They are no more characteristic of philosophy than any other scientific or rational inquiry" (Popper 1980, 16). And, in line with this advice, Popper himself, in the attempt to "exactifying" some of the crucial concepts and procedures introduced in his general philosophy of science, made extended use not only of modern logic but also of some abstract mathematical disciplines such as the formal theory of probability.

In the meantime, with the general progress of logic and the expansion of its field beyond the axiomatic first-order logic, new logical theories and methods were used in the rational reconstruction of scientific inference and of the theoretical structure of science (higher-order logics, alternative logics, intensional logic, proof-theory, model-theory, recursion theory etc.) alongside with the instruments of the so-called formal sciences: game theory, information theory, formal theory of probability, complexity theory etc. (For an overview and recent assessment of the logical studies of science see: van Benthem 2012, Friedman 2008, van Fraassen 2011, Leitgeb 2011, Horsten and Douven 2008.)

It is maybe instructive to present the conclusion of one of these contemporary "state of the art" examinations of the logical study of science:

> *As a result of these developments, the toolbox of the philosophers of science is now greatly expanded. This has opened up a vast space of possibilities, but it also presents new challenges. As a rule, it is reasonable to assume that formal methods can shed light on just about any important problem in the philosophy of science. But for each specific problem, a fitting formal framework has to be actively sought. A crucial component of research into a problem consists in seeing what a good formal framework is for it and why, and what the limitations of the framework are . . . Finding the right formal framework for a problem is a highly nontrivial task.* (Horsten and Douven 2008, 158)

For finding such "good frameworks" for representing the argumentative structure of theories, as these are involved in the real science, an important piece of advice, not a recipe, is to try to find a correspondence or similarity between the "internal forms" of scientific theories and the structural features of the logical technique of reconstruction, a sort of "intellectual symmetry" (J. van Benthem) between different levels of science and metascience.

It is this advice operative for finding an answer to our main problem: to formulate an exact philosophy of the real science? Such a deep internal connection can be observed in the case of so-called Suppes' program in the philosophy of science, a program for the formalization of scientific theories for which the main instrument is not logic but mathematics. As P. Suppes said in his first formulation of the new program, many philosophers of science "seems to labor under the misimpression that to axiomatize a scientific discipline, or a branch of mathematics, one needs to formalize the discipline in some well-defined artificial language." This is in Suppes' view "one of the major reasons for the lack of substantial positive results in the philosophy of science." The metatheoretical thesis advocated by Suppes was: "The basic methods appropriate for axiomatic studies in the empirical sciences are not metamathematical (and thus syntactical and semantical), but set-theoretical" (Suppes 1954, 244).

The procedure of the set-theoretical axiomatization of empirical theories, as presented by Suppes explicitly in his famous Chapter XII of the well-known *Introduction to Logic* (1957), consists of the following steps: (i) introducing an abstract structure of the theory (theory-matrix), defined by a special kind of set-theoretical predicate (which subsequently was called "Suppes predicate"); (ii) a second stage which can be termed "theoretical development" of this structure, and which can be pursued either proof-theoretically (as is the most common procedure in the axiomatization of mathematical theories, as illustrated by Suppes' *Axiomatic Set Theory*), or model-theoretically, or even group-theoretically (in this case it is very important or useful to prove some representation theorems); (iii) only after this development can be specified the empirical interpretation of the axiomatized theory, and this proceeds model-theoretically, by constructing different levels of models in order to connect the abstract structure to the "models of data." The standard applications of this new kind of axiomatic (re)construction of science were in the field of rational mechanics, theories of measurement and psychological disciplines.

This program was extended and further enriched with many essential components by J. D. Sneed, W. Stegmüller and a large group of collaborators, which eventually was recognized as a new formal philosophy of science under the name of "structuralist conception of theories" (or "non-statement view of theories," or "metatheoretical structuralism"). The standard work in which this new model of science with its main applications was presented is: W. Balzer, C. U. Moulines, and J. D. Sneed, *An Architectonic for Science: The Structuralist Approach*, 1987.

Sneed's concept of empirical theory was the first presented exhaustively in a model-theoretic setting: not only the applications of the theory or the relation between theories and experience (or the world) were formulated in terms of models of various types, but the very structural core of a theory and the representations of the physical systems are defined model-theoretically (or by sets of different kinds of models).

