The non-miraculous success of formal analogies in quantum theories

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The Higgs model was developed using purely formal analogies to models of superconductivity. This is in contrast to historical case studies such as the development of electromagnetism, which employed physical analogies. As a result, quantum case studies such as the development of the Higgs model carry new lessons for the scientific realism–anti-realism debate. I argue that, by breaking the connection between success and approximate truth, the use of purely formal analogies is a counterexample to two prominent versions of the 'No Miracles' Argument (NMA) for scientific realism, Psillos' refined explanationist defence of realism and the Argument from History of Science for structural realism (Frigg and Votsis 2011). The NMA is undermined, but the success of the Higgs model is not miraculous because there is a naturalistically acceptable explanation for its success that does not invoke approximate truth. I also suggest some possible strategies for adapting to the counterexample for scientific realists who wish to hold on to the NMA in some form.

1 Introduction

Historical case studies fuel the scientific realism—anti-realism debate. Core examples are the luminiferous ether models in the nineteenth century, which have been variously interpreted as (literally) false because the term 'ether' fails to refer (Laudan 1981), as giving an approximately correct representation of the structure of "the oscillations of something or other at right angles to the light" on which the modeled optical phenomena depend (Worrall 1989), as approximately true because the term 'ether' actually refers to the electromagnetic field (Psillos 1999), or as approximately true because light has the higher-order (i.e., multiply realizable), causal-nomologically specified property of satisfying a principle of superposition with respect to spatial components (Saatsi 2005). Mechanical ether models were one facet of a heuristic strategy of using analogies to develop a theory for electromagnetism. William Thomson initially drew analogies to Fourier's theory of heat to model electrostatics, and then James Clerk Maxwell picked up on Thomson's method of analogical reasoning and constructed analogue incompressible fluid and other mechanical models for electromagnetic phenomena. Later mechanical ether models were used as analogue models for electromagnetism. Analogical reasoning has also been widely used in quantum theory. However, the analogies that are employed in at least some cases in quantum theory are different in kind from those that figured in the development of electromagnetism. As a result, these case studies of analogical reasoning in quantum theory carry different morals for the scientific realism—anti-realism debate than the familiar luminiferous ether models.

My primary case study of the use of analogies in quantum theory is the development of the Higgs model by analogy to models of superconductivity. Quantum field theory (QFT) is the framework theory for the Higgs model and quantum statistical mechanics (QSM) supplies the framework for the pertinent models of superconductivity. Adam Koberinski and I have argued that the analogies drawn in this case are formal analogies that are not accompanied by physical analogies (Fraser and Koberinski 2016). That is, the analogical mappings from the source domain (superconductivity) to the target domain (the electroweak interaction) are *formal analogies* because they map elements of the models that play the same formal roles in the formal (mathematical) structures of the models. This is the principle on which the analogical mappings are determined, but of course this is compatible with the mapped elements also being physically similar in some respect, which would constitute accompanying *physical analogies*. However, in the Higgs case, the analogies are *purely formal analogies* (i.e., not also physical). This is a departure from the earlier use of analogical reasoning in the development of electromagnetism, in which there are both formal and physical analogies.

Cases of the successful use of formal analogies necessitate some modifications to our high level picture of how science works. The philosophical literature on analogies in science has been largely skeptical about the usefulness of purely formal analogies in science (e.g., Hesse (1966), Holyoak and Thagard (1995), Bartha (2010)). The reasons for skepticism about the efficacy of formal analogies are complex and varied, but one source is broadly realist intuitions about the relationship between success and truth in science that are captured by the 'No Miracles' Argument (NMA): the best explanation of the success of science is getting something approximately right about the world. The main line of argument developed in this chapter is that the successful use of purely formal analogies undermines this realist intuition by breaking the connection between success and approximate truth. Physical analogies are compatible with this realist intuition because they pick out physical similarities. Learning that a physical analogy holds between two systems confers knowledge of a physical fact about the target system. In contrast, learning that a purely formal analogy obtains does not deliver any substantial information about the physical world because a purely formal analogy does not rely on any physical similarities between the source and target domains.[1] Consequently, contrary to the NMA, the successful employment of purely formal analogies is not explained by the fact that we got something right about the world. The explanation held up by the NMA as the best explanation is not a candidate explanation in this case. However, this should not be taken to entail that the successful use of formal analogies is miraculous. I shall argue that there is a perfectly satisfactory explanation for the success of formal analogical reasoning, but that it does not involve getting something right about the world.

The central argument in this chapter is that the use of purely formal analogies in the development of the Higgs model (Sec. 3) is a counterexample to two versions of the NMA. The first version is Stathis Psillos' Refined Explanationist Defence of Realism, which concerns scientific methodology (Sec. 2 and 4). The second version is the Argument from the History of Science for structural realism (Frigg and Votsis 2011), which incorporates an inference to the approximate truth of the mathematical structure of theories (Sec. 5). When invoking either version of the NMA, it is tempting to cast the approximate truth of pertinent theories as the only correct explanation for the instrumental success of science. This position is ruled out by the successful use of purely formal analogies. Sec. 4.1, 5.1, and 6 consider possible responses to these arguments open to scientific realists who want to retain the NMA. It is the use of purely formal analogies that differentiates the Higgs model case study (and plausibly other cases in quantum theory (Sec. 3)) from the historical cases of the use of analogical reasoning such as electromagnetism, which informed these versions of the NMA. Thus, attention to quantum theories can contribute to the realism–anti-realism debate by bringing to light novel scientific methods not used in familiar historical cases.

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[1] This inference does not apply to Pythagorean views such as Tegmark's according to which the physical world is constituted by mathematics (Tegmark 2008). Such views will be set aside in this chapter.

