9 Scientific Fictions as Rules of Inference

Mauricio Suárez[1]

1. FICTIONALISM IN THE PHILOSOPHY OF SCIENCE

Hans Vaihinger's philosophy of "as if" introduced fictionalism into philosophical discussions in the early years of the 20th century.[2] Vaihinger's thesis was radical: A knowledge worth pursuing is thoroughly infused by fictional assumptions. Vaihinger distinguished carefully fictions from hypotheses, and considered most of science and mathematics to engage shamelessly in the production, dissemination, and application of both. Hypotheses are directly verifiable by experience and their truth is tentatively granted. Fictions are, for Vaihinger, accounts of the world and its systems that not only are plainly and openly false, but knowingly so, yet remain indispensable in theorizing—in science and elsewhere. However the fictions employed in scientific reasoning are not of the same kind as those that appear in other areas of human endeavor. Vaihinger distinguished scientific fictions from other kinds of fictions (such as poetic, mythical, or religious fictions), and he understood the difference to be one of function. Virtuous fictions play a role in a particular kind of practical rationality in scientific theorizing, a kind of "means–end" rationality at the theoretical level. In Vaihinger's terminology, they are *expedient*.[3] These are the fictions that figure in the scientific enterprise, and among the most prominent throughout the history of science Vaihinger identified forces, electromagnetic "lines" of force, the atom, and the mathematical infinity, as well as some of the main constructs of differential analysis such as infinitesimal, point, line, surface, and space.

Vaihinger's work is unfortunately not sufficiently well known today, but he should appear to philosophers of science as an extremely contemporary figure. A recent brief paper by Arthur Fine brings Vaihinger back to the philosophical fore.[4] Fine notes that "Vaihinger's fictionalism and his "as if" are an effort to make us aware of the central role of model building, simulation, and related constructive techniques, in our various scientific practices and activities" (Fine, 1993, p. 16). There has been in the last decade or two a remarkable resurgence of interest in the topic of modeling, which emphasizes the essential role played by idealizations, contradictions, abstractions, and simulations in the practice of scientific modeling.[5] Vaihinger's work fits right in: His concern to emphasize the use of false or contradictory assumptions in building models of systems and their workings is of a piece with this whole body of literature. So too is his concern to appreciate the pragmatic virtues that these assumptions might bring to scientific reasoning. For instance, Vaihinger also distinguished between *fictions* (which involve internal contradictions, or inconsistencies) and what he called *semi-fictions* (which involve contradictions with experience).[6] We would nowadays refer to the former as contradictions, and claim that they are logically false, while calling the latter idealizations, which we would claim are empirically false. This distinction will be appealed to freely in the text, and instances of both types of fiction will be identified. But I will not be concerned very much with the fact that fictions in science tend to entail falsehood. Although Vaihinger emphasized the falsehood of scientific fictions, his main concern was with their cognitive function.[7] The main interest throughout this chapter is in shedding some light on the cognitive function of scientific fictions, regardless of their truth value. In particular I urge that expediency in inference is the main defining function of a scientific fiction. This chapter is a first attempt at an elaboration and defense of this inferential expediency of scientific fictions. It can be seen as part of a larger argument for taking the cognitive value of a scientific fiction to lie entirely in its function in inquiry, and to be fully independent of its truth value.

The modeling scholarship of the last decade or so has made a strong case for a version of Vaihinger's main thesis: The use of fictions is as ubiquitous in scientific narratives and practice as in any other human endeavor, including literature and art; and scientists have demonstrated throughout history a capacity to create, develop, and use fictions for their own purposes that compares with that of any writers or artists. This is why this assumption will not be defended here, but will rather be taken as a matter of fact, and a starting point. The aim is instead to explore a philosophical issue that is key to the success of the philosophy of modeling movement, and to Vaihinger's conception in particular. This is the fundamental distinction between what Vaihinger identified as *scientific* fictions and other kinds of fictions.[8] It is this distinction that lies at the heart of the thesis that fictions are of particular use to science, or that science employs them in a particularly useful way. Without an elaboration and defense of the expediency that characterizes scientific fictions the main thesis, however true, would bear little content—and it would shed little insight on scientific practice.

2. FICTIONS IN THE HISTORY OF SCIENCE: TWO EXAMPLES

In order to characterize scientific fictions we may begin with some illustrious examples of productive use of fictions in the history of science, the ether theories and the models of the atom at the turn of the century. They are interesting in complementary ways. In the ether case the use in mathematical and experimental inference of what we nowadays take to be a fictitious entity was extremely productive and long-lasting—although convictions as to its reality differed and wavered considerably. The case of atomic models illustrates another possibility: a model of a putatively real entity that was never taken very seriously—the model was never assumed to be other than a fictional description of the entity—and was consequently short-lived, yet turned out to be extraordinarily useful as a heuristics for developing new, more detailed and powerful models. Therefore these cases illustrate the difference between representations of fictional entities and fictive representations of real entities; they also illustrate the difference between long-lasting formal tools and short-lived concrete models. Yet Vaihinger's thesis holds in both cases, because fictions are involved in an essential way, one way or another. The description that follows will emphasize some features that in both cases seem relevant to the distinction between scientific and nonscientific fictions. (Ultimately the philosophical discussion will focus on a further example from quantum theory.)

Throughout the 19th century the ether was taken to be the putative carrier of the light waves, and stellar aberration phenomena had established that the earth must have been in motion with respect to it. The most sophisticated mathematical theories of the ether were developed in Britain in the wake of Maxwell's theory of electromagnetism. Maxwell developed his theory in the years 1856 to 1873, the year of publication of his *Treatise on Electricity and Magnetism*.[9] The theory went roughly through three phases corresponding to the publication of "On Faraday's Lines of Force" (1856), "On Physical Lines of Force" (1861), and finally "A Dynamical Theory of the Electromagnetic Field" (1865) and the *Treatise*. In each step Maxwell's theoretical model acquires a higher degree of abstraction from the mechanical model of a luminiferous ether. The central concept throughout is that of field energy: the only concept toward which Maxwell shows an increasingly firmer ontological commitment over the years. By contrast, Maxwell's reluctance to accept the ontological implication of the existence of the mechanical ether is strong and explicit from the beginning. As Morrison has pointed out, in drawing the analogies in "On Faraday's Lines of Force" between electrostatics, current electricity and magnetism with the motion of an incompressible fluid, this fluid "was not even considered [by Maxwell] a hypothetical entity—it was purely fictional" (Morrison, 2001, p. 65). And later on as he developed a clearer view of what have come to be known as Maxwell's equations, Maxwell remained resolutely skeptical regarding the existence of the ether. The mechanical models of the ether were gradually stripped of ontological content as the dynamical equations were developed, yet these mechanical models remained indispensable to scientific theorizing, according to Maxwell, "as heuristic devices, or at best, descriptions of what nature might be like" (Morrison, 2001). In other words, the ether remained for Maxwell a fiction—with an essentially heuristic function in the development of increasingly sophisticated mathematical models that captured the empirical phenomena. This was its scientific virtue—to be a guide in the construction of more detailed, explanatory or predictive models of the phenomena.[10]

The Maxwellian tradition was continued among theoreticians in Cambridge, mainly through the work of Charles Niven and Joseph Larmor. Andrew Warwick has written a scholarly and detailed history of the Cambridge couching in electromagnetic theory from the very first lectures that Maxwell himself gave there on publication of his *Treatise* until the final demise of ether-based theories in favor of Einstein's theory in the 1920s (Warwick, 2003). What is remarkable about this history is the role that the ether played as basis for the application of electromagnetic theory to all kinds of practical and experimental problems. Although the Cambridge Maxwellians professed a belief in the ether (and thus, unlike Maxwell himself, took the ether to be a hypothesis rather than a fiction in Vaihinger's terms), they nonetheless employed the ether as a mental construction that allowed them to apply electromagnetic theory in a much simpler and straightforward way. The critical difference is that the ether theories allow for electromagnetic effects to be present all over as due almost entirely to the flow of energy "in the ether," while action-at-a-distance theories supposed that electromagnetic effects only occurred within conducting and dielectric material, not at all in empty space. As Warwick puts it, "the solution of problems using the field-theoretic approach therefore required very careful consideration of the electromagnetic action and boundary conditions applicable at or near the surface of conductors" (Warwick, 2003, p. 329). Confidence in the applicability of the equations is required for carrying out these calculations, but a belief in the existence of the ether is not strictly required. In fact, convictions as to the existence of the ether wavered a great deal, and differed between its different proponents.[11]

In other words, the fiction—or hypothesis—of the ether has for both Maxwell and Larmor a powerful positive heuristic for further research, giving guidance on how to generate more detailed models of the phenomena, allowing quick and effective inference of experimental and practical results that can then be readily checked against experience. It provides an excellent tool for the calculation of effects and the regimentation of knowledge. It also provides what Mary Hesse aptly called neutral analogies—unproved similarities between the ether models and real phenomena that call for exploration and investigation.[12] But the reality of the ether itself is not required for inference, taxonomy, or analogy. The ether provides a mental model of great expediency and ease of calculation, but it can well remain "a mere figment of the mind, not a fact of nature" (Maxwell, on referring to disturbances of the ether, as quoted in Morrison, 2000, p. 96).

The second example is even more startling in the fictitious nature of the description employed: J. J. Thomson's *plum pudding* model of the atom. Although the entity described is by no means considered a fiction by our present lights, the description of the entity given in the model in question certainly is fictional and in ways interesting to our present purposes.[13] The idea that electric conductivity phenomena may be underpinned by the fundamentally asymmetric nature of the distribution of positive and negative charges in atoms actually goes back to Lord Kelvin, who proposed it in his President's Address to the Royal Society in 1893. In fact, Kelvin had already proposed something very similar to a plum-pudding model for the atom as part of his defense that Crookes's experiments on cathode rays established that they were negatively charged particles. Thus Thomson did not "make up" the plum pudding model, but was following in Kelvin's footsteps in proposing and developing it in the years between 1897 and 1910. The model was part and parcel of the strategy followed by both Kelvin and Thomson in trying to prove the particulate nature of cathode rays, and the fundamental electrical asymmetry of conductivity phenomena.

According to the plum pudding model the atom is a roughly spherical *sponge* formed by evenly distributed positive charge in which minute negatively charged particles ("electrons") are inserted, like raisins in a traditional British Christmas cake. The model had the great advantage of explaining ionization phenomena, whereby negative charged particles are bounced off atoms by collisions with other atoms, creating electric currents. It also explained the production of cathode rays and sustained Kelvin's and Thomson's favored interpretation of them as negatively charged particles. But most importantly, the plum pudding model was a powerful heuristics in the development and application of Thomson's "working hypothesis" between 1897 and 1910 for the experimental inquiry into electrical phenomena in gases, namely, "that the negatively charged corpuscle is universal and fundamental, ionization results from the dissociation of a corpuscle from an atom, and electrical currents in gases at low pressures consist primarily of the migration of corpuscles" (Smith, 2004, p. 23).

