Scientific Models and the Semantic View of Scientific Theories

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I argue against the conception of scientific models advocated by the proponents of the Semantic View of scientific theories. Part of the paper is devoted to clarifying the important features of the scientific modeling view that the Semantic conception entails. The liquid drop model of nuclear structure is analyzed in conjunction with the particular auxiliary hypothesis that is the guiding force behind its construction and it is argued that it does not meet the necessary features to render it a model of the theory, as the Semantic View demands. Given that this model is indicative of how quantum mechanics is applied in the domain of nuclear physics, I claim that the Semantic View does not adequately account for scientific models.

1. Introduction. The study of models as a guide to understanding scientific theories and the ways by which the latter are applied to the phenomena occupies center stage in the last two decades. To this effect, the contribution of the Semantic View (SV) of theories has been significant and it comes as no surprise that this view may nowadays be considered the orthodoxy on the nature and function of scientific theories and models. The SV identifies theories with a class of model-types; a theory is a class of fully articulated mathematical structure-types that are defined either by the use of set-theoretical predicates (Suppes 1961, 1967; da Costa and French 1990) or by the use of the mathematical language dictated by the subject matter of the particular theory (van Fraassen 1980; Suppe 1989). The common viewpoint among the various versions of the SV, that theories are (or can be presented by) families of models, provides a unified way by which to conceive of scientific models. Different proponents of the SV, however, propose distinct ways by which to understand the representational function of scientific theories and of scientific models—and subsequently of how theories are applied.

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The general contentions of the SV could be summarized in the following theses:

1. $M_T \subseteq TS$, where M_T stands for model of the theory, TS for the theory structure, and $\subseteq$ for the relation of inclusion.
2. $(A \;\&\; E \;\&\; D) \propto M_D$, where M_D stands for model of data, A for auxiliary theories, E for theories of experimental design, D for raw empirical data, and $\propto$ for 'used in the construction of'.
3. $M_T \approx M_D$, where $\approx$ stands for mapping of the elements and relations of one structure into the other.

In other words, the traditional syntactic account of the relation between theory and evidence, which could be described, rather simplistically, by the schema: $T \;\&\; A \rightarrow D$ (where T stands for theory, and $\rightarrow$ for the material conditional), is abandoned and replaced by Theses 1, 2, and 3 above. By $M_T \subseteq TS$ the SV replaces the deducibility relation present in the syntactic view by model-theoretic entailment; by defining a theory structure, a class of model-types is laid down for the representation of physical systems. By $(A \;\&\; E \;\&\; D) \propto M_D$ the proponents of the SV distance themselves from past conceptions by claiming that theories are not directly confronted with raw experimental data (collected from the target physical systems) but rather that the latter are used, together with theories of experimental design and other auxiliary theories, in the construction of data structures, M_D. It is these data structures that are compared to a theoretical model, and the theory/experiment relation consists in a mapping of respective structures from each side of the comparison, i.e., $M_T \approx M_D$. Most proponents of the SV would, I believe, concur to the above and to the fact that theoretical representation of phenomena can be explicated exclusively by mapping of structures. They do differ, however, in their suggestions on how to interpret the relation $M_T \approx M_D$, which are the outcome of the different ways by which each author conceives the nature of the theory structure. For van Fraassen (1980) it stands for isomorphism between an M_D and an empirical substructure that is embedded in an M_T, for da Costa and French (1990) it stands for partial isomorphism, for Giere (1988) it stands for similarity, whereas for Suppe (1989) it stands for ". . . an abstract and idealized replica of . . . ."

Whichever the chosen version, the backbone of the account of theories and scientific modeling offered by the SV is the sharp distinction between theoretical models and data models. Understanding the nature of the theory/experiment relation in this manner accords with the contention that the theoretical models are constructed by pure ingredients of the theory, and all the auxiliary theories and the entire conglomeration—or relevant parts—of background knowledge that the scientist inherits enters in the construction of the data models. No doubt, by this distinction the proponents of the SV develop a theory of theories that entirely detaches auxiliaries from theory proper, thus overcoming the problems of correspondence rules faced by the logical positivist syntactic approach to theories.