2 The Refined Explanationist Defence of Realism and physical analogies

To motivate the analysis of the Higgs case study in the next section, consider the version of the 'No Miracles' Argument (NMA) advanced in Psillos (1999) and how it is supported by the historical development of electromagnetism. Psillos's Refined Explanationist Defence of Realism takes Boyd's explanationist defence of realism as its starting point (78). In accordance with a commitment to naturalism, the argument takes the form of an inference to the best explanation, a form of argument that is used in science, and the explanandum is the instrumental reliability of scientific methodology in general. Boyd asserts that all aspects of scientific methodology fall within the scope of the argument and offers as examples—in addition to the paradigm example of measurement procedures for theoretical magnitudes—"principles of experimental design, choices of research problems, standards for the assessment of experimental evidence and for assessing the quality and methodological import of explanations, principles governing theory choice, and rules for the use of theoretical language" (Boyd 1990, 361). Psillos concurs that "all aspects of scientific methodology are deeply theory-informed and theory-laden," and thus fall within the scope of the argument (78). Psillos refines Boyd's argument by explicitly recognizing that scientific methods sometimes fail and by localizing the inference to the approximate truth of only those aspects of theories that explain instrumental success (80). Here is Psillos' summary of his refined version of the argument:[2]

> *(REDR)* The best explanation of the instrumental reliability of scientific methodology is that: the theoretical statements which assert the specific causal connections or mechanisms by virtue of which scientific methods yield successful predictions are true. (78)

The core intuition is that the approximate truth of the theories that underwrite the methodologies is responsible for the instrumental success of the methodologies because the methods are theory-dependent.

Psillos argues that this core intuition and the REDR are borne out in the historical example of the development of electromagnetism. His interpretation of this case differs from the structural realist interpretation, but (as Psillos acknowledges) there is common ground between the two interpretations.[3] This common interpretation of the electromagnetism case study includes the noteworthy features that differentiate it from the Higgs model case study. Following Stein and Poincaré, Psillos emphasizes the role that analogical reasoning played in Maxwell's development of electromagnetism (137–145). Maxwell relied on the construction of analogue models for electromagnetic phenomena. For example, Maxwell (1861 [1890]) develops a mechanical model for a range of electromagnetic phenomena constructed out of molecular vortices connected by idle wheels. At the time, Maxwell regarded this model as a possible causal model for electromagnetic phenomena (i.e., that it is possible that electromagnetic phenomena are caused by the motions of the molecular vortices and idle wheel particles). If this possibility were actualized, then the model would not be merely an analogue of the model for electromagnetic phenomena, but identical with

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[2] More recently, Psillos has placed greater emphasis on the REDR being a two stage argument in order to clarify the role of inference to the best explanation reasoning (Psillos 2011). The arguments concerning formal analogies made here also apply to this articulation of the argument.

[3] And there are further differences between interpretations favoured by adherents of different variants of structural realism. Psillos addresses Worrall's variant of structural realism.

it. However, Maxwell believed that this was unlikely. Nevertheless, while this particular mechanical model was unlikely to be the correct model, he maintained that there was "good evidence" that electromagnetic phenomena have a mechanical cause (Maxwell 1873 [1954], 416–417).[4]

From our current perspective, Maxwell's vortex–idle wheel model incorrectly represents electromagnetic phenomena as having a mechanical cause. Nevertheless Maxwell was able to arrive at his equations for electromagnetism using this model. How? There is a *physical analogy* between his vortex–idle wheel model and the true model of classical electromagnetism: the causal relations between the centrifugal force of the molecular vortices and the rotation of light map to the causal relations between the magnetic force field and the rotation of the light. To more precisely characterize this analogy, the distinctions in Mary Hesse's 1966 account of analogies are useful. A *horizontal relation* is the analogical mapping of an element of the source model to an element of the target model. A *vertical relation* is a relation between elements within a single model (i.e., for either the source domain or the target domain). Hesse's paradigm example of vertical relations is causal relations.[5] In these terms, Maxwell's analogy maps vertical relations in the source domain (viz. the centrifugal force of the molecular vortices and the rotation of light) to vertical relations in the target domain (viz. the causal relations between the magnetic force field and the rotation of the light). This is a *physical analogy* because the mapped vertical relations are physically similar (i.e., both causal relations). In contrast, a *formal analogy* maps vertical relations that play similar formal (e.g., mathematical) roles. It is possible for analogies to be both physical and formal. *Purely formal analogies* are exclusively formal analogies. The completion of the treatment of electromagnetism within Lagrangian mechanics at the end of the nineteenth century supports this characterization of the physical analogy. It was recognized that an abstract Lagrangian can admit concrete models of different types, including both mechanical and non-mechanical models. The shared Lagrangian representation establishes that the models of the two types share the same causal structure. The abstract Lagrangian formulation of mechanics allows the posited energy of the ether to be expressed as a function of the classical fields (Stein 1989, 62).

It is common ground between Psillos and structural realists that Maxwell's reasoning invoked a physical analogy between vertical physical relations in the vortex–idle wheel model and vertical physical relations in the true model of classical electromagnetism. Psillos and structural realists part ways in their further specifications of what Maxwell got right. Psillos agrees that the *divide et impera* strategy of differentiated epistemic commitment to elements of theories is the right strategy for defending realism, but disagrees with an across-the-board epistemic commitment to structure (as opposed to content). He argues that the correct way to understand analogue ether models is to interpret the term 'ether' as having the same referent as the term 'electric field' in the fully developed theory of electromagnetism (296–297). The rationale for this interpretation is supplied by Psillos' casual descriptive theory of reference. The core natural kind-constitutive properties are shared by ether and the electric field, which allows them to play the same causal role in the production of electromagnetic phenomena. This diagnosis of the continuity between ether models and the full-blown classical field theory of electromagnetism also underwrites the application of the REDR. The method is the use of analogue models and the explanation for its success is

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[4] According to this view of Maxwell's, there is a physical analogy between vertical relations: the causal relations in the vortex–idle wheel model are mapped to causal relations in the true mechanical ether model. For example, in the vortex–idle wheel model, the centrifugal force of the vortices causes the magnetic rotation of light in the magneto-optical (aka Faraday) effect; there is a mechanical analogue of the centrifugal force in the true mechanical model (Harman 1998, 98–106).