As is well known, the plum-pudding model was refuted by the experiments performed in 1909 by one of Ernst Rutherford's collaborators in Manchester, Hans Geiger, together with a student, Ernst Marsden.[14] In these experiments thin foils of gold were bombarded with alpha particles (essentially a couple of protons and neutrons bound together as in helium nuclei) and a significant proportion of recoil was observed. (On the order of 1 in 20,000 alpha particles was deflected by an average angle of 90 degrees.) The effect is sometimes known as Rutherford scattering, and was effectively employed by Rutherford[15] in order to reject the plum pudding model because the electrons in the atom are too small and light to produce the recoil effect, while the diffuse "sponge" would be porous to the massive and energetic alpha particles. Hence Rutherford advanced his hypothesis of the existence of a massive and discrete nucleus at the center of empty space, orbited by minute electrons, in order to explain the scattering effect with the experimentally observed probability.

It would be uncharitable, however, to charge Thomson with the belief that his plum pudding model was a complete and true description of the atom (see Smith, 2004, particularly p. 25). Instead the model served three different heuristic functions: (i) it allowed Kelvin and Thomson to argue for the particulate as opposed to wave-like nature of cathode rays (electrons), a fact that Thomson's 1897–1899 papers were instrumental in establishing universally; (ii) it justified and provided motivation for Thomson's "working hypothesis" regarding conductivity in gases during the 1897–1910 years, which in turn led to many important experimental results and conclusions—including among others the establishment of the existence of electrons themselves; and (iii) it helped Rutherford target the experimental evidence available toward the missing or defective assumptions in the previous models, thus enabling him to discover the existence of the nucleus. (As is well known, Rutherford's "planetary" model was in turn superseded by Bohr's early quantum model [1913], which hypothesized spontaneous quantum transitions between electron orbitals, and hence a nonclassical structure of quantum energy levels within the atom.)

It is hard to overestimate the importance of the plum pudding model in helping focus inference making in all these three different areas. The historical facts rather point out that these three crucial and critical developments and discoveries in the history of modern physics could hardly have come about without the expediency in reasoning provided by the plum pudding model, no matter how fictitious. The model served an essential pragmatic purpose in generating quick and expedient inference at the theoretical level, and then in turn from the theoretical to the experimental level. It articulated a space of reasons, a background of assumptions against which the participants in the debates could sustain their arguments for and against these three hypotheses. As Thomson himself put it: "My object has been to show how the various phenomena exhibited when electricity passes through gases can be coordinated by this conception."[16]

3. FICTIONS IN CONTEMPORARY PHYSICS

The use of fictions is not confined to past or failed science. Let us now consider a couple of typical instances of fictions within contemporary successful science. First, an example from astrophysics is briefly discussed: the Vaihingerian semi-fictions involved in models of stellar structure. Then we turn to a striking case of Vaihingerian full fiction: the models of the theory of quantum measurement. Once again these case studies emphasize the inferential function of the fictional assumptions involved in both models.

3.1. The Semi-Fiction of a Star

Models of stellar structure in astrophysics provide a description of the inner workings of a star; in particular the fuel burning processes (nuclear fusion) that turn hydrogen into helium and generate the star radiation, while accounting for the star life cycle and evolution. These models match up the observational quantities of a star, which mainly pertain to the properties of its photosphere, that is, the outermost layer of the star. The observable quantities of stars include: (i) its luminosity (energy radiated per unit time, which depends upon apparent brightness and distance), (ii) its surface temperature (the temperature of the photosphere), (iii) the photosphere's chemical composition, and in rare cases (binary stars) the mass of the star. The models allow us to infer conclusions regarding the internal workings of a star on the basis of these observational quantities. Their cognitive value depends upon the reach, power, and ease of calculation of such inferences.

These models make at least four assumptions that are widely assumed to contradict either the physics of matter and radiation, the physical conditions of the interstellar medium, or both. Hence the models are knowingly strictly speaking false of real stars. I won't discuss them here in detail, but will just briefly discuss these four assumptions (see, e.g., Prialnik, 2000, pp. 6–8. Also Tayler, 1970). First, models of stellar structure assume that a star is an isolated bubble of gas; that is, they assume that a star is a physically closed system—no external forces (gravitational or electromagnetic) intervene. The only forces that can affect the internal structure of a star are consequently assumed to be the star's internal gravitational forces due to the rotational movement of the gas, and the forces that arise out of the nuclear burning inside the star. As far as external gravitational forces go, the assumption of isolation is not entirely unrealistic: A star is a dense concentration of hydrogen in the interstellar medium, and the nearest such concentration can be on average as far as 4.3 light years away (this is roughly the distance between the sun and Alpha Centauri, the star nearest to our sun). So external gravitational forces are bound to be tiny, and therefore negligible for all practical purposes. But the assumption of isolation is physically quite incorrect: The insterstellar medium is not empty space but is replete with irregularly dense (although on average much lighter) gas, mainly hydrogen, which in the surroundings of the star is gravitationally attracted into the star, while radiatively repelled. In other words, isolation suggests that the physical boundaries of a star are sharp, when as a matter of fact they are rather imprecise.

Second, stellar structure models assume that all stars possess identical chemical composition, namely, the sun's: 70% hydrogen and 30% helium. The presence of heavier elements has been confirmed in every star, but it is essentially irrelevant to the structure of the star in most hydrogen-burning models, so it is entirely neglected. In these models, a small difference in the proportion of hydrogen and helium in the initial composition of a star can have an important effect in its evolutionary life (it can particularly affect its luminosity and lifetime), but because the models have other parameters to adjust for these observable quantities, these differences are essentially ignored, and a blanket assumption is made.

Third, it is assumed that the shape of the star is spherically symmetrical throughout its life. Yet both internal rotational forces and magnetic forces are well-known causes of departures from spherical symmetry. Hence this assumption rules out such internal forces, which as a matter of fact are known to be large. Finally, a star is assumed to permanently stay in a state of thermal equilibrium, whereby the temperature of the gas is identical to the temperature of the radiation emitted (see Prialnik, 2000, p. 16, Chapters 3 and 5). The implication of this assumption is that radiation provides the only form of energy transfer within a star. It also follows that the energy spectrum of a star is a black-body spectrum. Yet, massive convective fluxes are known to occur in periods of heavy hydrogen burning within the star. So the assumption is that such convective forces have no impact on the temperature distribution inside the star. Because the inside of a star is entirely theoretical, the only justification for this assumption is the model's ability to correctly match the observable quantities of the photosphere.

These assumptions are not discussed any further here. I merely emphasize that they are all known to be empirically false, or at any rate unproven, yet in combination they afford a huge improvement in the expediency of the inferences that can be drawn from the models to the observable quantities, and between such quantities Their effect on the accuracy of predictions from the model cancels out, and is therefore negligible in comparison. In other words, the stars of contemporary astrophysics' models are Vaihingerian semi-fictions whose justification lies entirely in the great ease and expediency in inference making that they generate.[17]

3.2. The Full Fiction of Quantum Measurement

An example from present-day theoretical science is next discussed that exhibits the characteristic expediency of fictions in a prominent and illustrative manner. The model that quantum theory provides for measurement interactions is intended as a representation of a physical process—an image of a physical process provided by a highly formal and mathematical model. It might seem surprising that I am characterizing it as a fiction, because the formal machinery of quantum theory is so solidly entrenched among practicing physicists. And yet, its fictional character has actually been proved as a mathematical theorem—known as the insolubility proof of the measurement problem. First the basic assumptions underlying the model are discussed (sec. 3.2.1), and then reasons are provided for considering it a semi-fiction in Vaihinger's sense (sec. 3.2.2), a maximal semi-fiction, and a fully fledged fiction (sec. 3.2.3). Sections 3.2.1 and 3.2.2 are technically a little demanding (even though the most demanding technicalities have been confined to an appendix), and the uninformed reader may well want to skip them without loss.

3.2.1. The Quantum Theoretical Model of Measurement

Quantum theory provides an abstract mathematical model of physical interaction between a microscopic quantum object and a macroscopic device designed to test the state of the object. The theory, as first formulated by von Neumann (1932), ascribes a quantum state to the measuring device, and treats the interaction as a quantum interaction, that is, one that obeys the Schrödinger equation.

Suppose the initial state of the system is $W_o = \sum_n p_n P[\nu_n]$, where each ν_n may be expressed as a linear combination of eigenstates of the observable O of the system that we are interested in (i.e., $\nu_n = \Sigma\, c_i\, \phi_i$); and that the initial state of the measuring device is $W_a = \Sigma_n\, w_n\, P[\gamma_m]$. Throughout the chapter I refer to the observable represented by the operator $I \otimes A$, as well as that represented by A, as the pointer position observable. The eigenvalues of this observable are the set $\{\mu_n\}$. As the interaction between the object system and the measuring device is governed by the Schrödinger equation, there must exist a unitary operator U that takes the initial state of the composite system (object system + measuring device) into its final state at the completion of the interaction, as follows: $W_o \otimes W_a \rightarrow U\,(W_o \otimes W_a\,)\,U^{-1}$. (For further details of the interaction formalism, see Appendix 1.)

3.2.2. The Problem of Measurement

The intuition behind the so-called "problem of measurement" is easy enough to state. Take a system in an arbitrary superposition $\nu_n = \Sigma\, c_i\, \phi_i$. Then, due to the linearity of the Schrödinger equation, at the conclusion of an ideal measurement interaction with a measurement apparatus in any pure state, the composite (system + device) will be in a superposition of eigenstates of the pointer position observable. And according to the so-called eigenstate–eigenvalue link (e/e link), the pointer position observable cannot have a value in this state, because it is not in an eigenstate of the relevant observable. But surely quantum measurements do have some values—that is, they have some value or other. Hence the quantum theory of measurement fails to describe real quantum measurements, and the model expresses a fiction—to be exact, a *semi-fiction* in the terminology of Vaihinger, because it contradicts empirical reality.

3.2.3. The Model is a Maximal Semi-Fiction

Let us refer to a model as a maximal semi-fiction in Vahinger's sense if every assumption in the model can be shown to be false. Then the quantum theoretical model of measurements is a Vahingerian maximal semi-fiction.

All the assumptions required for a quantum theoretical model of measurements are strictly speaking false. In addition to the eigenstate–eigenvalue link and the assumption that the Schrödinger equation is the full dynamical description of events, there are two formal conditions that are required to derive the problem of measurement. I have elsewhere referred to them as the *transfer of probability condition* or (TPC), and the *occurrence of outcomes condition*, or (OOC). (They are both described formally in Appendix 2.) Informally, (TPC) states that the probability distribution over the eigenvalues of the initial object system should be reproduced as the probability distribution of the pointer position observable. (OOC) by contrast states that the final state of the composite is a mixture over states in which the pointer position observable takes a particular value or other with probability one, and is often thought to be inspired by the eigenstate–eigenvalue link.

(TPC) is strictly speaking false on at least two counts. First, it assumes that whether interactions are measurements is an all-or-nothing affair that does not depend on the actual initial state of the system to be measured at a particular time, but on all the possible states that the object may have had in accordance with the theory. This is hardly satisfied by any real measurement we know. For instance, in setting up a localization measurement of the position of an electron in the laboratory, we do not assume that the device should be able to discern a position outside the laboratory walls, even if it is theoretically possible that the particle's position be infinitely far away from us. All real measurement devices are built in accordance to similar assumptions about the *physically* possible, as opposed to merely theoretically possible, states of the object system, on account of the particular conditions at hand. So real measurement devices do not strictly speaking ever fulfill (TPC).