A recent conception of scientific models as partially-autonomous mediators between theories and phenomena has been proposed by some authors (Cartwright 1999; Morgan and Morrison 1999). This proposal does not constitute a well-articulated theory of scientific theories but it is, in addition to being an attempt to understand scientific modeling and the diverse roles of scientific models, an objection to the SV. The objection is multidimensional but we could discern two aspects that are foremost: firstly, scientific models, i.e., actual scientific constructions, do not always relate to the theoretical models of the SV in some way the SV could account for, secondly the theory/experiment relation is such that it could not be captured merely by some sort of mathematical mapping without obscuring the complexity of the relation. My argument, which is in the same spirit as these authors and could be seen as supplementary to Morrison's (1999) argument, has the following structure: If the SV asserts Theses 1, 2, and 3 above, as an adequate way to capture scientific theory application (i.e., scientific model construction and theoretical representation of phenomena), then the features of every scientific model (that qualifies as an application of a particular theory) that represents its target physical system should (in principle) be reducible to those of an M_T or those of an M_D. There are, however, models in science which, although related to theory, cannot be so reduced. Hence the SV does not fully account for the relation between theory and scientific models.

2. The SV's Reconstruction of Scientific Modeling: M_T's and M_D's. According to the SV, the class of M_T's could be defined by the laws of the theory. In classical mechanics by means of the *position* and *momentum* vectors we establish a relation: Newton's 2nd law. The specification of any force function would define an M_T. For instance, if the force function is specified as $F = -k\xi$ (for a position coordinate ξ and constant parameter k), then the 2nd law defines an M_T (known as the linear harmonic oscillator, LHO) that is expressed by the equation of motion: $\xi'' + (k/m)\xi = 0$. If the force function is specified as $F = -k\xi + b\xi'$, then the 2nd law defines an M_T (known as the damped harmonic oscillator) expressed through the equation: $\xi'' - (b/m)\xi' + (k/m)\xi = 0$, and so on. The theory structure, defined by the position and momentum vectors related through Newton's 2nd law, thus lays down an indefinite number of possible M_T's, which are available for representing mechanical systems.

The class of M_T's that constitutes the theory is interpreted differently by each proponent of the SV. For instance Suppe (1989), who maintains a distinct understanding of the nature of a scientific theory, claims that a scientific theory is propounded as an abstraction and an idealization, and as such, a theory does not inform us about what does happen but only about what would happen under specified circumstances. He rejects van Fraassen's (1980, 1987) view that theories are "candidates for the direct representation of observable phenomena" and that empirical substructures, which are isomorphic to data models, are embedded in the models of the theory. According to Suppe (1989), a *TS* is defined by a small number of parameters abstracted from the phenomena thus defining the domain of a scientific theory. The latter consists of a class of ideal systems whose behaviour is described by a corresponding class of M_T's. An M_T represents a target physical system *P* by describing an ideal system *S*. It follows that the correspondence between *S* and *P* is counterfactual: *S* is what *P* would have been if *P* were influenced only by the selected parameters and were the idealized conditions imposed by the theory met (in Portides 2005, I argued that this understanding of scientific modeling could be augmented with a theory of idealization). Da Costa and French (1990, 2003) also reject van Fraassen's isomorphism condition but from a different perspective. They agree that theories can represent the phenomena directly, but they claim that actual scientific practices are better understood by imposing the relation of partial isomorphism, meaning isomorphism between partial structures, i.e., structures in which only some of its ordered n-tuples satisfy the sentences expressing the n-ary relations between the individuals concerned (da Costa and French 1990, 2003). Since a theory structure has an indefinite number of M_T's available for modeling a theory's domain, any version of the SV can always resort to problems of mathematical tractability when the conditions of isomorphism, or the like, are not met in actual scientific practice. In other words, just like the damped harmonic oscillator above can model the mass-spring system more accurately than the linear harmonic oscillator, one can imagine that an ultimate model of the theory can in principle be defined such that the limiting case of isomorphism can obtain.