[5] Hesse also uses the development of electromagnetism as a case study of analogical reasoning, but, for various reasons, her treatment differs from those discussed here.

that—when correctly interpreted—the term 'ether' in the analogue models and the term 'electric field' in the theory refer to the same entity, and thus generate approximately true statements about the causal mechanism that produces electromagnetic phenomena. It is essential to Psillos' interpretation that the ether model and the full theory of electromagnetism plausibly represent the same casual connections. This essential condition is satisfied because the analogies that Maxwell draws track similarities between the structures of the causal relations that are captured by the abstract Lagrangian framework.

Psillos' REDR incorporates an explanation of the instrumental success of science that is well-suited to the method of using physical analogies that map (vertical) causal relations in the source model to (vertical) causal relations in the target model. However, analogies that do not map causal relations (or mechanisms) would not be explained by the REDR. Purely formal analogies fall into this category. Thus, from the perspective of REDR, the use of purely formal analogies should not be an instrumentally reliable scientific method.[6] As we shall see in the next section, the historical development of the Higgs model does not conform to this expectation.

3 Formal analogies in the development of the Higgs model

3.1 Overview

The use of analogies to models of superconductivity in the development of the Higgs model is a very sophisticated example of analogical reasoning. The complexity of this case means that tracing the core sets of analogies involved is a non-trivial exercise. One complication is that analogies are drawn to two models of superconductivity, the phenomenological Ginzburg-Landau (GL) model and the dynamical Bardeen-Cooper-Schrieffer (BCS) model (Ginzburg and Landau 2009; Bardeen et al. 1957). Fraser and Koberinski (2016) offers a detailed analysis of this case study. To simplify matters for the present purpose of assessing the NMA, this overview will focus on the tighter of the two sets of analogies, those between the GL model and the Higgs model.

Initially, the analogy to superconductivity was motivated by the presence of effectively massive photons and effectively massive plasmons and the absence of massless bosons in the superconducting phase in the BCS model. In the superconducting phase, the global $U(1)$ gauge symmetry is broken. These features were noteworthy because they contradicted widely held beliefs in the particle physics community. At the time, particle physicists believed that the gauge bosons in Yang-Mills-type theories—such as the photon in electromagnetism—are necessarily massless (Jona-Lasinio 2002). Furthermore, on the strength of Goldstone's theorem, particle physicists believed that broken symmetries are necessarily accompanied by massless Goldstone bosons, and experiments on electroweak interactions had not turned up unaccounted for massless particles. The BCS model of superconductivity was suggestive, but was not regarded as decisive evidence that models of particle physics with massive gauge bosons and without massless Goldstone bosons are possible because the models of superconductivity are non-relativistic and models in particle physics are relativistic (Higgs 2014, 851). The analogies between effectively massive particles in superconductivity and genuinely massive particles in electroweak interactions supplied a starting point, but it was the set of formal analogies that followed that led to the construction of the Higgs model. It was counterexamples such as this, constructed by formal analogy to superconductors,

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[6] Psillos (following Hesse and Achinstein) includes formal analogies in his exposition of analogical reasoning, but purely formal analogies play no role in his defence of realism (141–142). This is understandable because the electromagnetism case study and the other historical cases that he considers use physical analogies.

which supplied the convincing evidence that spontaneous symmetry breaking (SSB) in relativistic particle physics need not be accompanied by massless Goldstone bosons.[7]

At the heart of the set of formal analogies are the order parameters and the infamous Mexican hat diagram. (See Table 1 below.) In the GL model, the order parameter that distinguishes the 'normal' state of the metal from the superconducting state is $\psi(\mathbf{x})$, which is the effective collective wave function for the superconducting electrons. ($\mathbf{x}$ represents space.) $|\psi(\mathbf{x})|^2$ is zero in the symmetric phase and non-zero in the broken symmetry phase. In the Higgs model, the analogue of $\psi(\mathbf{x})$ is the complex scalar quantum field $\phi(x)$ which (after manipulations) is associated with the Higgs boson. (x represents spacetime.) In the GL model, the central equation is the following expression for the free energy at the critical temperature:

$$\mathcal{F}_s = \mathcal{F}_n + a\,|\psi(\mathbf{x})|^2 + \frac{b}{2}\,|\psi(\mathbf{x})|^4 \tag{1}$$

where $\mathcal{F}_n$ represents the free energy density of the 'normal' metal. Parameters a and b are both functions of temperature T; SSB is only possible when $a < 0$. In the simpler Abelian Higgs model,[8] the formal analogy between the Lagrangian $\mathcal{L}$ and the free energy in the GL model is particularly transparent. The Higgs potential terms in $\mathcal{L}$ are

$$V_H = \mu^2|\phi(x)|^2 + \lambda|\phi(x)|^4 \tag{2}$$

V_H takes the same form as the final two terms in $\mathcal{F}_s$. Symmetry is broken when $\mu^2 < 0$. The Mexican hat diagram for the Higgs model represents $V_H(\phi)$ when symmetry is broken.