Second, (TPC) appears to require measurements to be ideal in the technical sense of correlating one-to-one the initial states of the object system with states of the composite at the end of the interaction. However, many real measurements are not ideal in this sense. Most measurement apparatuses make mistakes, and no matter how much we may try to fine-tune our interaction Hamiltonian, we are likely in reality to depart from perfect correlation. So again, in most cases of real measurements (TPC) will not apply.

Let us now turn to (OOC). This is also strictly speaking false, because it assumes that the measuring device can only "point" to the eigenvalue of the pointer position observable that has probability one in the final state that results at the end of the interaction. But we can see that this assumption is false in most measurement interactions with quantum objects in mixed states where outcomes are produced, and pointers "point" in spite of the probabilistic nature of the transitions.

Finally, the application of the Schrödinger equation in this setup is also strictly speaking false because it implies the assumption that all quantum systems, not only composite systems involving measuring devices, are closed systems. It assumes that the quantum Hamiltonian can transform pure states into pure states, or mixtures into mixtures, but never a pure state into a mixture or vice versa. In reality, all systems are open and subject to a degree of state shift due to interaction with the environment and background noise—this phenomenon is known as decoherence.

3.2.4. The Model Is a Full Fiction

But in fact the insolubility proof of the quantum measurement problem shows that these three premises (together with a fourth premise named RUE, which I have ignored here) are inconsistent under the standard interpretation of quantum observables, the so-called eigenstate-eigenvalue link, or e/e link.[18] Hence the model is not only empirically false, and maximally so, but it turns out to be *necessarily* false, because it is internally incoherent. In Vaihinger's terminology, the quantum theoretical model of measurements is a *fully fledged scientific fiction*.

3.2.5. The Model Is a Scientific Fiction

The main feature of the model, shared with most theoretical models, is its inferential capacity. Once we understand how the model works we are in a position to draw inferences regarding the typical final state of a composite (object + measuring device) after the interaction. From this state we can further infer the possible values of the pointer position observable of the measuring device at the conclusion of the interaction (as long as the final state has a particular form that allows us to do just that). And from this inference we finally come to understand that there is an inconsistency in the account, which in turn leads us to consider which among the assumptions might be false.

Similarly, we have a large array of applications of measurement theory to different cases of physical interactions at the quantum level, each of them relaxing different assumptions of the model. For example, by relaxing the (e/e link) we have models within the modal interpretation of quantum mechanics; by relaxing the assumption of Schrödinger evolution of the composite we derive stochastic reduction and quantum state diffusion models; by relaxing the (OOC) assumption we obtain statistical interpretations of the measurement interaction, and hidden variable models. Finally, relaxing (TPC) allows us to encompass and develop models of highly nonideal interactions, such as destructive measurements.[19]

As in the previous example, the fictitious entity or process—the *ether* described by ether theories, the atom as plum-pudding, the internal structure of stars, measurement interactions as described by the quantum model—has in the appropriate formal model the capacity to generate various inferences to experimental or practical results, some of which can then be tested against experience. It is not the fiction itself that is in the first instance under experimental test, but the results of inferences that the fiction licences in appropriate formal frameworks, or in conjunction with further assumptions and background theory. In all these cases the inferences would either be arbitrary or impossible to even draw without the supposition of the fiction in the first instance. The fictitious entities or processes articulate a framework for quick and expedient inference-making that would be either impossible or arbitrary otherwise.

4. A SUBSTITUTIVE FUNCTIONAL ACCOUNT OF SCIENTIFIC FICTIONS

On the account defended here the hallmark of scientific fiction is *expediency in inference*. Note that this is not equivalent to the claim that the fictions employed in art and literature, unlike those from science, do not posses a capacity to generate useful (imaginative, pleasant, interesting) inferences. It is obvious that literary and artistic fiction can and must serve that purpose too. But expediency is not generally considered a virtue. To the contrary, it is often derided for good literary fiction. Nor is it ever required in such cases that the conclusion of our inferences be at least in principle testable against experience. There is thus a double norm that rules the use of fictions in science in comparison with nonscientific fictions. First, scientific fictions will be judged by their capacity to allow expedient inference-making. Second, at least some of the conclusions arrived at by means of such inferences will be taken to be empirically testable at least in principle. Most fictional assumptions in science will possess both functional virtues. By contrast, the fictions of art and literature can at best share in the first kind of virtue, but they need not even do so in order to fulfill their proper aesthetic function.

So how do these "fictitious" representations in science work? There is by now a large literature on the topic of representation, particularly as applied to artistic or pictorial representation. A comparison with such theories will be illustrative. The use of fictions in science seems to share some elements in common with Gombrich's substitutive account of fictions in art, and his account of pictorial representation more generally.[20] On this account, the function of pictures is to cognitively replace the objects that they depict—the replacement has a cognitive function in the sense that it allows surrogate reasoning. In reasoning about the properties of the picture, we may be able to infer properties of the object depicted. Gombrich employs the analogy of a hobbyhorse, which children play with in a similar substitutive fashion. In this example, the replacement is not merely cognitive, but also of a practical nature (often missing in the painting and in the scientific case), so actions can be performed around the hobbyhorse that would be performed around a real horse. In these activities children can sometimes lose track of the fictional nature of the entity—in fact there is a sense in which for it to perform its function correctly, it is essential that the fictional nature of the entity be in some ways suppressed. Although in Gombrich's substitutive account of representation we are not required to gain the (false) belief that the fictitious entity itself exists,[21] it seems that we are required to display at least some attitudes toward the fiction that we would display toward the real entity. In the hobbyhorse case this "pretence" attitudinal set includes practical action; in the painting case it merely includes cognitive factors.

Something very similar operates in the case of scientific fictional representation. What we do—what scientists do—when employing a fiction for scientific purposes—what Maxwell does in employing the ether, Thomson in employing the plum pudding model, or quantum physicists in applying quantum measurement theory—is to substitute the real process (with all its complications, disturbing factors, and exogenous causes) with a simpler, streamlined, and coarser-grained fictional account (one where all the factors and causes are fully and carefully identified), which is more expedient in the practice of reasoning and inference-making. We then go on to investigate the properties of the substitute rather than the real process.[22] It will be typical for many scientists engaged in that process to lose track of the fact that the entities invoked are fictitious. This is as it should be on a substitutive account, because the representational success of the model depends on its success in generating the same set of cognitive attitudes toward it that scientists would exhibit toward the entity modeled.[23] The attitudes of Larmor and Trouton toward Maxwellian ether-based electromagnetism just reflect this: Although there was never any experimental confirmation of the ether (and Larmor himself thought such confirmation was made impossible by the theory itself—i.e., by the ether-fiction itself), a realist attitude toward the ether assumption was a powerful heuristic in applying the theory to the most diverse phenomena. But although a realist cognitive attitude will be typical, a belief in the fiction is not necessary in order to operate the model successfully—we already saw that Maxwell himself displayed a much more cautious attitude toward the ontological import of the ether.

And *mutatis mutandis* in the quantum measurement case: To model quantum measurements in this way involves the cognitive attitude toward the model that we would adopt if confronted with real measurement processes. Thus it becomes possible to draw inferences regarding the real outcomes of real measurements from the model. But a belief that real quantum measurement interactions fully obey the formal assumptions is not required for such a cognitive attitude, which can be displayed simultaneously with a belief in the fictitious character of the entities or processes involved. (In fact, such a belief is, in the measurement case, impossible on pain of inconsistency and irrationality—as is shown by the insolubility proofs.) Thus the cognitive attitude that is needed to apply and use scientific fictions is pragmatically indistinguishable from belief, but it is *not* belief.

5. REPRESENTATION AND FICTION-BASED INFERENCE: AGAINST SIMILARITY AND ISOMORPHISM ACCOUNTS

Many of the most highly theoretical and mathematical models employed by scientists either involve fictional assumptions in their representations of real systems, or otherwise they refer, or purport to refer, to fictitious entities or processes. The representational character of these models can be explained roughly along the lines of a substitutive model of pictorial representation, which explains why the main cognitive function of these models is surrogate reasoning regarding its objects. This requires a "realist" attitude toward the model only in the sense of surrogate reasoning and inference, and as a powerful heuristic for further research. It does not require the belief that the model is an accurate representation nor that the entities described in the model are in fact real, and in fact it often will be inconsistent with such a belief.

In this final section I argue that this representational function of fictitious models in science is best understood by reference to a broadly construed "inferential" conception of scientific representation, such as the one proposed in Suárez (2004b). On this conception we can say of a model A that it represents an entity, system, or process B in case (i) the representational force of A is B, and (ii) A allows competent and informed agents to draw specific inferences regarding B. A virtue of this account is that it presupposes no relation of reference or denotation between A and B. The notion of representational force is defined so that it is fulfilled by any attempt at reference or denotation, however unsuccessful, that accords to the social practices and norms conventionally adopted in the use of such representational force. Also the notion of "inferential capacity" is fulfilled by any model that has sufficient internal structure to permit inferences regarding its "target," regardless of whether it denotes it, or indeed regardless of whether it is intended to denote it.[24]

One of the advantages that I have claimed for this account is its ability to provide the most natural account of fictional representation.[25] On this account there is no fundamental distinction in kind between a representation of a real entity or process, and a representation of a fictional entity (other than the obvious one of the existence of the entity so represented). Both are representations in virtue of fulfilling exactly the same conditions, and the nature of the representation is the same in both cases. Recall that according to this model there can be representation without reference: The existence of the target B is not required for conditions (i) and (ii) to obtain. In such cases we shall want to ask what the scientific interest of the inferences carried out under (ii) might be—and in most cases there will be inferences to true conclusions regarding observable aspects of the phenomena. Hence ether models allow a good deal of accurate predictions regarding the optical properties of light, and the plum pudding model allows, as we already saw, plenty of new and interesting predictions regarding atomic observed phenomena; stellar structure models allow us to predict the correlations between the observable surface properties of the star, and so on.

In both the ether-based theories and the atom models cases, conditions (i) and (ii) are fulfilled. Maxwell's theory was widely accepted to represent the electromagnetic configuration of an all-pervading medium capable of transmitting energy. As we saw, this was accepted by Maxwell himself, in spite of his rather skeptical views on the existence of the ether itself. The remarkable subsequent Cambridge scholarship in applying electromagnetic theory described in Warwick's book demonstrates that condition (ii) is also satisfied. Huge amounts of effort, time, and energy are spent in the task to determine the inferential consequences of the ether models. Similarly, the plum pudding model is a model of atomic structure—and this is its representational target. Its empirical refutation by Rutherford shows conclusively that condition (ii) is also satisfied—because it shows that it is possible to test experimentally some of its consequences.

Stellar structure models satisfy (i) and (ii) trivially, because they represent real stars and allow very efficiently for inference regarding some of their properties. The quantum theoretical model of measurement interactions satisfies both conditions too—in spite of the internal inconsistency revealed by the insolubility proof. First, nobody doubts that it is a model, or representation, of measurement interactions at the quantum level—and second, condition (ii) is also fulfilled by the diverse applications (which I mentioned in section 2) of different combinations of assumptions from the quantum formalism in the different interpretations of quantum mechanics.

In addition, the inferential conception explains the substitutional character of fictive representations in science that I described in the previous section. The inferential conception denies that substitution is the essential constituent relation of representation, because it claims that no relation between A and B is *required* for representation. Hence it denies that "A is a substitute for B" is necessary and sufficient for A to represent B. However, the inferential account accepts that substitution *à la* Gombrich can be a means of the representational relation.[26] That is, it accepts that this might be the mechanism or relation employed by scientists in surrogate reasoning about B on the basis of A.[27] It thus explains why substitution plays a representational role in these cases.