Although little effort has been put, by the proponents of the SV, into explicating the nature of data models, with the only possible exceptions being Suppes (1962) and Suppe (1977, 1989), it seems that there is a general consensus about one thing: that M_D's are constructed by the use of all those ingredients involved in scientific theorizing that are not derivable from theory proper. Models of data, according to Suppes (1962), are structures in which the experimental data are refined by various processes that involve the experimental design procedures and the theories of experiment (empirical parameters, empirical laws, auxiliary theories, etc.). In order for the data models to stand in a less oblique relation to the models of the theory, as Suppe (1977, 102–109) points out, firstly experiments must be carried out in highly controlled and isolated circumstances. Secondly, various influencing factors that are known to influence the experimental data but which the theory does not account for must be accommodated by an appropriate conversion of the data into canonical form. This conversion-transliteration results in a structure that reflects the experimental data after several factors have been taken into account, e.g., experimental design and procedures, ceteris paribus conditions that are assumed to hold, the theories of experiment and auxiliary theories etc. Accordingly, the finished products (that Suppes dubbed 'models of data', and which van Fraassen calls 'appearances'), are mathematical structures that are linked to M_T's exclusively by mathematical mapping.

It is not imprecise to claim that the data models are constructed inter alia by lumping together all the auxiliary theories used in the application of a scientific theory. Suppe (1977, 225; 1989, 103–104) helps us understand how this is supposed to be done. He claims that in applying a theory to phenomena the data collected from the target physical system is converted by means of theories of experimental design and auxiliary theories into what the data would have been had the target system been the isolated ideal system that the corresponding M_T (and hence the theory) dictates it is. The result of this conversion is an M_D that describes how the data would have been under the appropriate idealized conditions.

How this is done is demonstrated by means of the familiar example of the simple pendulum from classical physics for which, admittedly, the SV provides an adequate reconstruction. It is widely held that in order for a theoretical model as the simple pendulum to represent accurately the respective target system, we must add several correction factors, since the motion of the pendulum bob dictated by the respective M_T (described by the equation of motion $\xi'' + (g/l)\sin\xi = 0$) has the following (idealized) characteristics: a mass-point bob supported by a massless inextensible cord of length l oscillates uniformly about an equilibrium point. If, for purposes of mathematical tractability, infinitesimal displacements are assumed, then the equation of motion reduces to that of the LHO: $\xi'' + (g/l)\xi = 0$. The solution to the latter equation yields a relation among the period T_o, the cord length l and the acceleration g due to the Earth's gravity. Knowledge of the cord length and the period allows one to solve for the acceleration of gravity: $g = 4\pi^2 l/T_o^2$. The experimental problem of determining g, therefore comes down to measuring l and T_o. Because of the idealized assumptions underlying the LHO equation, the latter does not describe the actual pendulum apparatus. Hence measurement of l and T will not yield an acceptable value for g. Nelson and Olsson (1986) show how the value T_o can be corrected by introducing the different correction factors into the equation of motion. One of their examples is this: since the pendulum experiment takes place in air, it is expected that by Archimedes' principle the weight of the bob will be reduced by the weight of the displaced air. Since under such circumstances the effective gravity is reduced, the period is increased. By using the auxiliary hypothesis of Archimedes' principle the correction to the period given in terms of the mass of the displaced air m_a is computed: $\Delta T = \frac{1}{2}(m_a/m)T_o$. Similarly by using other auxiliaries they compute the corrections to the period of all other known factors, e.g., a drag force auxiliary for correcting how the air resistance acts on the oscillating system, Hooke's law for correcting how the stretching of the wire affects the period of oscillation, etc.