Table 1: Analogies between superconductor models and the Higgs model[9]

	Ginzburg-Landau (GL) model	**Higgs model**
1	$U(1)$ broken (global) gauge symmetry group	$SU(2)\times U(1)$ broken (local) gauge symmetry group
2	(limited-range) photon with effective mass (two transverse components)	massive W, Z bosons
3	plasmon with massive longitudinal component	massive Higgs boson
4	free energy density of superconducting state $\mathcal{F}_s$	Lagrangian $\mathcal{L}$
5	$a\|\psi(\mathbf{x})\|^2 + \frac{b}{2}\|\psi(\mathbf{x})\|^4$	$V_H = \mu^2\|\phi(x)\|^2 + \lambda\|\phi(x)\|^4$
6	collective wave function for superconducting electrons $\psi(\mathbf{x})$ as the order parameter	scalar particle field $\phi(x)$ as the order parameter
7	T	*no analogue*

Table 1 summarizes the analogical mappings between the GL and Higgs models. The rows of the table lay out the horizontally-related elements. The formal analogies are apparent in the mathematical expressions for the symmetries (row 1), Mexican hat terms of the free energy (GL) or Lagrangian (Higgs) (row 5), and order parameters (row 6), which are mathematical expressions of

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[7] Of course, this claim should not be read as Whiggish take on the history. See Wells (2018) for a discussion of the negative and skeptical attitudes with which the Higgs model was received.

[8] In the Abelian model, $U(1)$ symmetry is broken instead of $SU(2)\times U(1)$ symmetry. See Fraser and Koberinski (2016, 78) for details.

[9] Again, to minimize the technicalities, some entries in this table are drawn from the Abelian Higgs model.

the same type. The evidence that supports the conclusion that this set of analogies is purely formal comes from considering how the Mexican hat terms (i.e., Equations (1) and (2)) are derived and noting the substantial physical dissimilarities between the mapped elements. In both instances, the Mexican hat terms are produced by taking a symmetric Taylor expansion about some non-zero value of the order parameter. Coefficients multiplying odd powers of the order parameter are set to zero to ensure symmetry, and expansion to the fourth order is the lowest order expansion that leads to SSB. (In the case of the Higgs mechanism, this is also the largest renormalizable interaction term.) Thus, the formal similarities are largely due to the use of an approximation procedure that does not reflect any deep physical similarities between the two systems.

The mapped elements are formally similar, but there are substantial physical disanalogies because the mapped elements have different physical interpretations. For example, $\psi(\mathbf{x})$ is defined over space and is a collective (non-relativistic quantum mechanical) wave function that represents the collection of superconducting electrons; in contrast, $\phi(x)$ is defined over spacetime and is a (relativistic quantum field theoretic) scalar quantum field. More significant, however, are the disanalogies in the vertical relations. A noteworthy feature of the formal analogical mappings from the GL to the Higgs model is that they do not map vertical relations to vertical relations with the same physical interpretation. To see this, consider spontaneous symmetry breaking. In the GL model, SSB is a temporal process. For example, the model describes a temporal process in which a system at time t_1 is in a non-superconducting state and then transitions to a superconducting state at time t_2. This transition can be brought about by reducing the temperature of the system from the initial temperature T to a temperature below the critical temperature T_c, or vice versa. A popular table top demonstration of this effect is a maglev (i.e., magnetic levitating) train. The magnetic train track is initially cooled by placing it in dry ice, and then the magnetic train levitates above the track and moves almost frictionlessly along it. When the train is operated at room temperature, the track gradually warms until train no longer levitates. This is the point at which a phase transition occurs. The phase in which the train levitates is the broken symmetry phase; the phase in which the train does not levitate is the symmetric phase. There is no analogue of this temporal process in the Higgs model. The analogical mappings laid out in Table 1 do not map the temporal process in which symmetry is spontaneously broken in the GL model to a temporal process in the Higgs model.[10] Furthermore, the causal process of SSB in the GL model is not mapped to a causal process of SSB in the Higgs model. This follows from the fact that (whatever one's philosophical views on the relationship between temporal and causal order) causal processes are temporal processes. That the set of analogical mappings does not assign an analogue of the temperature T is a symptom of the fact that the analogical mappings do not respect the causal structure of the GL model.

Yet a further physical disanalogy is that the modal relations in the GL model are not mapped to modal relations of the same type in the Higgs model. For a given condensed matter system represented using the GL model, symmetric ground states and states in which the symmetry is broken can both be physically possible. In contrast, for a given particle physics system represented using the Higgs model, ground (i.e., vacuum) states which are symmetric and states in which the symmetry is broken are not both physically possible.[11]

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[10] The differences in the manners in which time is represented are particularly transparent in the algebraic frameworks for QSM and QFT. See Fraser and Koberinski (2016, 80–81)

[11] Note that this observation about the relationship between symmetric and broken symmetry vacuum states is separate from the much-discussed question in the philosophy of physics literature of whether, in the standard textbook presentation, the broken symmetry vacuum states related by the gauge transformation are physically equivalent. See Ruetsche (2011, Chapter 14) for further discussion. Struyve (2011) points out that early treatments

3.2 Explaining the successful development of the Higgs model

Anticipating the discussion of the ‘No Miracles’ Argument, what is the explanation for the successful application of formal analogical reasoning in this case? The contribution that this set of analogies made to the development of the Higgs model was to correct misconceptions that were prevalent in particle physics circa 1960, namely that it is not possible to have massive Yang-Mills bosons and that SSB is necessarily accompanied by massless Goldstone bosons. In the case of the massless Goldstone bosons, Goldstone’s theorem appeared to show that it was not possible to construct consistent mathematical models with the desired features. The formal analogies allowed particle physicists to recognize that the space of mathematically possible models was larger than they had realized. For probing mathematical or logical possibility, formal analogies are sufficient; a physical analogy is not necessary. Moreover, in this case the physical disanalogies actually contributed to the heuristic usefulness of the formal analogies. As a result of the physical disanalogies, key features of the superconductivity model were accessible to experiment. For example, the Meissner effect: beyond a small penetration depth, neither electric nor magnetic fields will be present within the superconductor, and the short range of the electromagnetic interaction is regarded as an indication of the effective mass of a photon. In contrast, it proved much more difficult to experimentally test the formally analogous features of the Higgs model. The genuinely massive W and Z bosons were not detected until 1983. Finally, this is admittedly speculative, but it seems plausible that the availability of an intuitive picture of SSB in superconductors aided the construction of the models. The collective behaviour of the spins on the lattice as temperature varies is intuitively pictureable, whereas there was no intuitive picture of the interaction of particles (or fields or ?) in QFT circa 1960. Recall that this was the hey day of the S-matrix program, which in its strongest form dispensed with field representations of the interacting system entirely.