The inferential conception was proposed in response to the deficiencies of other proposals for understanding scientific representation, namely, the isomorphism and similarity accounts.[28] I believe we have here yet one more reason to adopt it in the face of its competitors, because neither isomorphism nor similarity can provide a similar explanation of the substitutional character of fictive representation in science. Take first the case of what we may call *fictional representation*, that is, representation of a nonexistent entity, such as the case of the ether. According to the isomorphism account, A can only represent B if they share their structure. But in the case of fictional representation this is either false or an empty truism, for it seems impossible to ascribe structure to a nonexistent entity. If the ether does not exist it can not possess any real structure, so isomorphism can not obtain. There might arguably be also a sense in which the ether (a fictional entity) can be ascribed "fictional" structure, but in this sense it can not fail to have the structure that the theory ascribes to it, because it is fully defined by the theory. This points out a significant difference between fictional representations in science and elsewhere: The (fictional) properties of fictional entities represented by scientific models are implicitly defined by the models themselves, which need not always be the case with fictional representation in art or everyday life (for instance, some pictures of Santa Claus may be said to *misrepresent* him).

The same argument seems to apply straightforwardly to the similarity case. Suppose that everything there is about representation in science can be understood through the similarity account; that is, suppose that it were true that A represents B if and only if A and B are similar. Then if similarity requires the sharing of actual properties between A and B, there can be no "fictional" representation in science because B lacks any real properties. We cannot represent the ether by means of models that share actual properties with the ether if there is no ether. If on the other hand it is permissible to ascribe fictional properties to fictional objects and speak of a similarity between a real and a fictional object in virtue of a (fictional) sharing of actual properties—or an actual sharing of fictional ones—then similarity is automatic in cases of the fictions employed by science. It is built into the definition of the entity represented by the theoretical model that it (fictionally) has the properties ascribed to it in this model.

Now let us take the rather different case of the plum pudding model of the atom. What we have here is arguably a very different case of misrepresentation by a deficient model of a real entity *simpliciter*. Let us refer to this type of misrepresentation as *fictive* representation. The similarity conception fares a bit better here because it can be used to characterize the degree and respects in which the model differs from the entity modeled. (Version of the isomorphism conception can arguably do this too.) However, these conceptions can crucially not *explain* the heuristic power of the model, which seems by and large unrelated to any actual similarity or isomorphism between representational sources and targets. Of the three respects in which the model acts a heuristic guide to research (see section 2) these conceptions can only account for the third: Rutherford's experimental refutation of the model. The other two respects in which the model proved heuristically powerful turned out to have nothing to do with any similarities between plum puddings and atoms, nor any isomorphisms between the mathematical structure of plum puddings and that of atoms.[29]

Mutatis mutandis, on either account, for the case of quantum measurement interactions. Whether there are genuine physical interactions between microscopic entities and measurement devices might turn out to be a question of interpretation of the theory (in some versions of the many worlds or many minds theories the notion of genuine physical interaction arguably fails to play a role). In any case, similarity and isomorphism will not shed much light on the heuristic power of a fictional representation of a nonexistent process, nor on the fictive representation (i.e., misrepresentation) of a real one. These practices of fictive and fictional representation may at best be accommodated within these conceptions, but the heuristic value associated with such practices cannot be explained.

Yet in the inferential account, representation is neither false nor trivial in any of these cases. This is straightforward in cases of fictive representation. But then take the harder cases of fictional representation, such as Maxwell's mechanical ether. In the inferential account, representational force could have failed to obtain (and indeed in the present-day, post-Einstein understanding of classical electromagnetism, this theory is no longer intended to represent features of the ether), and the models could have been mathematically so complex as to be completely useless for inference-making and surrogate reasoning—this would be the case for instance if the equations were not analytically solvable. Hence on the inferential conception the substitutive use of the virtuous fictional entities employed in science is a genuine achievement, which requires huge creativity, deep knowledge of the science, and a considerable cognitive ability in the use and development of sophisticated mathematical models.

6. CONCLUSIONS

The substitutive character of the fictions employed in science is best understood by means of an inferential conception of scientific representation. Although cases of fictional and fictive representation may be accommodated within the similarity or isomorphism accounts, the heuristic value of such kinds of representation cannot be convincingly explained. In other words, the isomorphism and similarity conceptions do not elucidate the distinction so dear to Vaihinger and to his present-day followers between scientific fictions and other kinds of fictions. According to Vaihinger this distinction can only be drawn at the level of cognitive function, and I have argued that the inferential conception of representation draws it precisely at the right level.

APPENDIX 1: THE INTERACTION FORMALISM

In this appendix I describe the tensor-product space formalism provided by the quantum theory of measurement to represent the interaction between an object system and a measuring device. Given two Hilbert spaces, H_1 and H_2, we can always form the tensor-product Hilbert space $H_{1+2} = H_1 \otimes H_2$, with dim $(H_1 \otimes H_2)$ = dim $(H_1) \times$ dim (H_2). If $\{v_i\}$ is a basis for H_1 and $\{w_j\}$ is a basis for H_2, then $\{v_i \otimes w_j\}$ is a basis for H_{1+2}. Similarly, if A is an observable defined on H_1 with eigenvectors $\{v_i\}$ and eigenvalues a_i, and B an observable on H_2 with eigenvectors $\{w_i\}$ and eigenvalues b_j then $A \otimes B$ is an observable on H_{1+2} with eigenvectors $v_i \otimes w_j$, and corresponding eigenvalues a_ib_j.

Consider two systems S_1 and S_2. If S_1's state is W_1 on H_1, and S_2's state is W_2 on H_2, we can represent the state of the combined system S_{1+2} as the statistical operator $W_{1+2} = W_1 \otimes W_2$ acting on the tensor-product Hilbert space H_{1+2}. If either W_1, W_2 is a mixture, then W_{1+2} is also a mixture. If, on the other hand, *both* W_1, W_2 are pure states then W_{1+2} is pure. Suppose that $W_1 = P_{[\psi]}$, and $W_2 = P_{[\phi]}$, where $\psi = \Sigma_i c_i v_i$ and $\phi = \Sigma_j d_j w_j$. Then $W_{1+2} = \Sigma_{i,j} c_i d_j v_i \otimes w_j$, which is a superposition of eigenstates of $A \otimes B$ in H_{1+2}. More specifically, if S_1, S_2 are in eigenstates of A,B, the combined system S_{1+2} is in an eigenstate of $A \otimes B$. If $W_1 = v_i$ and $W_2 = w_j$, then $W_{1+2} = v_i \otimes w_j$, a so-called *product state*.

For an arbitrary (pure or mixed) state W_{1+2} of the combined system, and arbitrary observable $A \otimes B$, the Generalized Born Rule applies. The probability that $A \otimes B$ takes a particular a_ib_j value is given by:

$$\mathrm{Prob}_{W1+2}\,(A \otimes B = a_ib_j) = \mathrm{Tr}\,(W_{1+2}\, P_{ij})$$

and the expectation value of the "total" $A \otimes B$ observable in state W_{1+2} is:

$$\mathrm{Exp}_{W1+2}\,(A \otimes B) = \mathrm{Tr}\,((A \otimes B)W_{1+2})$$

We will sometimes be given the state W_{1+2} of a composite system, and then asked to figure out what the reduced states W_1, W_2 of the separated subsystems must be. Given a couple of observables A and B on H_1, H_2, there are some relatively straightforward identifications that help to work out the reduced states, namely:

$$\mathrm{Tr}\,((A \otimes I)W_{1+2}) = \mathrm{Tr}\,(AW_1)$$

$$\mathrm{Tr}\,((I \otimes B)W_{1+2}) = \mathrm{Tr}(BW_2)$$

where I is the identity observable. This amounts to the demand that the probability distribution over the eigenspaces of observable A (B) defined by the reduced state W_1 (W_2) be the same as that laid out over $A \otimes I$ ($I \otimes B$) by the composite state W_{1+2}, thus effectively ensuring that the choice of description (either in the larger or smaller Hilbert space) of a subsystem in a larger composite system has no measurable consequences as regards the monadic properties of the individual subsystems.

APPENDIX 2: THE FORMAL CONDITIONS OF THE QUANTUM MEASUREMENT THEORY

To formally describe the problem of measurement, we need to first introduce some notation, and denote by Prob(W, Q) the probability distribution defined by $Prob_w(Q = q_n)$, for all eigenvalues q_n of Q. And let us denote *Q-indistinguishable* states W, W' as W ≡ W'. Two states W, W' are *Q-indistinguishable* if and only if Prob(W, Q) = Prob(W', Q).

We may now enunciate the following two conditions on measurement interactions:

The Transfer of Probability Condition (TPC)

$$Prob\ (U(W_o \otimes W_a)U^{-1}, I \otimes A) = Prob\ (W_o\ , O)$$

This condition expresses the requirement that the probability distribution over the possible outcomes of the relevant observable O of the object system should be reproduced as the probability distribution over possible outcomes of the pointer position observable in the final state of the composite (object + apparatus) system. (TPC) entails the following minimal condition on measurements employed by Fine (1970) and Brown (1985): A unitary interaction on a (object + apparatus) composite is a W_a measurement only if, provided that the initial apparatus state is W_a, any two initial states of the object system that are O-distinguishable are taken into corresponding final states of the composite that are (I ⊗A)- distinguishable. So we can use the pointer position of the measuring apparatus to tell apart two initial states of the object system that differ with respect to the relevant property.

The Occurrence of Outcomes Condition (OOC)

$$U(W_o \otimes W_a)U^{-1} = \Sigma\ c_n\ W_n \text{ where } \forall W_n\ \exists\ \mu_n\text{: } Prob_{Wn}(I \otimes A = \mu_n) = 1$$

This condition is often taken to express the requirement, inspired by the eigenstate–eigenvalue link, that the final state of the composite be a mixture over eigenstates of the pointer position observable. But to be precise, it expresses the more general idea that the final state of the composite must be a mixture over states in each of which the pointer position observable takes one particular value or other with probability 1.

NOTES

1. I am grateful for comments and reactions from audiences at the Fictions conference at Madrid's Complutense University (2006), the APA Pacific

Division conference in Oregon (2006), the ZiF workshop at Bielefeld (2007), the Dubrovnik IUC conference (2007), and the workshop on scientific models at the University of Barcelona (2007). Thanks in particular to my commentators Carl Hoefer, Alfred Nordmann, and Eric Winsberg, and to Ron Giere for his detailed comments on a draft version of the chapter.