This program intended not only to reconstruct many theories present in actual science (from mathematical physics, economics, linguistics, chemistry etc., theories accepted as exemplars of "real science"), but also to offer a logical reconstruction of the main theses of the so-called historical philosophy of science, as represented by Th. S. Kuhn, P. Feyerabend, R. N. Hanson et al. In the works of W. Stegmüller, this second intention was presented as an important step towards the "unification" of contemporary approaches in the philosophical study of science. In part, this effort was acknowledged by Kuhn himself: "If only simpler and more palatable ways of representing the essentials of Sneed's position can be found, philosophers, practitioners, and historians of science may, for the first time in years, find fruitful channels for interdisciplinary communication" (Kuhn 1975, reprinted as Kuhn 1976, 181). In a very long and rather sympathetic review of Stegmüller book on the structuralist conception of theories, Paul K. Feyerabend remarks that this view on theories has many advantages in comparison with the so-called statement view of theories, but, at the same time, it neglects some important results of the traditional logical analysis of science; Feyerabend admits that "the structural model combined with Kuhn's philosophy will enable us to look at science in a new way and to improve our understanding of it. But I still conjecture that future work in this area (and in every area) will gain more from a healthy eclecticism than from commitment to a single point of view, however perfect" (Feyerabend 1977, 369). The main objection to Stegmüller's program (and to its second intention, "Kuhn Sneedified") was an objection against every logical reconstruction intended as a unique manner of the "second rationalization": We may have to use different reconstructions on different occasions and "the assumption that a single scheme (statement view, structural view, Hegelianism) will cover *all* of science, *all* of physics, or even all of quantum mechanics may be nothing but a pious dream" (361–362).

This rapprochement to real science was made possible by some important modifications of the "classical" model of logical reconstruction, modifications which represented a sort of minimal condition for a "soft solution" to our main problem. These modifications included: (a) discarding the constraint to formally reconstruct scientific theories in the framework of a logic-axiomatic (syntactic and/or semantic) system and freely using mathematical theories and methods for the rational reconstruction of empirical theories (this corresponds with the organizational-constitutives and "logical" role of mathematics in actual theoretical practices), and (b) consenting to an intuitive formulation of set theory as the formal theory subjacent to every "natural" theory.

Metatheoretical structuralism was conceived from the beginning as a progressive research program: it consists of a (general) metatheory of scientific theories which is applied to special (empirical) theories in order to be extended (to construct its intended domain) and tested in these case studies. It evolved in many directions: (i) conceptual—being enriched with many new ideas and structural developments (e.g.: approximation, theory-holon, theory-evolution, structural explanation, pragmatic aspects, "linguistic dual" etc.); (ii) "empirical"—by formal reconstructions in this framework of a great diversity of concrete theories (from physics, chemistry, economics, sociology, theory of accounting, psychology, psychoanalysis, linguistics, literary theory, history of ideas etc.); (iii) epistemological—by rationally reconstructing some very important ideas and concepts from different philosophies of science.

For C. U. Moulines, this extensive development of structuralism was crucial, because this wide range of applications not only "shows its methodological potential, but also because it gives some empirical support to one of the theory's central claims, viz. that there are some common features in the deep structure of all empirical disciplines and that these features can actually be captured by the metatheory. This is what we should require, anyway, from any general theory of science which aims at a serious treatment of its subject matter. It should be checked against many examples" (Moulines 1996, 1–2). This opinion is not universal among the representatives of the metatheoretical structuralism. As A. Ibarra and Th. Mormann noted, this kind of extensive application must not be encouraged; it can be a sign of superficiality, because it is difficult to admit such similarities at a deep level between disciplines with very different conceptual frameworks and functions. In this case it is important to consider Aristotle's advice: "It is the mark of an educated man to look for precision in each class of things just as too far as the nature of the subject admits; it is evidently foolish to accept probable reasoning from a mathematician and to demand from a rhetorician scientific proofs" (*Nichomachean Ethics*, I, 3, quoted by Ibarra and Mormann 2010, 81). (It is possible that the future evolution will be accelerated by Sneed's "return to the front," after so many years of silence, with another masterpiece: a structural reconstruction of quantum mechanics—Sneed 2011.) In spite of this large amount of reconstructions of particular scientific theories and of the initial impact among some important philosophers of the "epistemological application" of the structuralist framework for the rational reconstruction of the main historiographical philosophies of science, and, more recently, for the epistemological foundation of structural realism, this program represents only a starting point for a more general approach towards a new philosophy of science which will be at the same time exact and relevant for the real science.

Together with the challenge from the real science, the formal philosophy of science is confronted nowadays with an intensive challenge from other types of the philosophical investigation of science: the naturalist approach; the non-foundational perspective on science or the "local," differential research; the "experimental" philosophy of science (not to be confused with so-called "experimental epistemology"); the phenomenological-hermeneutic conception of science; the "engineering philosophy of science" etc.