I take this to be a satisfactory explanation of the instrumental success of formal analogies in this case. However, one might wonder, is there a post hoc explanation of the success of the analogical reasoning that reintroduces physical analogies? Table 1 lists no analogue for temperature T. Again Hesse’s distinctions are useful: a *positive analogy* is an analogy that is supported by evidence (at a time t) and a *neutral analogy* is an analogy that it is neither supported nor undermined by empirical evidence (at a time t). Was there a neutral analogy between temperature T in the GL model and temperature T in the electroweak theory in the early 1960’s that, with subsequent theorizing and experiment, has become a positive analogy? Contemporary wisdom is that SSB in the the electroweak sector occurred once in the early universe, when the temperature was approximately 200MeV (LeBellac 1996, xi). Do theoretical developments since 1964 offer a way to introduce temperature into the Higgs model as the analogue of temperature in the GL model, and thereby introduce analogical maps from temporal and causal processes in the GL model to such processes in the Higgs model?

The short answer is no. In brief, the problem with trying to consistently extend the set of analogies to include temperature (or causal or temporal processes more generally) is that time is already represented in the Higgs model. Within this model, it is not possible to add variables (e.g., T) that introduce new temporal processes because the time evolution of the system is already described by the Higgs model. Changing the description of the time evolution changes the model (i.e., describes a different system or the same system in different possible states). This would not help to explain why the original set of analogies between the Higgs model and the GL model is

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of the Abelian Higgs model were gauge invariant, including the derivation of the same effective Lagrangian as in standard textbook presentations.

successful.[12]

The contrast with the historical case of electromagnetism is illuminating. In that case, there are physical analogies that map causal relations in Maxwell's vertex–idle wheel model to causal relations in the subsequent field model for classical electromagnetism. In contrast, in the GL–Higgs case, causal relations in the GL model are not mapped to causal relations in the Higgs model, and the analogies are purely formal. Furthermore, the abstract Lagrangian formulation of electromagnetism subsumes the concrete ether and classical field models. The fact that both are concrete models of one abstract Lagrangian entails that the kinetic and potential energies attributed to elements of Maxwell's vortex–idle wheel model are functionally related to the values attributed to fields in the classical field model. In contrast, in the GL–Higgs case the models do not share a Lagrangian. The formal analogy is drawn between terms of the free energy of the superconducting state and the potential in the Lagrangian for the Higgs system (see row 5 of Table 1). This analogical mapping is intimately related to the fact that causal relations do not map to causal relations.[13]

Finally, a different approach to arguing that there is a physical analogy that lies behind the

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[12] At somewhat greater length: The account of the phase transition in the electroweak theory is given by relativistic field theory at finite temperature (aka thermal field theory), which was first proposed in 1965 and then rediscovered in the mid-1970s (LeBellac 1996, xi). Relativistic field theory at finite temperature is statistical mechanics for relativistic field theories; QSM is statistical mechanics for non-relativistic quantum mechanics (NRQM). That is, relativistic field theory at finite temperature is to QFT as QSM is to NRQM. The relationship between relativistic field theory at finite temperature and QFT does not lend itself to an extension of the set of analogies to include temperature because relativistic field theory at finite temperature is an application of statistical mechanics, not an extension of QFT. The details of relativistic field theory at finite temperature are complex, but temperature and other statistical mechanical properties are introduced in ways familiar from other applications of statistical mechanics. For example, particle physics systems are modeled in contact with heat baths (LeBellac 1996). This system is different from the system described by the Higgs model. An important difference in kind is that whereas the Higgs model describes a closed system, when a heat bath is added the Higgs model system is an open system (see Fraser and Koberinski (2016, Sec. 5.2) for further discussion). As a result, relativistic field theory at finite temperature does not help to add a temperature variable to the description of the system of interest, which is the system represented by the Higgs model. Put another way, relativistic field theory at finite temperature is applied to describe a statistical mechanical phase transition which breaks symmetry in a particle physics system, but this does not correspond to the representation of electroweak SSB in the Higgs model. To appeal to the statistical mechanical phase transition is to change the subject.

Another way of seeing that the set of analogical mappings cannot be consistently extended to include temperature is to trace the details of theoretical development of relativistic field theory at finite temperature from QSM. The strategy employed is to define a relativistic extension of an identity between the partition function in QSM and the trace in NRQM (LeBellac 1996, Chapters 2 and 3). For simplicity consider one dimension (the time dimension):

$$\begin{gathered} QSM:\ Z(\beta) = Tr(e^{-\beta H}) \\ NRQM:\ Tr(e^{-iH(t_f - t_i)}) \end{gathered}$$

where β is inverse temperature. The expressions are identified after the NRQM expression is transformed by (1) analytically continuing time ($t \to it$) and (2) setting $t_i = -\beta/2$ and $t_f = +\beta/2$. Time in relativistic field theory at finite temperature cannot both be identified with temperature in QSM *and* be taken (as a component of spacetime) as the analogue of space in QSM as it is in the analogies underlying SSB.