2. Vaihinger (1911, 1924).
3. Vaihinger (1924, p. 99).
4. Fine (1993).
5. For some examples see the essays collected in the volumes edited by Morrison and Morgan (1999), Magnani et al. (1999), Jones and Cartwright (2004), and de Chadarevian and Hopwood (2004).
6. Vaihinger (1924, p. 97ff).
7. This agrees with much of the recent literature on fictions in metaphysics and aesthetics—which tends to distinguish carefully fiction from falsehood. For instance, in Walton's (1990) account of fiction as make believe, what characterizes fictions is their role as props in the prescription of imaginings, regardless of whether these turn out to be true or false. (Walton's theory strikes me as inappropriate for scientific fictions for other reasons, which are not relevant to my discussion here.)
8. Fine draws a similar distinction between virtuous and vicious fictions (Fine, 1993, p. 5).
9. In the account that follows I am indebted to Morrison (2000, esp. chap. 3) and Warwick (2003, esp. Chapters 6 and 7).
10. See also Morrison's extended discussion in this volume.
11. For instance, Trouton's and Larmor's ontological commitments to the ether could not have been more different. Trouton took second-order effects of the ether's motion with respect to the earth to be measurable by ordinary optical instruments on the earths' surface, whereas Larmor took any observable effects to be impossible as a matter of principle. See Warwick (1995).
12. Hesse (1966).
13. My exposition is indebted to the essays in Buchwald and Warwick (2004), and in particularly to Chapter 1, Smith (2004).
14. Geiger and Marsden (1909).
15. Rutherford (1911).
16. Thomson (1903, p. v).
17. Stellar astrophysics models provide a nice illustration of yet another thesis of mine, namely, that in scientific representation often the target is constructed along with the representation itself. I leave the detailed defense of this claim for another occasion (but see Suárez, 1999, for a preliminary account).
18. One of the earliest such proofs is due to Fine (1970). For details see Suárez (2004a).
19. Some of these options are described in Busch et al. (1991).
20. Gombrich (1984, Chapter 1).
21. I agree with Lopes (1996, p. 79) that this requirement is too strong on substitutive accounts, and would yield contradiction.
22. This "substitutive" character of models has been noted in the recent modeling literature, particularly in the "mediating models" literature (Morgan & Morrison, 1999), where models replace their targets as the main "focus of scientific research."
23. In *fictive* representation, the modeled entity (the target) is a real entity. In *fictional* representation, however, the target is also an imagined entity, just like the model.
24. Not all inferences will do, only those specific inferences that do not follow merely from the representational relation itself between A and B.

25. Suárez (2004b, p. 770).
26. For more on the notions of "constituents" and "means" see Suárez (2003, 2004b).
27. I am assuming here that it makes sense to speak of a *relation* between an existing model and a fictional entity or process; the assumption that some intensional relations might lack the corresponding extensions is of course controversial, but it does not alter anything substantial in what follows.
28. The names of Ron Giere and Bas Van Fraassen are often associated to such accounts, but I believe the association is not altogether fair. Both Van Fraassen (1994) and Giere (2004) make it clear that intentional elements are also needed for representation. But I am not here arguing against straw men. Others have embraced such accounts on their behalf, and many others have assumed that the accounts were properly theirs.
29. To speak of the "mathematical structure" of concrete objects, such as plum puddings, is problematic in any case, because there is a well-known issue of underdetermination of any abstract structure by a concrete object or sets of objects.

References

Abraham, F., Broughton, J., Bernstein, N., and Kaxiras, E. (1998). Spanning the length scales in dynamic simulation. *Computers in Physics*, *12*(6), 538–546.

Akerlof, G. A. (1970). The market for 'lemons': Quality uncertainty and the market mechanism. *Quarterly Journal of Economics, 84*, 488–500.

Alexandrova, A. (2006). Connecting economic models to the real world: Game theory and the FCC spectrum auctions. *Philosophy of the Social Sciences, 36*, 173–192.

Ankeny, R. A. (2000), Fashioning descriptive models in biology: Of worms and wiring diagrams. *Philosophy of Science, 67*, S260–S272.

Ankeny, R. A. (2001a). Model organisms as models: Understanding the "lingua franca" of the human genome project. *Philosophy of Science, 68*, S251–S261.

Ankeny, R. A. (2001b). The natural history of *C. elegans* research. *Nature Reviews Genetics, 2*, 474–478.

Batterman, R. (2005). Critical phenomena and breaking drops: Infinite idealizations in physics. *Studies in History and Philosophy of Modern Physics*, *36*, 225–244.

Bechtel, W. (1993). Integrating cell biology by creating new disciplines: The case of cell biology. *Biology and Philosophy, 8*, 277–299.

Bechtel, W., & Graham, G. (Eds.). (1998). *A companion to cognitive science.* Oxford: Blackwell.

Black, M. (1962). *Models and metaphors*. Ithaca, NY: Cornell University Press.

Blumberg, A. E., & Feigl, H. (1931). Logical positivism: A new movement in European philosophy. *Journal of Philosophy, 28*, 1–96.

Bogen, J., & Woodward, J. (1988). Saving the phenomena. *Philosophical Review, 97*, 303–352.

Bohr, N. (1913). On the constitution of atoms and molecules. *Philosophical Magazine*, *26*, 1–25, 476–502, 857–875.

Bohr, N. (1921). Atomic structure. *Nature, 107*, 1–11. Reprinted in *Niels Bohr collected works*, vol. 4, pp. 71–82. vol. 4: The Periodic System (1920–1923), J. R. Neilsen (ed.). Amsterdam: North-Holland Publishing, pp. 71–82.

Bokulich, A. (2008a). *Reexamining the quantum-classical relation: Beyond reductionism and pluralism*. Cambridge University Press.

Bokulich, A. (2008b). Can classical structures explain quantum phenomena? *British Journal for the Philosophy of Science*, *59*(2), 217–235.

Bolker, J. A. (1995). Model systems in developmental Biology. *BioEssays, 17*: 451–455.

Bono, H., Ogata, H., Goto, S., et al. (1998). Reconstruction of amino acid biosynthesis pathways from the complete genome sequence. *Genome Research, 8*, 203–210.

Bono, J. (1990). Science, discourse and literature: The role/rule of metaphor in science. In S. Peterfreund (Ed.), *Literature and science: Theory and practice* (pp. 59–89). Boston: Northeastern University Press.

Boumans, M. (1999). Built-in justification. In M. S. Morgan & M. Morrison (Eds.), *Models as mediators: Perspectives on natural and social science* (pp. 66–96). Cambridge: Cambridge University Press.

Boumans, M. (2006). The difference between answering a 'why'-question and answering a 'how much'-question. In J. Lenhard, G. Küppers & T. Shinn (Eds.), *Simulation: Pragmatic Constructions of Reality. Sociology of the Sciences Yearbook* (pp. 107–124). New York: Springer.

Boumans, M., & Morgan, M. S. (2001). *Ceteris paribus* conditions: Materiality and the application of economic theories. *Journal of Economic Methodology, 8*, 11–26.

Brandom, R. (1994). *Making it explicit*. Cambridge, MA: Harvard University Press.

Brenner, S. (1988). Foreword. In W. B. Wood and the Community of *C. elegans* Researchers (Eds.), *The nematode* Caenorhabditis elegans (pp. ix–x). Cold Spring Harbor, NY: Cold Spring Harbor Laboratory Press.

Broughton, J., et al. (1999). Concurrent coupling of length scales: Methodology and application. *Physical Review B*, *60*(4), 2391–2403

Buchwald, J., & Warwick, A. (Eds.). (2004). *Histories of the electron: The birth of microphysics*. Cambridge, MA: MIT Press.

Busch, P., Lahti, P., & Mittelstaedt, P. (1991). *The quantum theory of measurement*. Berlin: Springer-Verlag.

Caldwell, B. J. (1982). *Beyond positivism: Economic methodology in the twentieth century*. London: Allen & Unwin.

Callender, C. (2001) "Taking Thermodynamics Too Seriously" *Studies in History and Philosophy of Modern Physics*, 32: 539–53.

Campbell, J. (2000). *Artificial viscosity for multi-dimensional hydrodynamics codes*. http://cnls.lanl.gov/Highlights/2000–09/article.htm

Campbell, N. (1920). Atomic structure. *Nature, 106*(2665), 408–409.

Cangelosi, A., & Parisi, D. (1997). A neural network model of *Caenorhabditis elegans*: The circuit of touch sensitivity. *Neural Processing Letters, 6*, 91–98.

Caramana, E. J., Shashkov, M. J., & Whalen, P. P. (1988). Formulations of artificial viscosity for multi-dimensional shock wave computations. *Journal of Computational Physics, 144*, 70–97.

Carroll, S., Grenier, J., & Weatherbee, S. (2001). *From DNA to diversity*. Malden, MA: Blackwell.

Cartwright, N. (1983). *How the laws of physics lie*. Oxford: Oxford University Press.

Cartwright, N. (1989). *Nature's capacities and their measurement*. Oxford: Oxford University Press.

Cartwright, N. (1998). Capacities. In J. B. Davis, D. W. Hands, & U. Mäki (Eds.), *The handbook of economic methodology* (pp.). Cheltenham: Edgar Elgar.

Cartwright, N. (1999a). *The dappled world*. Cambridge: Cambridge University Press.

Cartwright, N. (1999b). *The vanity of rigour in economics: Theoretical models and Galilean experiments*. Discussion paper series 43/99. Centre for Philosophy of Natural and Social Science.

Chafe, W. L. (1970). *Meaning and the structure of language*. Chicago: University of Chicago Press.

Chalfie, M., Sulston, J. E., White, J. C., et al. (1985). The neural circuit for touch sensitivity in *Caenorhabditis elegans*. *Journal of Neuroscience, 5*, 959–964.

Chalmers, D. J. (1996). *The conscious mind. In search of a fundamental theory*. New York: Oxford University Press.

Chalmers, D. J. (2002). Does conceivability entail possibility? In T. Gendler & J. Hawthorne (Eds.), *Conceivability and possibility* (pp. 145–200). Oxford: Oxford University Press.