Suppes' Program—the Second Step: New Tools of Science and of Scientific Philosophy

In my opinion, the main important challenge concerning the relevance of the formal (exact) philosophy of science for the real (actual) science is related not so much with the amount and diversity of "empirical applications" of a metatheoretical framework, but rather with the capacity of such framework to adequately reconstruct the most representatives theories from contemporary science. To correspond to actual science means in this second sense to correspond to those theories of contemporary science which are determinative for its high level of abstraction and fundamental character, to its new epistemological style. This, I believe, was the second intention of Suppes' program, expressed by the idea that a good formalization of empirical theories must use the most developed instruments of the mathematics available at every stage in the development of science. This implies that we do not possess a rigid and universal logical framework for reconstructing all kinds of scientific theories, but we have to use for each scientific domain and time the best mathematical instruments which are also used in the actual theoretical practices of science. An adequate metatheory of science must imply an internal coherence between the level of abstraction present in the real construction of science and the formal theorizing about science. In this sense, for contemporary science this coherence can be realized only by the recourse at both levels to the most abstract mathematical theories. In order to reconstruct the real theoretical architecture of contemporary science as is it present in the specific areas at the forefront of scientific research it is imperative to resort to the new instruments, concepts and methods of contemporary abstract mathematics, which are also essentially involved in the edification of the fundamental scientific theories. In this manner, the philosophical reconstruction of science can not only be relevant for the real practices of science but at the same time it can creatively interact with or contribute to the foundational research in advanced science. Synthetically expressed, a real philosophy of science must adequately represent the new architecture and the argumentative structure of the contemporary theoretical construction of science. This idea contains in itself also the requirement that for a metatheory to be adequate to contemporary science it has to offer a conceptual framework for reconstructing the main characteristics of contemporary science representative for its fundamentality and exemplarity, i.e., to have explanatory relevance at the fundamental (foundational) level of science.

In this perspective, among the most important conceptual-theoretical characteristics of contemporary science (of a foundational significance) can be considered: the emergence of a new kind of internal organization of science, having as its nuclear center the architecture of a fundamental theoretical program; the new level of abstraction, instantiated by the abstract-structural patterns, theory-frames for large theoretical developments, the actual representatives of the fundamental level of science; a new type of scientific structuralism, dynamic or holistic structuralism, which can integrate other types of structural construction of science and which make necessary the reconceptualization of all kinds of metatheoretical structuralism; the reformulation of the basic theories of science as "effective field theories," which has very important consequences for the methodology and metaphysics of science; the proposals to develop "fundamentally new ways of constructing theories of physics" (Döring and Isham 2007/2008, 1), in which the first step is represented by introducing "a novel structural framework within which *new* types of theories can be constructed" (ibid.), as the topos foundations of physics program or the categorial foundations of physics; the radically new role of mathematics in constructing scientific theories, in which a physical theory built on very abstract and complex mathematical structures is accepted as a good theory of physics even if it cannot be subjected to empirical tests, even "in principle." All these traits of contemporary science are all only different aspects or manifestations of the new role of mathematics in the construction of science. The thesis of my paper is that this new role of mathematics can be assumed also at the metatheoretical level.

In recent years it had been increasingly recognized that the most abstract theory of contemporary mathematics, category theory, represents the "main tool for building theories," and that at the same time it has an "enormous potential for any serious version of 'formal philosophy'" (Abramsky 2010/2012, 1). As the best candidate for this constructive role in science and philosophy, category theory, as a general theory of abstract mathematical structures and constructions, possesses an inexhaustible potential not only for the unification and foundation of mathematics or for the (re)construction of contemporary physical theories (the so-called "categorification of physics") and of other empirical sciences, or for theoretical computer science, but, in my opinion, also for building a formal philosophy of science in conformity with the requirements of contemporary actual science considered at the level of fundamental and foundational research.

The question, "what is category theory?" can be answered in the first instance by a slogan: "it is the theory of general abstract nonsense" (Norman Steenrod). At another level, we find the following determination: "it is a general mathematical theory of structures and of systems of structures. As category theory is still evolving, its functions are correspondingly developing, expanding and multiplying. At minimum, it is a powerful language, or conceptual framework, allowing us to see the universal components of a family of structures of a given kind, and how structures of different kinds are interrelated" (Marquis 2010/2011, 1). Category theory is not a theory in the common sense of the word, with a well determinate meaning and a stable universe of discourse or a set of domains. It is not a rigid framework, being in a steady process of expansion and extensive and intensive generalization. As a consequence, categories as thematic units of this kind of theorizing are not uniquely defined, but their very definition "evolved over time, according to the author's chosen goals and mathematical framework" (ibid.). They are "algebraic structures with many complementary natures, e.g., geometric, logical, computational, combinatorial, just as groups are many-faceted algebraic structures" (ibid.). In different contexts and at different times, categories were defined in purely abstract terms, like the abstract concept of group (Eilenberg, MacLane), or set-theoretically (Grothendieck), or more generally, as a mathematical structure with an appropriate structure-preserving map. In the first kind of definition, a category *C* is an "aggregate" *Ob* of abstract elements, called objects of *C*, and abstract elements *Map*, called mappings (or morphisms) of the category. As in the case of the group with their defining operations, these mappings are subjected to some axiomatic constraints. (For technical details, conceptual issues and the historical evolution of the category theory see Marquis 2009, Krömer 2007.)