[13] The deeper justification for this analogical mapping comes from the effective action formalism for QFT (Jona-Lasinio 1964; Peskin and Schroeder 1995). This analysis compares the generating functional of correlation functions in statistical mechanics to the generating functional for propagators (or vacuum expectation values) in QFT. A further formal analogy is that, in both QFT and QSM, variational principles are used to determine the stable vacuum (QFT) or ground (QSM) states. The quantity in QFT that plays the formally analogous role to energy density in statistical mechanics is the Lagrangian density.

success of the reasoning in this case would be to contend that mass is the relevantly similar physical property of the two systems. After all, the motivation for drawing the analogy in the first place was that in the superconducting phase the superconductor has effectively massive photons and plasmons. However, while the physical property of effective mass motivated drawing analogies, the set of analogies that resulted from this starting point does not support the inference that there are relevant physical similarities between effective mass in the superconductor and genuine mass in the electroweak system. The physical interpretation of effective mass of the photon in the superconductor is tied to the physical process of mass gain (and shortening of range) when the system undergoes phase transitions, and there is no physical process in which mass is gained in the Higgs case. The physical interpretation of the mass of the plasmon comes from the collective behaviour of the lattice of atoms. This is also a physical dissimilarity between the superconductor and particle physics models: there is not even a lattice of material particles in the particle physics case. Mass in the superconductor is not physically similar to mass in the Higgs model; however, alternatives to the Higgs model ("Beyond the Standard Model" models) have been proposed in which the Higgs is a composite particle analogous to the Cooper pair bosons in the BCS model of superconductivity (e.g., the minimal technicolor model). But, once again, these models are based on a different set of analogies; the analogies invoked are not a consistent extension of the set laid out in Table 1.

4 The Refined Explanationist Defence of Realism revisited

Recall Psillos' summary of his Refined Explanationist Defence of Realism:

> *(REDR)* The best explanation of the instrumental reliability of scientific methodology is that: the theoretical statements which assert the specific causal connections or mechanisms by virtue of which scientific methods yield successful predictions are true.

The Higgs case study defies an explanation of this type. The method used is purely formal analogical reasoning. The application of this method in this case has been instrumentally successful. The most direct instrumental success of the Higgs model has been the detection of a particle consistent with the Higgs boson at the Large Hadron Collider in 2012, but the Higgs model has had many other more indirect instrumental successes. Even if the Higgs model were to eventually be supplanted by some "Beyond the Standard Model" model, it presumably has already surpassed the minimal standards for instrumental success required by Boyd and Psillos. Thus, the instrumental success of the method of formal analogical reasoning in the Higgs case is an instance of scientific methodology, the instrumental reliability of which is what Boyd and Psillos seek to explain.

However, the best explanation proposed by the REDR is not a possible explanation for the success of the method of purely formal analogical reasoning in the Higgs model case study. If the analogical mappings respected the causal structure, then getting this shared causal structure approximately right in both the superconductor and the electroweak models would be a candidate explanation of the successful use of the analogies. In Psillos' terms, the explanation would be that the theoretical statements asserting the causal connections in both models are approximately true. However, the analogical mappings *do not* map causal processes in the GL model of superconductivity to causal processes in the Higgs model. There is no shared causal structure of SSB that is common to the GL and Higgs models; therefore, the truth or falsity of the theoretical statements asserting causal connections within each of the two models is not relevant to explaining the success of formal analogical reasoning in this case.

In order for this Refined Explanationist Defence of Realism to support Psillos' own brand of realism, which relies on a causal-descriptive theory of reference, the restriction to "specific causal connections or mechanisms" is essential. However, in the context of his discussion of the Explanationist Defence of Realism, Psillos allows that the explanans may have a broader scope that includes "truth-like descriptions of causal mechanisms, entities, and laws" (81). Expanding the scope of the explanans in this way seems unlikely to serve to make it applicable to the GL–Higgs case. Recall from Sec. 3 that the purely formal analogies invoked in the development of the Higgs model do not relate similar physical descriptions of entities. An in depth discussion of what sorts of accounts of laws of nature would be robust enough to underwrite this explanation is beyond the scope of this chapter, but a significant obstacle to the appeal to laws is that the analogical mappings do not preserve the modal structure either. SSB in the GL model employs a notion of physical possibility that pertains to states dynamically accessible to a specified system. In contrast, SSB in the Higgs model employs a notion of physical possibility that does not pertain to states dynamically accessible to a specified system. Symmetric and broken symmetry vacuum states are possibilities for systems in different worlds which are not accessible from our world.

Ultimately, the problem with applying the explanationist defence of realism to the method of formal analogical reasoning does not lie with how causal connections, mechanisms, or laws of nature are spelled out. Consider this minimal version of the REDR:

> *(REDR′)* The best explanation of the instrumental reliability of scientific methodology is that: the theoretical statements by virtue of which scientific methods yield successful predictions are true.

Even this minimal version of the argument is inapplicable to the case study because the truth of statements in the GL model of superconductivity is not relevant to the success of the method for formulating the Higgs model for particle physics because there are no physical analogies between the models. Assume that we have gotten something approximately right about the superconductor system when we describe it with the GL model. We draw formal analogies to construct a new model for electroweak interactions in particle physics—the Higgs model. The Higgs model turns out to be instrumentally successful. The approximate truth of theoretical statements in the GL model *that describe superconductors* does not explain the instrumental success of the Higgs model *that describes electroweak interactions* because the GL model and Higgs model are related by purely formal analogies. The fact that the analogies are purely formal means that there are no relevant physical similarities between the condensed matter and particle physics systems (as described by the respective models). Neither the horizontally related elements nor the mapped vertical relations are physically similar. Thus getting something approximately right about the superconductor that is captured by theoretical statements in the GL model does not give us any reason to believe that we have thereby gotten the same something right about the analogue particle physics system that is captured by theoretical statements in the Higgs model.