Chang, H. (2004). *Inventing temperature*. Oxford: Oxford University Press.
Chelikowski, J., & Ratner, M. (2001). Nanoscience, nanotechnology, and modeling. *Computing in Science and Engineering*, *3*(4), 40–41.
Clarke, A. E., & Fujimura, J. (Eds.). (1992). *The right tools for the job: At work in twentieth-century life sciences*. Princeton, NJ: Princeton University Press.
Cohen, M. R. (1923). On the logic of fictions. *Journal of Philosophy, 20*, 477–488.
Contessa, G. (2007). Representation, interpretation, and surrogative reasoning. *Philosophy of Science, 71*, 48–68.
Contessa, G. (in press). Scientific models as fictional objects. *Synthese*.
Creager, A. N. H. (2002). *The life of a virus: Tobacco mosaic virus as an experimental model, 1930–1965*. Chicago: University of Chicago Press.
Currie, G. (1985). What is fiction? *Journal of Aesthetics and Art Criticism*, 385–392.
Currie, G. (1990). *The nature of fiction*. Cambridge University Press.
Currie, G., & Ravenscroft, I. (2002), *Recreative minds*, Clarendon Press.
Darden, L. (1991). *Theory change in science: Strategies from Mendelian genetics*. New York: Oxford University Press.
Darrigol, O. (1992). *From c-numbers to q-numbers: The classical analogy in the history of quantum theory*. Berkeley: University of California Press.
Davidson, D. (1984). On the very idea of a conceptual scheme. In *Inquiries into truth and interpretation* (pp. 183–198). Oxford: Oxford University Press.
Davidson, D. (1986). A nice derangement of epitaphs. In E. LePore (Ed.), *Truth and interpretation* (pp. 433–446). Oxford: Blackwell.
de Chadarevian, S. (1998). Of worms and programmes: *Caenorhabditis elegans* and the study of development. *Studies in the History and Philosophy of Science, 29*, 81–105.
de Chadarevian, S., & Hopwood, N. (2004). *Models: The third dimension of science*. Stanford, CA: Stanford University Press.
Delos, J. B., & Du, M.-L. (1988). Correspondence principles: The relationship between classical trajectories and quantum spectra. *IEEE Journal of Quantum Electronics, 24*, 1445–1452.
Delos, J. B., Knudson, S. K., & Noid, D. W. (1983). Highly excited states of a hydrogen atom in a strong magnetic field. *Physical Review A, 28*, 7–21.
Dewey, J. (1916). *Essays in experimental logic*. Chicago.
Doležel, L. (1998). *Heterocosmica: fiction and possible worlds*. Baltimore: Johns Hopkins University Press.
Du, M.-L., & Delos J. B. (1988). Effect of closed classical orbits on quantum spectra: ionization of atoms in a magnetic field. I. Physical picture and calculations. *Physical Review A, 38*, 1896–1912.
Duhem, P. (1977). *The aim and structure of physical theory*. New York: Atheneum.
Earman, J. (2003). *Spontaneous symmetry breaking for philosophers* (preprint).
Eco, U. (1979). *The role of the reader. Explorations in the semiotics of texts*. Bloomington: Indiana University Press.
Eco, U. (1983). *The name of the rose*. New York: G. K. Hall & Company.
Eco, U. (1990). *The limits of interpretation*. Bloomington: Indiana University Press.
Ehrenfest, P., & Ehrenfest, T. (1907). Über zwei bekannte Einwände gegen Boltzmann's H-Theorem. *Physische Zeitschrift, 8*, 311.
Elgin, C. Z. (1983). *With reference to reference*. Indianapolis, IN: Hackett.
Elgin, C. Z. (1991). Understanding in art and science. In P. French, T. Uehling, & H. Wettstein (Eds.), *Philosophy and the arts* (pp. 196–208). Notre Dame, IN: University of Notre Dame Press.
Elgin, C. Z. (1996). *Considered judgment*. Princeton, NJ: Princeton University Press.
Elgin, C. Z. (2004). True enough. *Philosophical Issues*, *14*, 113–131.

Fine, A. (1970). Insolubility of the quantum measurement problem. *Physical Review D*, *2*, 2783–2787.
Fine, A. (1986). Unnatural attitudes: Realist and instrumentalist attachments to science. *Mind, 95*, 149–79.
Fine, A. (1993). Fictionalism. *Midwest Studies in Philosophy, XVIII*, 1–18. Reprinted in this volume.
Fisher, R. A. (1918). The correlation between relatives on the supposition of Mendelian inheritance. *Transactions of the Royal Society of Edinburgh*, *52*, 399–433.
Fisher, R. A. (1922). On the dominance ratio. *Proceedings of the Royal Society of Edinburgh. 42*, 321–341.
Fleck, L. (1979). *Genesis and development of a scientific fact*, F. Bradley and T. Trenn (Trans.). Chicago: University of Chicago Press.
Frank, J. (1970). *Law and the modern mind*. Gloucester, MA.
Frank, P. (1949). *Modern science and its philosophy*. Cambridge, MA.
Fraser, C. M., Gocayne, J. D., White, O., et al. (1995). The minimal gene complement of *Mycoplasma genitalium*. *Science, 270*, 397–403.
French, S. (2003). A model-theoretic account of representation (Or, I don't know much about art . . . but I know it involves isomorphism). *Philosophy of Science, 70,* 1472–1483.
French, S., & Ladyman, J. (1999). Reinflating the semantic approach. *International Studies in the Philosophy of Science, 13*, 103–121.
Friedman, M. (1953). The methodology of positive economics. In *Essays in positive economics* (pp.). Chicago: Chicago University Press.
Frigg, R. (2003). *Re-presenting scientific representation*. PhD dissertation, London School of Economics, London.
Frigg, R. (in press). Models and fiction. *Synthese* (2008).
Frigg, R., & Hartmann, S. (2006). Models in science. *The Stanford Encyclopedia of Philosophy*. http://plato.stanford.edu/archives/spr2006/entries/models-science/
Galison, P. (1987). *How experiments end*. Chicago: University of Chicago Press.
Galison, P. (1997). *Image and logic*. Chicago: University of Chicago Press.
Garton, W. R. S., & Tomkins, F. S. (1969). Diamagnetic Zeeman effect and magnetic configuration mixing in long spectral series of BA I. *Astrophysical Journal*, *158*, 839–845.
Geiger, H., & Marsden, E. (1909). On a diffuse reflection of the α-particles. *Proceedings of the Royal Society*, *82*, 495–500.
Gibson, D. G., Benders, G. A., Andrews-Pfannkoch C., et al. (2008). Complete chemical synthesis, assembly, and cloning of a mycoplasma genitalium genome. *Science Online,* 24 January.
Giere, R. N. (1988). *Explaining science: A cognitive approach*. Chicago and London: University of Chicago Press.
Giere, R. N. (1991). *Understanding scientific reasoning* (3rd ed.), New York: Harcourt Brace Jovanovich.
Giere, R. N. (1999). *Science without laws*. Chicago: Chicago University Press.
Giere, R. N. (2002). Scientific cognition as distributed cognition. In P. Carruthers, S. Stich, & M. Siegal (Eds.), *Cognitive bases of science* (pp.). Cambridge: Cambridge University Press.
Giere, R. N. (2004). How models are used to represent reality. *Philosophy of Science, 71*, 742–752.
Giere, R. N. (2006). *Scientific perspectivism*. Chicago: University of Chicago Press.
Giere, R. N. (in press-a). An agent-based conception of models and scientific representation. *Synthese*.

Giere, R. N. (in press-b). Models, metaphysics and methodology. In S. Hartmann, C. Hoefer, & L. Bovens (Eds.), *Nancy Cartwright's philosophy of science*. Oxford: Routledge.

Glass, J. I., Assad-Garcia, N., Alperovich, N., et al. (2006). Essential genes of a minimal bacterium. *Proceedings of the National Academy of Sciences USA, 103*, 425–430.

Godfrey-Smith, P. (2006). The strategy of model-based science. *Biology and Philosophy, 21*, 725–740.

Gombrich, H. (1961). *Art and illusion: A study in the psychology of pictorial representation*. Princeton, NJ: Princeton University Press.

Gombrich, H. (1984). *Meditations on a hobby horse*. Chicago University Press.

Goodfield, J. (1981). *An imagined world: A story of scientific discovery*. New York: Harper & Row.

Goodman, N. (1968). *Languages of art*. Indianapolis, IN: Hackett.

Gould, J. A. (1970). R. B. Perry on the origin of American and European pragmatism. *History of Philosophy, 8*(43), 1–50.

Granger, B. E. (2001). *Quantum and semiclassical scattering matrix theory for atomic photoabsorption in external fields*. PhD thesis, University of Colorado, Boulder.

Gruber, H. (1981). Darwin on man: A psychological study of scientific creativity. Chicago: University of Chicago Press.

Gutzwiller, M. (1971). Periodic orbits and classical quantization conditions. *Journal of Mathematical Physics, 12*, 343–358.

Gutzwiller, M. (1990). *Chaos in classical and quantum mechanics*. New York: Springer-Verlag.

Hacking, I. (1983). *Representing and intervening*. Cambridge: Cambridge University Press.

Hacking, I. (1984). Language, truth and reason. In M. Hollis & S. Lukes (Eds.), *Rationality and relativism* (pp. 48–66). Cambridge, MA: MIT Press.

Hacking, I. (1986). Making up people. In T. C. Heller, M. Sosna, & D. E. Wellbery (Eds.), *Reconstructing individualism* (pp. 222–236). Stanford, CA: Stanford University Press.

Hacking, I. (1992). The self-vindication of the laboratory sciences. In A. Pickering (Ed.), *Science as practice and culture* (pp. 29–64). Chicago: University of Chicago Press.

Hacking, I. (1999). *The social construction of what?* Cambridge, MA: Harvard University Press.

Hacking, I. (2002). *Historical ontology*. Cambridge, MA: Harvard University Press.

Hagberg, G. L. (1994). *Meaning and interpretation: Wittgenstein, Henry James, and literary knowledge*. Ithaca, NY: Cornell University Press.

Haggerty, M. R., Spellmeyer, N., Kleppner, D., & Delos, J. B. (1998). Extracting classical trajectories from atomic spectra. *Physical Review Letters, 81*, 1592–1595.

Hanna, P., & Harrison, B. (2004). *Word and world*. Cambridge: Cambridge University Press.

Harris, T. (2003). Data models and the acquisition and manipulation of data. *Philosophy of Science, 70*, 1508–1517.

Haugeland, J. (1998). *Having thought*. Cambridge, MA: Harvard University Press.

Hausman, D. (1990). Supply and demand explanations and their *ceteris paribus* clauses. *Review of Political Economy, 2*, 168–187.

Hausman, D. (1992). *The inexact and separate science of economics*. Cambridge: Cambridge University Press.

Hegselmann, R., & Siegwart, G. (1991). Zur Geschichte der 'Erkenntnis'. *Erkenntnis, 35*, 461–471.
Heidegger, M. (1950). *Holzwege*. Frankfurt am Main: Vittorio Klostermann. English tr. 2002. *Off the beaten track* (J. Young, Trans.). Cambridge: Cambridge University Press.
Heilbron, J. (1967). The Kossel-Sommerfeld theory and the ring atom. *Isis, 58*(4), 450–485.
Hempel, C. G. (1965). *Aspects of scientific explanation and other essays in the philosophy of science*. New York: Free Press.
Hempel, C. G. (1975). The old and the new 'Erkenntnis'. *Erkenntnis, 9*, 1 4 .
Hesse, M. (1963). *Models and analogies in science*. Notre Dame, IN: University of Notre Dame Press.
Hobbes, T. (1985). Dialogus physicus (S. Schaffer, Trans.). In S. Shapin & S. Schaffer, *Leviathan and the air pump* (pp. 346–391). Princeton, NJ: Princeton University Press.
Holle, A., Main, J., Wiebusch, G., Rottke, H., & Welge, K. H. (1988). Quasi-Landau spectrum of the chaotic diamagnetic hydrogen atom. *Physical Review Letters, 61*, 161–164.
Horwich, P. (1991). On the nature and norms of theoretical commitment. *Philosophy of Science, 58*, 1–14.
Hughes, R. I. G. (1989). Bell's theorem, ideology, and structural explanation. In *Philosophical consequences of quantum theory: Reflections on Bell's theorem* (pp. 195–207). Notre Dame, IN: University of Notre Dame Press.
Hughes, R. I. G. (1997). Models and representation. *Philosophy of Science, 64*, S325–S336.
Hughes, R. I. G. (1999). The Ising model, computer simulation, and universal physics. In M. Morrison & M. Morgan (Eds.), *Models as mediators* (pp. 97–145). Cambridge: Cambridge University Press.
Humphreys, P. (1994). Numerical experimentation. In P. Humphreys (Ed.), *Patrick Suppes, Scientific philosopher* (Vol. 2, pp.). Dordrecht: Kluwer.
Humphreys, P. (2002). Computational models. *Philosophy of Science, 69*, S1–S11.
Humphreys, P. (2004). *Extending ourselves: Computational science, empiricism, and scientific method*. New York, Oxford University Press.
Hutchison, T. W. (1938). *The significance and basic postulates of economic theory*. London: MacMillan.
John, E. (1998). Reading fiction and conceptual knowledge: Philosophical thought in literary context. *Journal of Aesthetics and Art Criticism, 56*, 331–348.
Jones, M., & Cartwright, N. (2004). *Correcting the model: Idealisation and abstraction in the sciences*. Rodopi.
Kalderon, M. E. (2005). *Fictionalism in metaphysics*. Oxford University Press.
Kitano, H., Amáis, S., & Luke, S. (1988). The perfect *C. elegans* project: An initial report. *Artificial Life, 4*, 141–156.
Kitano, H., S. Hamahashi, and S. Luke (1988), "The Perfect C. elegans Project: An Initial Report", Artificial Life 4: 141–156.
Kitcher, P. (1993). *The advancement of science*. Oxford: Oxford University Press.
Klein, U. (2003). *Experiments, models, paper tools*. Stanford, CA: Stanford University Press.
Kleppner, D., & Delos, J. B. (2001). Beyond quantum mechanics: Insights from the work of Martin Gutzwiller. *Foundations of Physics, 31*, 593–612.
Knuuttila, T. (2005). Models, representation, and mediation. *Philosophy of Science, 72*, 1260–1271.
Knuuttila, T. (2006). From representation to production: Parsers and parsing in language technology. In J. Lenhard, G. Küppers, & T. Shinn (Eds.), *Simulation: Pragmatic constructions of reality. Sociology of the Sciences Yearbook* (pp. 41–55). New York: Springer.