Category theory has found many important applications primarily in the field of mathematics, as a powerful foundational, unifying or organizational instrument (being at the same time "context" and "structure"), and then outside of mathematics, in physics (in the variants of "topos-foundation" of physical theories or of "categorification" as a means of re-constructing theories; see, in this sense: Döring and Isham 2007/2008, Abramsky 2010/2012, Coecke 2011, Halvorson 2011), computer science, cognitive science, theory of music. In line with these developments one can consider the "scientific applications" of category theory as one of the new and most important aspects of "applied mathematics" (mathematics applied at the fundamental level).

In philosophy, although we can incidentally encounter such titles as "category theory's conception of the world," it was only recently introduced as a new formulation of the structuralist view of theories (Mormann 1996), or as a possible foundation for structural realism (the so-called categorial structural realism, proposed by J. Bain); in some papers, J. Carter, D. Ellerman, C. Drossos, D. Corfield et al. have explored the importance of the category theoretical approach to some metaphysical issues like the ideas of necessity, new "formal unities" and the concrete universals, the general form of description theory etc. For a possible impact of category theory on the fundamental topics of contemporary philosophy (language, knowledge and mind), see Peruzzi 2006. My purpose in this study is to indicate a new way for the philosophical application of category theory and to realize some first steps in the construction of a categorial-theoretic metatheory of science.

A New Thematic Concept of the Scientific Metatheory and the "Categorical Imperative" in the Philosophy of Science

In order to understand the perspective of such research we must pay attention to some methodological traits of category theory. As Marquis emphasized, in the case of category theory the question "What is category theory?" is not easy to answer (even if we abstract from the fact that in most cases if such a question is not a trivial one it concerns not the proper object of the theory but its philosophical and methodological significance) because it cannot be simply said, as in other cases, that, for example, "number theory is the study of properties of natural numbers, topology is the study of invariant properties of spaces under continuous transformations or deformations" (for this theory everyone has an "informal idea" of its objects). The case of category theory is verisimilar to algebraic structures. And the problem as in all such cases is that "the objects dealt with have an ambiguous status. The easy answer, 'category theory is the theory of categories,' does not help much. For it does not say what category theory is, what categories are for and why they would be of any interest to mathematicians, logicians, computer scientists, philosophers, cognitive scientists, mathematical physicists and even theoretical biologists" (Marquis 2006, 221–222). To understand the "object" of category theory we must understand the context, form and function of various modalities of categorial theorizing, with their particular role within mathematics as well as within all fields of science and philosophy.

> *When categories were introduced, only certain roles were foreseen by mathematicians at the time. In fact, categories were introduced with certain specific functions in mind. The concept had a certain* ***form****, given by the axioms of original theory, precisely to capture these roles. Some creative mathematicians then saw that this form, perhaps slightly modified, could serve other original functions and these led to the modification and introduction of new forms associated with the theory . . . My claim, thus, is that to understand what category is, and I believe that this claim could be made for* ***any*** *algebraic structure, one has to understand how a specific algebraic form is introduced for a specific* ***usage*** *in a given context and how this usage leads via analogies, abstractions and generalizations, to the introduction of new context, new usages and new forms, the later having sometimes an impact on our understanding of the original form*. (Marquis 2006, 222)

These changes can affect the form, context or even the usages of the categorial ideas and all these can imply severe transformations of their cognitive significations.

My "informal idea" is that, starting from a suggestion made first by F. W. Lawvere (1967) for first-order theories, we can formulate, on the basis of the analogy with mathematical category theory, a possible abstract theory of theories or a "categorial metatheory." We intend not only to extend this kind of categorial representation to other richer theories (from a logical spectrum of theories), but at the same time we will try to formulate this categorial approach of theories by transferring to another methodological and epistemological typology of scientific theories this categorial analogy, and in this manner offer a proper (meta) mathematical characterization for the *fundamental* theories of science. I have found some recent proposals to apply category theory instead of set theory to illuminate one of the main problems of the philosophy of the last century, the structure of scientific theories, in the works of some category theorists (A. Peruzzi, A. Rodin, R. Krömer), but these are confined to the analysis of deductive-axiomatic systems.