The SV could offer a reconstruction of the process of introducing correction factors into the model, by considering these corrections as part of the construction of the data model. They are not literally corrections to T_o but are, in fact, corrections to the experimental value of the period such that the latter could be converted into what its value would have been had the idealized conditions imposed by the theory been met. Claiming that all these considerations enter into the construction of the data model is a reconstruction of actual scientific practice that aims in keeping the theory per se detached from all auxiliaries. Recently, da Costa and French (2003) propose that we reconstruct this practice by taking the data model to be a more restricted structure and to assume that some of the auxiliaries are lumped into a 'model of the phenomena'; the latter are understood to be intermediaries in the mathematical mapping relation between the theoretical and respective data models. Whatever the details of the latter reconstruction the fact remains that its main guiding principle is still a sharp distinction between M_T's and M_D's. Although such a reconstruction seems to be adequate in understanding scientific modeling for some theories (e.g., Classical Mechanics), I question whether we can adopt it in order to understand all kinds of scientific modeling in science. In particular we cannot adopt it in order to understand modeling that is guided by auxiliaries that cannot be viewed through the lens of the theory, as is quite often the case in the application of quantum mechanics.

3. The Liquid Drop Model of the Nuclear Structure. I argue against the adequacy of the SV reconstruction to illuminate modeling techniques that we encounter in the application of quantum mechanics, through the example of the liquid drop model of nuclear structure. In the 1930s there existed two conflicting hypotheses about the nuclear structure. The first hypothesis considered the nucleus as a collection of closely-coupled particles and only collective modes of nuclear motion were assumed (possible relative motions between the nucleons were ignored). This hypothesis underlies the construction of *strong interaction models*, such as the *liquid drop model*. The second hypothesis assumed that the nucleons moved in an average nuclear field in rather independent ways (collective modes of motion were ignored). This hypothesis underlies the construction of *independent particle models* such as the *single particle shell model* of nuclear structure. Interestingly enough these two kinds of models are constructed in very different ways and both ways can teach us about how theories get applied via scientific model construction (Portides 2006). For the purposes of my present argument I focus only on the former.

The liquid drop model (Moszkowski 1957; von Buttlar 1968) is based on the analogy that the mean free path of nucleons must be significantly small compared to the nuclear radius, just as the mean free path of molecules in a liquid drop is small compared to the radius of the drop. According to the model, because any energy acquired by a nucleon is quickly shared, nuclear excitations involve collective displacements of many nucleons. Thus the motions of individual nucleons are ignored and the nuclear wavefunction is entirely described in terms of the position of the nuclear surface. To set up the energy equation a series of idealizing classical assumptions take place such as: (1) The nucleus in its stable state has spherical shape. (2) For small deviations from sphericity, where the surface undergoes deformation oscillations at constant density, the surface tension of the nucleus acts as a restoring force. (3) The energy of the nucleus is the sum of the volume energy, surface energy and Coulomb energy and that, on the assumption of incompressibility, the volume energy is independent of the nuclear shape, the surface energy is least for spherical shape and increases with deviation from sphericity, and the Coulomb energy decreases with deviation from spherical symmetry. The result is a classical energy function for the collective motion, where $E(0)$ is the energy for spherically symmetric shape, C_λ are nuclear-deformation-resistance coefficients (which are classical coefficients that can be computed by elementary reasoning in geometric and electrostatic terms), the quantities B_λ are mass parameters, and $\alpha_{\lambda\mu}$ are deformation functions (that are treated as classical time-dependent spherical tensors):

$$H = E(0) + \sum_{\lambda}\sum_{\mu}\left(\tfrac{1}{2}B_\lambda|\dot{\alpha}_{\lambda\mu}|^2 + \tfrac{1}{2}C_\lambda|\alpha_{\lambda\mu}|^2\right). \quad (1)$$

At this stage the equation of motion is quantized by introducing momenta $\pi_{\lambda\mu}$, canonically conjugate to the $\alpha_{\lambda\mu}$, so that the Hamiltonian operator takes the form

$$H = E(0) + \sum_{\lambda}\sum_{\mu}\left(\frac{1}{2}\frac{|\pi_{\lambda\mu}|^2}{B_\lambda} + \frac{1}{2}C_\lambda|\alpha_{\lambda\mu}|^2\right). \quad (2)$$