Knuuttila, T., & Voutilainen, A. (2003). A parser as an epistemic artefact: A material view on models. *Philosophy of Science, 70*, 1484–1495.

Kohler, R. (1994). *Lords of the fly. Drosophila genetics and the experimental life*. Chicago: University of Chicago Press.

Kuhn, T. (1977). A function for thought experiments. In *The essential tension* (pp. 240–265). Chicago: University of Chicago Press.

Kuorikoski, J., Lehtinen, A., & Marchionni, C. (2007). *Economics as robustness analysis*. Paper presented at Models and Simulations 2, Tilburg, The Netherlands. http://philsci-archive.pitt.edu/archive/00003550/

Lambrecht, K. (1994). *Information structure and sentence form: Topic, focus and the mental representations of discourse referents*. Cambridge; Cambridge University Press.

Lehtinen, A., & Kuorikoski, J. (2007). Computing the perfect model: Why do economists shun simulation. *Philosophy of Science, 74*, 304–329.

Lenhard, J. (2006). Surprised by a nanowire: Simulation, control, and understanding. *Philosophy of Science, 73*, 605–616.

Lester, E. (1966, September 18). Playwright Edward Albee: 'I am still in process.' *The New York Times,* Arts & Leisure, p. 113.

Levins, R. (1966). The strategy of model-building in population biology. *American Scientist*, *54*, 421–431.

Lewis, D. (1979). Attitudes *de dicto* and *de re*. *Philosophical Review*, *88*, 513–543.

Lewis, D. (1982). Logic for equivocators. *Noûs, 16*, 431–441. Reprinted in Lewis, D. (1983). *Philosophical papers*. Oxford: Oxford University Press.

Lewis, D. (1983). Truth in fiction. In D. Lewis (Ed.), *Philosophical papers* (Vol. 1, pp. 261–280). Oxford: Oxford University Press. (Original work published 1978)

Lipton, P. (1991). *Inference to the best explanation*. Routledge.

Lopes, D. (1996). *Understanding pictures*. Oxford: Oxford University Press.

Lu, K. T., Tomkins, F. S., & Garton, W. R. S. (1978). Configuration interaction effect on diamagnetic phenomena in atoms: Strong mixing and Landau regions. *Proceedings of the Royal Society of London A*, *362*, 421–424.

Lucas, R. E., Jr. (1980). Methods and problems in business cycle theory. *Journal of Money, Credit and Banking, 12*(4), 696–715.

Lucas, R. E., Jr. (1981). *Studies in business-cycle theory*. Cambridge, MA: MIT Press.

Lycan, W. (1994). *Modality and meaning*. Dordrecht: Kluwer Academic.

Lynch, M. (1990). The externalized retina: Selection and mathematization in the visual documentation of objects in life sciences. In M. Lynch & S. Woolgar (Eds.), *Representation in scientific practice* (pp. 153–186). Cambridge, MA: MIT Press.

Machlup, F. (1955). The problem of verification in economics. *Southern Economic Journal, 22*, 1–21.

Machlup, F. (1967). Theories of the firm: Marginalist, behavioral, managerial. *American Economic Review, LVII*, 1–33.

Machlup, F. (1978). *Methodology of economics and other social sciences*. New York: Academic Press.

Magnani, L. (1999). *Model-based reasoning in scientific discovery*. Dordrecht: Kluwer Academic.

Main, J., Weibusch, G., Holle, A., & Welge, K. H. (1986). New quasi-Landau structure of highly excited atoms: The hydrogen atom. *Physical Review Letters*, *57*, 2789–2792.

Mäki, U. (1990). *Studies in realism and explanation in economics*. Helsinki: Suomalainen tiedeakatemia.

Mäki, U. (1992). On the method of isolation in economics. *Poznań Studies in the Philosophy of Science and Humanities, 26*, 316–351.

Mäki, U. (1994). Reorienting the assumptions issue. In R. Backhouse (Ed.), *New directions in economic methodology* (pp. 236–256). London: Routledge.

Mäki, U. (1996). Scientific realism and some peculiarities of economics. In R. S. Cohen, R. Hilpinen, & Q. Renzong (Eds.), *Realism and anti-realism in the philosophy of science* (pp. 427–447). Dordrecht: Kluwer.

Mäki, U. (2002). *Fact and fiction in economics*. Cambridge: Cambridge University Press.

Mäki, U. (2004). Realism and the nature of theory: A lesson from J. H. von Thünen for economists and geographers. *Environment and Planning A*, *36*, 1719–1736.

Mäki, U. (2005). Models are experiments, experiments are models. *Journal of Economic Methodology, 12*, 303–315.

Mäki, U. (2006). Remarks on models and their truth. *Storia del Pensiero Economico, 3*, 7–19.

Mäki, U. (in press), Realistic realism about unrealistic models, to appear in H. Kincaid and D. Ross (Eds.), *The Oxford Handbook of the Philosophy of Economics*. Oxford University Press.

Matzkin, A. (2006). *Can Bohmian trajectories account for quantum recurrences having classical periodicities?* arXiv.orgpreprint quant-ph/0607095.

Maxwell, J. C. (1965). *The scientific papers of James Clerk Maxwell* (W. D. Niven, Ed.). New York: Dover.

McDowell, J. (1994). *Mind and world*. Cambridge, MA: Harvard University Press.

McKeon, R. (Ed.). (1973). *Introduction to Aristotle*. Chicago: University of Chicago Press.

McMullin, E. (1985). Galilean idealization. *Studies in History and Philosophy of Science, 16*, 247–273.

Morgan, M. S. (2003). Experiments without material intervention: Model experiments, virtual experiments, and virtually experiments. In H. Radder (Ed.), *Philosophy of scientific experimentation* (pp. 216–235). Pittsburgh: University of Pittsburgh Press.

Morgan, M. S. (2005). Experiments versus models: New phenomena, inference and surprise. *Journal of Economic Methodology, 12*, 317–329.

Morgan, M. S., & Morrison, M. (Eds.). (1999). *Models as mediators. Perspectives on natural and social science*. Cambridge: Cambridge University Press.

Morrison, M. (1998). Modelling nature: Between physics and the physical world, *Philosophia Naturalis*, *35*, 65–85.

Morrison, M. (1999). Models as autonomous agents. In M. S. Morgan & M. Morrison (Eds.), *Models as mediators: Perspectives on natural and social science* (pp. 38–65). Cambridge: Cambridge University Press.

Morrison, M. (2000). *Unifying scientific theories: Physical concepts and mathematical structures*. Cambridge: Cambridge University Press.

Morrison, M. (2002). Modelling populations: Pearson and Fisher on Mendelism and biometry. *British Journal for the Philosophy of Science*, *53*, 39–68.

Morrison, M. & Morgan, M.S. (1999). Models as mediating instruments. In M. S. Morgan and M. Morrison (Eds.), *Models as mediators. Perspectives on natural and social science* (pp. 10–37). Cambridge: Cambridge University Press.

Musgrave, A. (1981). 'Unreal assumptions' in economic theory: The F-Twist untwisted. *Kyklos, 34*, 377–387.

Musil, R. (1906). *Young Törless* (E. Wilkins & E. Kaiser, Trans.). New York.

Nakano, A., et al. (2001). Multiscale simulation of nano-systems. *Computing in Science and Engineering. 3*(4), 56–66.

Nanney, D. L. (1983). The cytoplasm and the ciliates. *Journal of Heredity, 74*, 163–170.

Nersessian, N. J. (1992). How do scientists think? In R. N. Giere (Ed.), *Cognitive models of science* (pp. 3–44). Minnesota Studies in the Philosophy of Science (Vol. XV). Minneapolis: University of Minnesota Press.

Neurath, O. (1983). Encyclopedia as model. In R. S. Cohen & M. Neurath (Eds.), *Neurath: Philosophical papers* (pp. 145–158). Dordrecht: Reidel.
Nickles, T. (Ed). (1980). *Scientific discovery: Case studies*. Dordrecht: Riedel.
Norton, S., & Suppe, F. (2001). Why atmospheric modeling is good science. In C. Miller & P. Edwards (Eds.), *Changing the atmosphere* (pp. 68–105). Cambridge, MA: MIT Press.
Novitz, D. (1987). *Knowledge, fiction and imagination*. Philadelphia, PA: Temple University Press.
Nussbaum, M. (1990). *Love's knowledge*. New York: Oxford University Press.
Oja, M. F. (1988). Fictional history and historical fiction: Solzhenitsyn and Kiš as exemplars. *History and Theory, 27*, 111–124.
Papineau, D. (1988). Mathematical fictionalism. *International Studies in the Philosophy of Science, 2*, 151–175.
Pavel, T. G. (1986). *Fictional worlds*. Cambridge, MA: Harvard University Press.
Pearson, K. (1904). Mathematical contributions to the theory of evolution. XII. On a Generalized Theory of Alternative Inheritance with Special Reference to Mendel's Laws. *Proceedings of the Royal Society A*, *203*, 53–86.
Popper, K. R. (1985). Natural selection and its scientific status. Reprinted with omissions In D. Miller (Ed.), *Popper selections* (pp.). Princeton, NJ: Princeton University Press. (Original work published 1978)
Portides, D. (2005). "Scientific Models and the Semantic View of Theories" *Philosophy of Science*, 72: 1287–1298.
Prialnik, D. (2000). *An Introduction to the Theory of Stellar Structure and Evolution*. Cambridge: Cambridge University Press.
Prince, E. F. (1981). Toward a taxonomy of given-new information. In P. Cole (Ed.), *Radical pragmatics* (pp. 233–237). New York: Academic Press.
Putnam, H. (1978). Literature, science, and reflection. In *Meaning and the moral sciences* (pp.). London: Routledge and Kegan Paul.
Quine, W. v. O. (1953). Two dogmas of empiricism. In *From a logical point of view* (pp. 139–160). Cambridge, MA: Harvard University Press.
Quine, W. v. O. (1969). Propositional objects. In *Ontological relativity and other essays* (pp. 20–46). New York: Columbia University Press.
Rader, K. A. (2004). *Making mice: Standardizing animals for American biomedical research, 1900–1955*. Princeton, NJ: Princeton University Press.
Railton, P. (1980). *Explaining explanation: A realist account of scientific explanation and understanding.* PhD dissertation, Princeton University, Princeton, NJ.
Ramsey, F. P. (1990). General propositions and causality. In *Philosophical papers* (pp.). Cambridge: Cambridge University Press. (Original work published 1929)
Redhead, M. (1980). Models in physics. *British Journal for the Philosophy of Science*, *31*, 145–163.
Rheinberger, H. J. (1995). From microsomes to ribosomes: 'Strategies' of 'representation', 1935–1955. *Journal of the History of Biology, 48*, 49–89.
Rheinberger, H. J. (1997). *Toward a history of epistemic things*. Stanford, CA: Stanford University Press.
Robbins, L. (1935). *An essay on the nature and the significance of economic science* (2nd ed.). London: MacMillan.
Ronen, R. (1994). *Possible worlds in literary theory.* Cambridge: Cambridge University Press.
Rorty, R. (1980). *Philosophy and the mirror of nature.* Oxford: Basil Blackwell.
Rosen, G. (1994). What is constructive empiricism? *Philosophical Studies*, *74*, 143–178.
Rosen, G. (2005). Problems in the history of fictionalism. In M. E. Kalderon (Ed.), *Fictionalism in Metaphysics* (pp. 14–64).