If we look at the various transformations of the conception of scientific theory in the recent philosophy of science we can find this analogy not only well founded but also as having important interpreting value.

In order to fully exploit this new potential instrument for scientific philosophy it is important for the contemporary scientific and metascientific structuralist programs (which are the natural starting points for a new philosophy of science) to realize some preliminary requirements and transformations, which in a similar manner concern the context, form and function of a theory of theories. Or, equivalently, to admit some new thematic perspectives in the philosophical study of science.

A. To recognize as the new unit of scientific cognition (a new “thematic unit” of science) the *fundamental scientific program* and to study its architectural and modular organization. A fundamental program is a multilevel net of theories containing (i) at the first level a core theory of the abstract general type—the matrix of the entire theoretic development, (ii) a mediating “theory”—a mixture of previous theories, hypotheses, theoretical and empirical models, “phenomena” (empirical regularities or laws) and (iii) a family of interconnected special theories with determinate domains of signification and truth. This idea was implicitly contained for the first time in the construction of science in the Newtonian program of natural philosophy and was also followed by Kant in his new transcendental metaphysics. In an explicit manner the concept of fundamental theoretical program or of theoretical program in physics was formulated by Einstein in the 20th century and it was instrumental in his construction and interpretation of relativistic physics as in the methodological and metaphysical interpretation (and critique) of quantum mechanics.

B. To admit the diversity of *theory-types*, defined essentially on the basis of the mathematical forms of the fundamental laws of theories (C.-F. von Weizsäcker), and correspondingly, the different roles, functions and epistemological values of such kinds of theories in the general framework of a fundamental scientific program.

C. To identify as the basic matrix of such fundamental theoretical programs the *abstract-structural theories*; such theory-cores of the large programs represent in the first place the theoretical expression of the deep generative structures, of the potentiality and “competence” realized in the theoretical construction of science. At this core level of a theoretical program we must establish the ontological project of the entire scientific program.

D. To recognize and explore new kinds of inter-theoretic relations, defined between different types of theories with different roles and functions in a multilevel architecture of scientific disciplines.

E. To recognize the fundamental status of the structural laws of theories (the principle of invariance, symmetry and conservation laws) and their role in constructing the ontological commitments of fundamental theories.

F. To bring into prominence the difference between fundamental research programs determined by the “internal logic” of the theoretical construction of science (represented essentially by the modalities of articulating a basic structure in the development of an abstract theory) and such programs determined by external constraints as a result of the fine interaction of the cognitive structure of science with social frames of knowledge production.

G. To abandon the great foundational scenarios and to accept a move towards local or “differential” approaches in the philosophical study of science.

H. Finally, to rise the examination of science at a new level of abstraction and generality; this can be achieved by representing the nature and structure of theories on the basis of a new concept in scientific philosophy, namely, the idea of a *general form of the abstract-structural theories*, which can be at the metatheoretical level the correspondent of the abstract structural determinations of mathematical category theory, or, in a condensed form, the idea of the "category of categories," formulated by Lawvere. (This is the main proposal of this study and it will be presented below.) This concept can afford a top-down approach in the theory of theories, similar with the construction of various kinds of categories in Lawvere's conception, which starts from the category of categories and introduces each type of categories as a specific "object" of the generalized mathematical universe. In this manner we can have a detailed image of the relations between different structures and types of theories. This can be understood by analogy with one of the "leading ideas S. Mac Lane advocated as central to a categorial 'philosophy' of mathematics that each mathematical form has many different realizations and category theory aims at an axiomatic description of such forms, which also makes the basic patterns of their mutual relations explicit" (Peruzzi 2011, 290). In the same sense in which category theory represents the most abstract mathematical form of scientific structuralism (of structural disciplines from contemporary science), the idea of the general form of an abstract theory represents at the most abstract level the idea of the form of scientific theory; and this is the key-concept of a "categorial metatheory." This level of abstraction expressed by the "categorial" concept of a general form of theories is to be understood in two complementary meanings: the first signifies a level of the abstraction in the sense of the relation of particulars to general, the second means a change of the theory types from theories of cognitive performance to theories of cognitive competence. On can say that, in a certain sense, this second kind of abstraction justifies the original Kantian inspiration of Mac Lane's category theory, which can be interpreted as the new theory of categories for any future metatheory "that will be able to come forward as a science."