Though the liquid drop model is what we would call a semiclassical model, it served, at a certain stage of the development of models of the nuclear structure, an explanatory function primarily in our understanding of nuclear fission and the electric quadrupole moments of nuclei, and thus was an essential ingredient of later more elaborate nuclear models. How could proponents of the SV accommodate this model into their conception of theories? A first option could be to classify it into the class of M_T's. This, however, would require a theoretically systematic set of rules by which to convert (and justify the conversion) the coefficients $\alpha_{\lambda\mu}$ to the canonically conjugate generalized momenta $\pi_{\lambda\mu}$. Such rules are not available. A second option could be to regard the liquid drop as a data model or a 'model of phenomena'. This of course would require that we have a respective M_T to contrast it to. But we do not, hence it would relate to the theory in some way for which the SV does not enlighten us. A third option could be to undervalue the model's importance and, more or less, altogether dismiss it. Da Costa and French (2003, 54–57) opt for the last. They suggest that such models could be understood as 'developmental' or that they belong to 'preliminary physics' and thus combat Morrison's (1999) argument by claiming that if they seem autonomous from theory they are only temporarily so. However, just because particular models do not fit underlying conceptions of 'representation', this is not sufficient reason to dismiss their significance by appealing to their short life duration or inaccuracy. Firstly, by doing so for the particular example we would be ignoring the role the liquid drop model played in the research program of nuclear models that culminated in the construction of the *unified model* of nuclear structure (see Portides 2006). But more importantly, the question that has to be addressed is whether such models *represent* their target physical systems and if they do, how do they do it. The liquid drop model, I claim, represents the nucleus albeit partially because it explains certain properties of nuclei (if this also means, following Morrison (1999), that the model is partially autonomous from theory it is a separate issue that I do not examine here).

To understand why, one must look at the guiding principles of the construction of the model. Before the proposal of an adequate nuclear model, with the development of mass-spectroscopy it was found that the nuclear mass is related to the masses of its constituent particles and to the nuclear binding energy, B: $M_{\text{nucl}} = ZM_p + NM_n - c^{-2}B$; a result that showed that nuclear binding energies are sufficiently large to affect nuclear mass. Another result about nuclear binding energies was their approximate constancy for different nuclei (except the lightest). Along with other experimental results, these led in 1935 to von Weizsäcker's semiempirical result about the binding energy of the nucleus. His semiempirical mass formula consists of five components, where Z is the proton number and

A is the total nucleon number

$$B = C_{\text{vol}}A - C_{\text{surf}}A^{2/3} - C_{\text{coul}}Z^2A^{-1/3} - C_{\text{sym}}(A - 2Z)^2A^{-1} - C_{\text{pair}}A^{3/4}\delta. \tag{3}$$

The first three terms are just of the form suggested by the classical analogy with the charged liquid drop (Assumption (3) above). If we consider an infinitely extendible liquid (of constant density) then the energy would be proportional to the number of particles. In the nuclear analogy this volume energy is the average energy due to saturated bonds between the nucleons, which increases B. But since the nucleus is finite, the nucleons near the surface should interact with fewer nucleons (i.e., there should be unsaturated bonds). Thus B should decrease by an amount proportional to the surface area, i.e., to $A^{2/3}$. Furthermore, the binding energy reduces more on account of the Coulomb repulsion between any two protons. This is inversely proportional to the distance between two protons, which turns out to be inversely proportional to $A^{1/3}$. At this point the classical analogy ceases to help, and the following two considerations suggest the addition of the last two terms in equation (3). The tendency of nuclei to have equal numbers of protons and neutrons N gives rise to the symmetry term for which $Z = N$ diminishes. Also a pairing term must be added in order to reproduce the special stability of even-even nuclei and the almost complete absence of stable odd-odd nuclei. Thus in the Weizsäcker formula, $\delta = +1$ for odd-odd nuclei, $\delta = 0$ for odd-nucleon nuclei, and $\delta = -1$ for even-even nuclei.