Notice that the Higgs model case study undermines the REDR—an argument offered in support of scientific realism—and not scientific realism directly. The formal analogies presented in Table 1 do not rule out giving both the GL and Higgs models physical interpretations that include specifications of causal connections. What is ruled out are specifications of causal connections such that the analogical mappings in Table 1 map causal relations in the GL model to causal relations in the Higgs model. This leaves open the possibility of interpreting other relations in the Higgs model as causal relations. However, independent realist interpretations of the GL and Higgs models would not rescue the REDR. Since the causal structures in the GL and Higgs models would not be related by the formal analogies in Table 1, appeal to the sets of causal relations in each model would not explain the instrumental success of analogies.

Again, my thesis is not that the instrumental success of the method of formal analogical reasoning is miraculous. There is, I submit, a perfectly satisfactory explanation for the success of formal analogies: that formal analogies served to correct misconceptions about the mathematically possible models of SSB in particle physics. For this purpose, purely formal analogies are sufficient. Ironically, it is the REDR that makes a miracle out of the success of science in this case by insisting that success is to be explained by approximate truth.

4.1 Possible responses

The scientific realist who wants to hold on to this version of the NMA has several options for responding to case studies of purely formal analogical reasoning. One option is to rule out cases of this sort by considering them to fall outside the scope of scientific methods covered by the REDR. This would require principled grounds for exclusion. It would not be sufficient to exclude the method of formal analogical reasoning merely on the basis that it is used in the context of discovery rather than justification. Even supposing that a satisfactory distinction can be drawn between the contexts of discovery and justification, the case has been made that a variety of heuristic methods for formulating new theories are legitimate inductive methods (e.g., Post (1971)[14], Thagard (2012)). Furthermore, Boyd and Psillos are explicit that scientific methodology in general is the target of the argument and list examples of methods that fall squarely in the context of discovery (e.g., choice of research problems) (Boyd 1990, 361).

An apparently more promising strategy would be to exclude the method of purely formal analogical reasoning in particular from the scope of the argument on the grounds that it is not an instrumentally reliable method. Methods such as literally dreaming up new hypotheses and trial and error could be used to discover new theories, but fall outside the class of instrumentally reliable methods covered by the argument. However, this strategy for defending the REDR only appears to be more promising; ultimately, it seems unlikely to pan out. There are some clear differences between these unreliable methods and formal analogical reasoning. For instance, the method of formal analogical reasoning is more systematic and principled than either dreaming or trial and error. Formal analogical mappings are constrained by the requirement that they map elements that play similar formal roles in the theories for source and target domains. But the systematic and principled nature of the method does not automatically translate into instrumental reliability.

A number of philosophical accounts of analogical reasoning offer criteria for evaluating the strength of arguments from analogy (e.g., Hesse (1966), Holyoak and Thagard (1995), Bartha (2010)). In each of these accounts, sufficiently strong arguments from analogy confer plausibility on a hypothesis. Unfortunately, all of these accounts base their conclusions on physical analogies, not purely formal analogies, and the arguments do not carry over straightforwardly.

The reason that that formal analogical reasoning in the Higgs case is not tantamount to lucky guessing is that the success of the method is explicable. In the early 1960's, particle physicists mistakenly believed that it was not possible to construct models with SSB and the desired physical features (e.g., massive bosons). Formal analogies to models of superconductivity served as a corrective. Formal analogical reasoning was an appropriate method to use in this case because it allowed particle physicists to probe the space of mathematically possible models. This explanation

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[14] Post notes that the list of heuristic criteria covered in his paper is not exhaustive, and then cites formal analogies as an example (248).

of the success of formal analogical reasoning in this case undermines the charge that the method is instrumentally unreliable.

A stronger argument in support of the instrumental reliability of formal analogical reasoning would involve establishing that formal analogical reasoning has also led to instrumental success in other cases and that this instrumental success is also explicable. This is a large project, but a plausibility argument can be made for the first conjunct. Analogical reasoning has been a widely used method in the development of quantum theories. Of course, each of these cases needs to be analyzed individually to determine whether the analogies are formal, physical, or both. However, there is a suggestive pattern to these cases. Consider the two domains of condensed matter physics (e.g., phase transitions in superconductors) and particle physics (e.g., scattering of a few particles). There are many examples of concepts or mathematical frameworks that were passed back and forth between theories for these two domains. Dirac's 'hole theory' of the electron was possibly inspired by ionic crystal models of conductors constructed by Frenkel in the 1920s, and Dirac's idea was certainly picked up in solid state physics in the 1930s (Kojevnikov 1999). Renormalization techniques developed for QED in the 1940s and the associated concept of dressed electrons were exported from QED to solid state physics in the 1950s (e.g., Bohm and Pines' electron gas model for metals introduces an effective heavy electron and plasmons) (Blum and Joas 2016). During the same period, Feynman diagrams were borrowed from QED to solve formally analogous perturbative expansions in quantum statistical mechanics (QSM) in which the formal analogue of time in QED is imaginary inverse temperature in QSM (Matsubara 1955; Abrikosov et al. 1975). In the early 1970's, Kenneth Wilson and collaborators developed renormalization group (RG) methods for condensed matter physics and particle physics by pushing analogies between classical statistical mechanical models of phase transitions and quantum field theoretic models of interactions (Wilson and Kogut 1974). In this case, the analogue of time t in QFT is imaginary space ix. (Fraser (forthcoming) offers an account of these analogies and argues that the analogies are purely formal.) The pattern is that in each of these cases the analogies are drawn between a non-relativistic quantum or classical model and a relativistic quantum field theoretic model. In the GL–Higgs case study, the root cause of the analogical mappings failing to respect temporal, causal, and modal structure is that a non-relativistic model is mapped to a relativistic model. Plausibly, the analogical mappings in the other cases carry similar implications.