This general concept of the form of an abstract theory is able to express at the same time the "operational" aspect of a structural theory (its variable part, which is essentially involved in the determination of different types of theoretical programs in science), together with the new level of abstraction required by the transition from a conception centered on objects to another centered on processes (mappings, transformations, functions, functors etc.) (A similar transformation is proposed for logic by van Benthem, 1997/1999). The introduction of this metatheoretical key-concept is necessitated by the intentionality to develop a metatheory which in principle can adequately rationally reconstruct and "represent" science at its fundamental level. And this level is "presented" in contemporary mature scientific disciplines by their abstract-structural theories (or as sometimes is preferred, by "scientific structuralism"), the general theoretical cores for large research programs. To establish the "form" of contemporary theorizing means to establish the general form of abstract theories. And this concept can be *mathematically* "formalized" in category-theory's terms (which usually implies a very strong compression of a large theory with a huge quantity of particular results, *y compris* the metatheoretical results, in some mathematical formulas and theorems). But this is the task of the second part of my study. Now we intend only to introduce in a quasi-informal manner the fundamental concept of this kind of categorial theory of theories.

One more preliminary note: this kind of reconstruction which lies at the basis of this new metatheoretical concept of a general theory-form is not an instance of traditional logical reconstruction (or conceptual analysis) of scientific theories, a common procedure of all standard analytic philosophy, but a rather genuine theoretical construction, a different kind of "theoretical reconstruction" aiming to establish on the basis of a new abstractive process the determinative structure which is the core of the entire cognitive potential of a general kind of scientific theorizing and creates a new "logical space" for further developments (for more details, see Pârvu 2004). This kind of reconstruction requires the introduction of a high level of abstraction which can organize and unify the different types of the "theoretical articulation" of an abstract structure, the representatives of the processes which are involved essentially in edifying effective research programs. This requirement is sometimes termed as "the new categorical imperative" of science construction (and reconstruction).

In the last part of this paper I will introduce in a schematic manner the structural components and functions of this central concept of a categorial theory of theories, the idea of the *general form of abstract-structural theories* (GFAT). In this sense, an abstract theory can be represented in the following manner:

$T = < S, I, V, P >$, where,

S is a mathematical structure, the core-structure of the entire theory, presented in a formal manner; it is so to speak, the constant, invariable part of the theory;

I is a set of "generic interpretations," containing possible primary interpretations of the formal structure, interpretations which will determine the general orientation and signification of the fundamental theoretical program;

V is a set of possible ways of "theoretical articulating" of the formal structure in order to construct the entire theory-core of the program; this is the "variable" part of the abstract-structural theory and its role is essential in "developing" the formal structure as a theory in the full sense and to construct different domains or specific theories of the program;

P is a set of theoretical "paradigms" with natures and functions determined by the generic interpretations and theory-articulations.

The constant and unique (a singleton) component of the abstract theory, the mathematical formal structure can be introduced ("defined") in a variety of modalities; it is possible that some of them be correlated in the frame of a theoretical practice with specific modes of theoretical articulation. Of these modalities of defining this formal structure, the most important are: (i) "axiomatic definition" in the sense of Hilbert's "implicit definition" of a set of concepts by the set of axiomatic formulas; (ii) a set-theoretic predicate or a Suppes predicate, or a formalized conception of "species of structures" as in Bourbaki's reconstruction of mathematics; (iii) a set of models; (iv) a "doctrinal function" in the sense proposed by J. C. Keyser (a concept which represents an intensional generalization at the level of an entire theory of the common idea of "propositional function"); (v) a "general function" or a functional; (vi) an undetermined "object" of a category, etc.

The set *I* of "generic interpretations" introduces a "minimal interpretation" of the formal structure, the most important variants of such "constitutive," internal interpretation being: ontological, epistemological and informational-theoretical interpretations (the classical model for this kind of interpretations is offered by Carnap's "Konstitutionsystem" with its fundamental rules). In a logical reconstruction these interpretations can be specified by some fundamental postulates defining the ontological project of a theory-frame, or epistemological general requirements, or some general rules for information processing and communication etc.

The most important component of an abstract theory, which, from our point of view, was quasi-ignored in most theories of theories or philosophical conceptions of science, is the "variable" component referring to the ways in which a formal structure becomes a theory in a complete sense of the word, and which is not only a conceptual-formal framework or instrument for building possible theories. This idea of theoretical articulation of the formal structure is inspired by some proposals of structuralist concepts or programs in physics—as, for example, Heisenberg's idea of the "unfolding of an abstract structures," or the program constructed by the German physicist G. Ludwig in his work *Die Grundstrukturen einer physikalischen Theorie* (1978); at the same time my model for this reconstruction was the modality in which W. Stegmüller presented the main ways in which logical theories can be constructed, in his synthesis *Struktur-*

typen der Logik (1984). Starting from some similarities with Kuhn's conception of science development we can also use for these kinds of internal development of a formal-structural core the expression "paradigm-articulations."