The liquid drop model is a valuable guide for *explaining* the Weizsäcker formula, despite the fact that more detailed models are required to relate the magnitudes of the various terms to the basic interactions between nucleons. The success of the formula, however, in yielding relatively accurate values and in reproducing all important nuclear trends, except for the lightest nuclei, can therefore be regarded as an indicator of the relative success of the model. One such success of the model is in providing the mechanism for explaining the phenomenon of nuclear fission of heavy elements, the discovery of which enhanced research into strong interaction models. Nuclear matter is assumed to be incompressible, just as a liquid almost is, but deformation is possible. If a spherical nucleus is deformed into an elongated shape the following things would happen. First the Coulomb repulsion is diminished because the average distance between protons increases. Second the surface energy increases because the surface area increases. These two changes, that have opposing effects on the magnitude of the binding energy, mean that heavy nuclei will demonstrate instability against deformation. This is so because the Coulomb energy increases with Z^2, whereas the surface energy increases with $A^{2/3}$, hence for large Z the Coulomb energy prevails. For light nuclei, on the other hand, the surface tension is more significant hence the spherical shape is the stable configuration. A deformation of a large nucleus, whether spontaneous or initiated by the capture of a particle, may therefore lead to a large deformation and subsequently to a split into two or more parts of comparable mass. The liquid drop model does not just offer this qualitative explanation but it also provides, to a first approximation, good quantitative results for fission.

Even though some important properties of the nucleus are not adequately accounted by the model (for example the special stability of the 'magic-number' nuclei, and fluctuations of the pairing energies), the primary purpose for discussing the liquid drop model is not to argue about its infallible predictive and elaborate explanatory power. It is to show that in the construction of a model there is constant interplay between theory, model and semiempirical results. In doing this I emphasize the primary role of the auxiliary Weizsäcker formula in the construction of the model. Auxiliaries such as this, that describe the properties of the target physical systems, in addition to being a guiding heuristic in constructing representational models, are the explanandum of the model and what the model must tie to the theory of quantum mechanics. Thus the liquid drop serves a twofold function. On the one hand it provides an explanation—however incomplete—for three of the terms of the Weizsäcker formula, thus it represents some of the factors that are responsible for such effects as nuclear fission, and on the other hand it connects the auxiliary to the theoretical assertions of quantum mechanics. It is hard to see how the sharp M_T/M_D distinction that the SV demands can be used to reconstruct this case.

In fact, the M_T/M_D distinction would obscure the fact that in many cases of actual scientific modeling practices if we do not have auxiliaries (such as the Weizsäcker formula) that describe the physical systems, we are not able to devise a representational model. Auxiliaries have a variety of functions, e.g., they guide the application of scientific theories. If their role was solely to correct the data models thus matching them to respective theoretical models and thus approximating the limiting case of isomorphism, then scientific theories would have limited applications since, as Cartwright (1983, 1999) has argued, the stock models (i.e., the tractable M_T's) of scientific theories are limited in number.

The kinds of auxiliary theories used in the application of scientific theories are not all of the same kind and neither do they function the same way nor are they related in the same manner to the theory. By lumping them all in the construction of data models (or models of the phenomena) that relate to the theoretical models only by mathematical mapping, the SV obscures their roles and functions. In particular it obscures the functions of those kinds of auxiliaries that are used when no bridge principles exist, in Cartwright's (1999) sense, that can licence the use of an M_T for the description of a particular physical system. In such cases, the use of auxiliary semiempirical hypotheses, like the Weizsäcker formula, that offer a description of the properties of a physical system in rather concrete terms, act both as heuristics for constructing a representational model and as connections of the model to the more abstract terms of the theory.

4. Conclusion. The case of the liquid drop model leads to the conclusion that the sharp distinction between M_T and M_D that the SV demands is not a necessary component of theoretical representation of phenomena. There exist, in actual scientific practice, representational models that are constructed in such ways that it is not possible to reconstruct them into the pair of M_T and M_D. The liquid drop model demonstrates such a case. Hence the SV does not adequately account for the relation between theory and scientific models. Hence either the mapping relation between M_T and M_D must be supplemented by other nonstructural relations that possibly hold between the theory and the auxiliaries employed, or the distinction between M_T and M_D as one that captures our full understanding of scientific representation must be abandoned.

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