Rouse, J. (1987). *Knowledge and power*. Ithaca, NY: Cornell University Press.

Rouse, J. (2002). *How scientific practices matter*. Chicago: University of Chicago Press.

Rudd, R. E., and Broughton, J. Q (2000). Concurrent coupling of length scales in solid state systems. *Physica Status Solidi B, 217*, 251–291.

Russell, B. (1968). On denoting. In *Logic and knowledge* (pp. 39–56). New York: Capricorn.

Rutherford, E. (1911). The scattering of α and β particles by matter and the structure of the atom. *Philosophical Magazine*, *21*, 669–688.

Ryckman, T. (1991). Conditio sine qua non: 'Zuordnung' in the early epistemologies of Cassirer and Schlick. *Synthèse, 88*, 57–95.

Sainsbury, M. (2005). *Reference without referents*. Oxford: Oxford University Press.

Salmon, W. (1984). *Scientific explanation and the causal structure of the world*. Princeton, NJ: Princeton University Press.

Sapp, J. (1987), *Beyond the gene*. Oxford: Oxford University Press.

Scanlon, T. M (1998). *What we owe to each other*. Cambridge, MA: Harvard University Press.

Schaffner, K.F. (2000). Behavior at the organismal and molecular levels: The case of *C. elegans*. *Philosophy of Science, 67*, S273–S288.

Schaper, E. (1965). The Kantian 'as if' and its relevance for aesthetics. *Proceedings of the Aristotelian Society, 65*, 2, 19–34.

Schaper, E. (1966). The Kantian thing-in-itself as a philosophical fiction. *Philosophical Quarterly, 16*, 233–243.

Scheffler, I. (1963). *The anatomy of inquiry: Philosophical studies in the theory of science*. New York: Knopf.

Scheffler, I. (1982). Epistemology of objectivity. In *Science and subjectivity* (pp. 114–124). Indianapolis, IN: Hackett.

Schelling, T.C. (1978). *Micromotives and macrobehavior*. New York: Norton.

Schlick, M. (1932). Positivism and realism. In *Logical positivism* (A. J. Ayer, Ed., pp. 82–107). New York: . (Original work published 1932)

Seigel, D. (1991). *Innovation in Maxwell's electromagnetic theory*. Cambridge: Cambridge University Press.

Sejnowski, T. J., Koch, C., & Churchland, P. S. (1988). Computational neuroscience. *Science, 241*, 1299–1306.

Sklar, L. (1993). Idealization and explanation: A case study from statistical mechanics. In *Minnesota studies in philosophy*, *Vol. XVII, Philosophy of science* (pp. 258–270.). Notre Dame, IN: University of Notre-Dame Press.

Smith, E. E., & Medin, D. L. (1981). *Categories and concepts*. Cambridge, MA: Harvard University Press.

Smith, G. E. (2004). J. J. Thomson and the electron, 1897–1899. In J. Buchwald & A. Warwick (Eds.), *Histories of the electron: The birth of microphysics* (pp. 21–76). Cambridge, MA: MIT Press.

Solow, R. M. (1997). How did economics get that way and what way did it get? *Daedalus, 126*, 39–58.

Spariosu, M. (1989). *Dionysus reborn: Play and the aesthetic dimension in modem philosophical and scientific discourse*. Ithaca, NY: .

Stanford, P. K. (2006). *Exceeding our grasp: Science, history and the problem of unconceived alternatives*. Oxford: Oxford University Press.

Suárez, M. (1999). Theories, models, and representations. In L. Magnani, N. J. Nersessian, & P. Thagard (Eds.), *Model-based reasoning in scientific discovery* (pp. 75–83). New York: Kluwer.

Suárez, M. (2003). Scientific representation: Against similarity and isomorphism. *International Studies in the Philosophy of Science, 17*, 225–244.

Suárez, M. (2004a). Quantum selections, propensities and the problem of measurement. *British Journal of Philosophy of Science*, *55*(2), 219–255.

Suárez, M. (2004b). An inferential conception of scientific representation. *Philosophy of Science, 71*, 767–779.

Sugden, R. (2002). Credible worlds: The status of the theoretical models in economics. In U. Mäki (Ed.), *Fact and fiction in economics: Models, realism, and social construction* (pp. 107–136). Cambridge: Cambridge University Press.

Suppes, P. (1962). Models of data. In E. Nagel, P. Suppes, & A. Tarski (Eds.), *Logic, methodology and philosophy of science: Proceedings of the 1960 international congress* (p. 252–261). Stanford, CA: Stanford University Press.

Suppes, P. (1974). The structure of theories and the analysis of data. In F. Suppe (Ed.), *The structure of scientific theories* (pp. 266–283). Urbana, IL University of Illinois Press.

Swoyer, C. (1991). Structural representation and surrogative reasoning. *Synthese*, *87*, 449–508.

Tayler, R. J. (1970) *The Stars: their structure and evolution*. Cambridge: Cambridge University Press.

Teller, P. (2001). Twilight of the perfect model model. *Erkenntnis, 55*, 393–415.

Teller, P. (2008). Representation in science. In M. Curd & S. Psillos (Eds.), *The Routledge companion to the philosophy of science*. pp. 435–441.

Teller, P. (in preparation). Some dirty little secrets about truth.

Thomson, J. J. (1903). *Conduction of electricity through gases*. Cambridge University Press.

Thomson-Jones, M. (in press). Missing systems and the face value practice. *Synthese*.

Tufte, E. R. (1997). *Visual and statistical thinking: Displays of evidence for making decisions*. Cheshire, CT: Graphics Press.

Uebel, T. (1992). *Overcoming logical positivism from within*. Amsterdam: Rodopi.

Vaihinger, H. (1911). *Die Philosophie des Als Ob*. Berlin: Verlag von Reuther & Reichard.

Vaihinger, H. (1924). *The philosophy of 'as if'* (C. K. Ogden, Trans.). London: Kegan Paul. (Original work published 1911)

Vaihinger, H. (1952). *The philosophy of 'as if': A system of the theoretical, practical and religious fictions of mankind* (C. K. Ogden, Trans.). London: Lund Humphries. (Original work published 1911)

Van Fraassen, B. (1980). *The scientific image*. Oxford: Oxford University Press.

Van Fraassen, B. (1985). *Laws and symmetry*. Clarendon Press.

Vichniac, G. (1984). Simulating physics with cellular automata. *Physica D*, *10*, 96–116.

Voltolini, A. (2006). *How ficta follow fiction: A syncretistic account of fictional entities*. New York: Springer.

Von Baeyer, H. C. (1995). The philosopher's atom. *Discover, 16*(11).

Von Neumann, J., & Richtmyer, R. D. (1950). A method for the numerical calculation of hydrodynamical shocks. *Journal of Applied Physics, 21*, 232–247.

Wade, N. (1999, December 14). Life is pared to basics; Complex issues arise. *The New York Times,* Science, p. 1.

Walsh, D. (1969). *Literature and knowledge*. Middletown, CT: Wesleyan University Press.

Walton, K. (1990). *Mimesis as make-believe: On the foundations of the representational arts*. Cambridge, MA: Harvard University Press.

Warwick, A. (1995). The sturdy protestants of science: Larmor, Trouton and the earth's motion through the ether. In J. Buchwald (Ed.), *Scientific practice* (pp.). Chicago: University of Chicago Press.

Warwick, A. (2003). *Masters of theory; Cambridge and the rise of mathematical physics*. Chicago: University of Chicago Press.

Weber, M. (2007). Redesigning the fruit fly: The molecularization of *Drosophila*. In A. Creager, E. Lunbeck, & M. N. Wise (Eds.), *Science without laws* (pp. 23–45). Durham, NC: Duke University Press.

Weinberg, S. (1995). *The quantum theory of fields, Vol. 1, Foundations*. Cambridge: Cambridge University Press.

Weisberg, M. (2006). Robustness analysis. *Philosophy of Science, 73*, 730–742.

Weisberg, M. (2007). Who is a modeler. *British Journal for the Philosophy of Science, 58*, 207–233.

Welch, G. R., Kash, M. M., Iu, C., Hsu, L., & Kleppner, D. (1989). Positive-energy structure of the diamagnetic Rydberg spectrum. *Physical Review Letters, 62*, 1975–1978.

White, H. (1984). The question of narrative in contemporary historical theory. *History and Theory, 23*, 1–33.

White, J. G., Southgate, E., Nicol Thomson, J., et al. (1986). The structure of the nervous system of the nematode *Caenorhabditis elegans:* The mind of a worm. *Philosophical Transactions of the Royal Society of London, Series B*, *314*, 1–340.

Wilke, C. O., & Adami, C. (2002). The biology of digital organisms. *Trends in Ecology & Evolution, 17*, 528–532.

Wilson, C. (1983). Literature and knowledge. *Philosophy, 48*, 489–496.

Wilson, M. (2005). *Wandering significance*. Oxford: Oxford University Press.

Wimsatt, W. C. (1987). False models as means for truer theories. In M. H. Nitecki & A. Hoffman (Eds.), *Neutral models in biology* (pp. 23–55). New York: Oxford University Press.

Winsberg, E. (2003). Simulated experiments: Methodology for a virtual world. *Philosophy of Science, 70*, 105–125.

Winsberg, E. (2006a). Models of success vs. the success of models: Reliability without truth. *Synthese*, *152*, 1–19.

Winsberg, E. (2006b). Handshaking your way to the top: Simulation at the nanoscale. *Philosophy of Science*, *73*, 582–594.

Wollheim, R. (1980). *Art and its objects*. Cambridge University Press.

Woodward, J. (2003). *Making things happen: A theory of causal explanation*. Oxford: Oxford University Press.

Yablo, S. (1993). Is conceivability a guide to possibility? *Philosophy and Phenomenological Research*, *53*, 1–42.