These are genuine types of theory-construction, and their significance for the general understanding of the "logical construction of science" is of a fundamental character.

If we look at the "development" of formal theories in science we can determine (by a sort of theoretical reconstruction, or "abstract history") the following main types of "theoretical articulation" of a basic (formal, mathematical) structure: (a) axiomatic-deductive or, in the case of a formalized theory, a "proof-theoretical"; (b) model-theoretical; (c) group-theoretical or algebraic or invariantive construction; (d) category-theoretical (or, simply, categorial). In some scientific domains we can find also two new important types of theory-articulation: game-theoretical and informational-theoretical.

We can illustrate this pattern with many scientific disciplines from various domains of science. In logic, for example, well-known are the proof-theoretical and model theoretical "representations" (constructions, "developments") of a formal logical system; inspired by the "Erlangen Program" in geometry defined by Felix Klein, F. Mautner introduced an analogue mode of the invariantive construction of logic (1946), which was also developed latter by A. Tarski and his followers; and in recent years there has been a flourishing domain of "categorial logic," which extends the general approach of mathematical category theory in logic. We can also indicate the presence of game-theoretical and information-theoretical developments of logic or semantic systems. It is not the place here to discuss the relations between such modalities of the construction of logic and to evaluate their comparative merits and the different applications in science construction or in the formal representation of rational argumentation, of scientific inferences and constructions, etc. Only one suggestion: as in all cases, the categorial formulation (articulation) of logic enables us to establish in a very clear manner the internal relations between these types of theory construction, to "compress" the main metatheoretical results in very abstract and general "statements," and to construct in this sense a formal theory of theories in the proper language of the theories themselves.

The paradigm case for such "abstract developments" of theories is the science of geometry. If we consider only the "classical" or Euclidean geometry, we can find here exemplified all these types of "theoretical articulation," with all their epistemological "extensions." (By the way, geometry has always been the topos or labor for confrontation, testing and assaying of all epistemological conceptions.) The same situation is to be found in general (or "rational") mechanics, in "abstract quantum mechanics," in the theoretical science of language etc.

P, the last structural component set of the GFAT, is introduced by the non-unambiguous term "theoretical paradigms" with which we intend to denote a special basic ingredient of a fundamental theory, namely, some "formal principles" which represent the guiding laws for all theoretical extensions (in particular, "guiding principles for the construction of theories of physics" as exemplified by Einstein's general covariance and equivalence principle, or Bohr's complementarity idea; see Heunen et al. 2008), and which can receive an internal mathematical form or "expression," operative at each level of theory-development. Such formal principles can be also illustrated by the formal principle of "relativity" as conceived by Einstein, which is determinative for a large category of relativistic theories, or the formal principle of the description theories (introduced by Russell in *On Denoting*, 1905) and which was transformed in the source or model for the structuralization of many empirical theories, from linguistics to physics (Ramsey-sentence and Carnap-sentence of a theory, Sneed's empirical statement of a theory, etc.) and biology (Price's equation). A classical paradigm for physical theories was the idea of determinism, which characterizes a large class of "deterministic theories" and which is locally instantiated by special mathematical "formulas." We can find some recent proposals of categorizing such guiding principles, as for example, Einstein's idea of general covariance was reformulated in topos theory as "the principle of general tovariance" (Heunen et al. 2008).

The main philosophical significance of this general form of theories, if we take into consideration the things at the level of the *general philosophy of science*, is related to the possibility to characterize the essential types of the theoretical construction or of the argumentative structure of science. On the basis of the main types of "theoretical articulation" of a theoretical formal structure we can determine a series of such kinds of general *theoretical* ("logical," in the usual terminology) *constructions of science*: deductive-axiomatic (or, alternatively, constructive-axiomatic), model-theoretic, group-theoretic (algebraic), category-theoretic, and information-theoretic. So, we must admit for contemporary scientific disciplines a multiplicity of general ways of theory construction in comparison with the single classical model of science, developed in only two subspecies: deductive-axiomatic (Aristotelian representation) and constructive-axiomatic (Euclidean representation). This is not a sign of a "fragmentation of reason," as was claimed with great emphasis by post-modern philosophers, because all these construction types can be systematically correlated in contemporary metascience as an integral architectonic unity, for which the "natural" formal framework can be offered by mathematical category theory. In this theory, by its genesis and contemporary structure, we have a "natural" correlation of the different objectives of the theorization. In this sense we can rely on the following observation made by R. Krömer concerning the many nonexclusive facets of category theory: "CT is used to *express* in algebraic topology, to *deduce* in homological algebra and, as an alternative set theory, to *construct objects* in Grothendieck's conception of algebraic geometry" (Krömer 2007, 26).

Leaving the field of the general philosophy of science, we can find many important consequences of the idea of GFAT for the modern meaning and structure of a formal *metatheory*. In this sense for each type of "structural articulation" of a formal theory we can determine special metatheoretical constraints and can prove some specific meta-theorems. Again, categorial theoretical formalism represents an important medium for an integrated view concerning the correlation and relevance of all such metatheoretical studies. And, as a working hypothesis, we can represent mathematically such correlations starting from the idea of a "category of categories" (Lawvere) as a formal representative of our concept of general form of theories, and representing the different couples <formal structure, theoretical articulations> as special categories, having a kind of mathematical structure as their "object" and the different articulations as morphisms preserving that structure, and at another level, we can propose to any "natural" constructions on structures of some particular kind a functor from one category to another. In this manner we can build a rigorous top-down metatheory of science.

In another perspective, this approach to science centered on the thematic idea of GFAT represents a good *methodological instrument* for understanding in principle the possibilities for further generalization of theories or for theoretical generalization in abstract science (we can in this manner formulate a genuine theory of the constructive extension of science at the fundamental level). Again, the key for such a construction is represented by the GFAT, and in particular by its "variable" component. So, if we start with a proof-theoretic or a deductive-axiomatization we have the possibility to build a more general theory by applying the procedure known as "rational generalization" or "axiomatic generalization"; in this case we can suppress an axiom and in this manner we can obtain directly (without recourse to the empirical research of any domain of facts) a new and more general theory. In the case of a model-theoretic approach for raising the level of generality we must "control" the constraints defining different sets of models, and in the case of a group-theoretic generalization the "generalization operator" must be placed on the group of transformations characteristic for that theory. And so on. In the last case, as in the case of categorial-theoretic generalization, we can encounter not only a new level of abstraction, modifying either the "objects" or the "morphisms" of the category, but we must transcend every special kind of categories and can attend a new kind of generality, expressed by the "category of categories," which can give a mathematical expression of theoretical competence not only to theoretical performances. This progression in theoretical generalization can be encountered also at the level of metatheoretical theories, as illustrated by "general logic" (Rantala, Peirce), the abstract theory of models (Barwise), general algebra, the abstract theory of groups etc.

Another important implication of our structural analysis of the general idea of scientific theory consists of its capacity to indicate in the different types of theory-articulation the main source of the *epistemological* significance or interpretation of different research programs (or types of fundamental theoretical programs in science) generated by these different ways of unfolding an abstract structure. But this is a very complex subject which deserves a separate study. (Only one suggestion: it is possible and necessary to reconstruct the very idea of "knowledge" in this framework and to distinguish the "variants," concepts or representations of knowledge: deductive-propositional, model-theoretic, invariantive or group-theoretical, information-theoretic, game-theoretic, computational and categorial ones.)

In the same direction one has to explore the ontological implications of this approach (some steps are made in the studies of J. Bain, J. Carter et al.) as well as its capacity to open new vistas in the historiography of science.

❑

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Abstract

Between Logic and Science, or How Is Possible an *Exact* Philosophy of the *Real* Science?

The purpose of this paper is to present one of the main methodological problems of the contemporary philosophy of science and to indicate a possible way towards a constructive solution. In various ways and at different levels of reflection it is stated that the most profound difficulty of today's general philosophy of science is the tension between the propensity to use exact and formal methods in the study of science and the actual relevance of such procedures for the understanding of real science. In the spirit of one the most important programs in the exact (formal) philosophy of science, devised by P. Suppes, the paper suggests that the new concepts of the mathematical category theory can offer a constructive modality to solve this tension, by providing the necessary instruments for the effective (re)construction of science at the fundamental level and at the same time for a formal metatheoretical analysis of scientific practices. The contribution of this article consists of introducing (as a preliminary analysis for such approach), the concept of the general form of scientific theories, which will allow us to use the mathematical category theory in order to formally represent the structure of fundamental theories and to build a unified mathematical metatheory of the different contemporary forms of the theoretical construction of science. As a side-effect, this approach can contribute to the reexamination from a new perspective of the possibility that metatheoretical studies can contribute effectively to foundational research.

Keywords

logical study of science, category theory, scientific structuralism, general form of theories