There is also a practical consideration that makes excluding formal analogical reasoning from philosophical consideration seem unappealing. If formal analogical reasoning is indeed as prevalent a tool in the development of recent and contemporary quantum theories as it seems to be, then disregard for this scientific method in philosophy of science carries the cost of making philosophy less relevant to live foundational issues in physics. Carefully tracing complex patterns of analogical reasoning and attending to the interpretive consequences is the the kind of project that philosophers are well placed to undertake.

5 The Argument from the History of Science for structural realism

A shift from variants of realism committed to continuity of reference of theoretical terms (e.g., Psillos' position) to variants of realism committed to continuity at the level of physical structure (e.g., variants of structural realism) is accompanied by a shift in the formulation of the NMA. The Higgs case undermines the structural realist version of the NMA in a different way because structural realism's attention to the mathematical structure of theories emphasizes the same aspect of theories that informs formal analogies. In their 2011 review paper on structural realism, Roman Frigg and Ioannis Votsis survey Poincaré's and Worrall's arguments from the history of science for what has come to be known as epistemic structural realism. They extract the following argument incorporating a version of the NMA:

> (4a) Only two elements of a theory get preserved through theory change: (a) the theory's mathematical formulation, and (b) the empirical interpretation of the theory's terms.
> (4b) A theory's mathematical formulation 'encodes' the structure of that theory's target domain.
> (4c) Preservation of an element is a reliable guide to its (approximate) truth.
> (4d) Non-preservation of an element is a reliable guide to its (approximate) falsity.
> Therefore, the preservation of structural elements through theory change is a reliable guide of their (approximate) truth. The non-preservation of non-structural elements is a reliable guide of their (approximate) falsity. (243)

They note that premises (4c) and (4d) "incorporate an instance of the NMA" (243). In contrast to Psillos' REDR, the explanandum is not the instrumental reliability of scientific methodology, but the instrumental success of a given theory. The explanans appeals not to specific causal connections or mechanisms, but to the physical structure of the theory's target domain (which may or may not include causal relations).

Cases of formal analogical reasoning undermine this argument by presenting a counterexample to premise (4c). The instantiation of (4c) that is important for the structural realist is that in which the element is the theory's mathematical formulation: *Preservation of a theory's mathematical formulation is a reliable guide to the (approximate) truth of a theory's mathematical formulation* where (by 4(b)) truth means " 'encoding' " the (physical) structure of the theory's target domain. The use of purely formal analogical reasoning in the the GL–Higgs case study constitutes a counterexample to this inference because the theory's mathematical formulation is preserved but this does not supply any indication about whether the theory's mathematical formulation is approximately true. In this case, the theory is the GL model. Core aspects of the mathematical formulation of the GL model are (approximately) preserved in the Higgs model; this is what the formal analogical mappings establish. However, contrary to (4c), the mathematical formulation that is preserved cannot be taken to be an approximately true 'encoding' of the shared physical structure of the superconductor and electroweak systems because the systems do not share a physical structure. There are no physical analogies; the formal analogies do not map physical relations to physical relations of the same type. In particular, neither causal nor modal relations are preserved by the mappings, which precludes two prominent structural realist strategies for characterizing physical structure.

5.1 Possible responses

The structural realist may object that cases of formal analogical reasoning are irrelevant because they do not relate versions of one theory which are diachronically related. Premise (4a) concerns "elements of a theory [that] get preserved through theory change." An example would be a nineteenth century version of electromagnetism that includes ether and a twentieth century version of electromagnetism that posits classical fields and does not include ether. In contrast, the GL model of superconductivity and the Higgs model are not diachronically related versions of the same theory; they apply to different domains of phenomena and are contemporaneous. However, this objection does not address the argument in Sec. 5. The argument is an argument against premise (4c), which states that preservation of mathematical structure is a reliable guide to its (approximate) truth. Cases of formal analogical reasoning are counterexamples: cases of successful theory development in which there is shared mathematical structure between theories and not shared physical structure. The Higgs case demonstrates that the preservation of mathematical structure by intertheoretic relations is not an indicator of shared physical structure. Why couldn't the same situation arise in the special case in which the theories in question are theories for the same domain?

The problem posed by formal analogical reasoning is familiar to structural realists: in order to constitute a genuine variant of realism, the preserved mathematical structure must represent physical structure. Mathematical structure that does not play a representative role would reduce the position to Pythagoreanism; mathematical structure that represents empirical structure but not underlying physical structure would reduce the position to anti-realist empiricism. (See Ruetsche (this volume) for further discussion of the latter challenge.) The Higgs case study eliminates some of the structural realist's best resources for steering a course between Pythagoreanism and anti-realist empiricism. For example, French (2014) defends a variant of ontic structural realism according to which physical structure is modal structure, but the GL and Higgs models cannot be interpreted as encoding the same modal structure.

One variant of ontic structural realism may be equipped with a strategy for responding to this challenge posed to the Argument from the History of Science for epistemic structural realism by the Higgs case study. In their review of Wallace's defence of the Everett interpretation of quantum theory in *The Emergent Multiverse*, Guido Bacciagaluppi and Jenann Ismael reflect that

> ...the book provides the most comprehensive and best exemplar of a new—and distinctly modern—way of doing metaphysics. On this way of doing metaphysics, one takes one's fundamental ontology from physical theories at face value and simply does the hermeneutic work of trying to understand the structures implicit in the formalism, connecting them with structures that are most readily manifest in our experience of the world, and seeing what needs to be done to accommodate old ideas (about ourselves and our place in nature) to a new world-view. (18)

Applying this interpretive approach to the Higgs case, the response would be that none of our familiar notions of physical structure are preserved by the analogies, but this just means that we need to exercise ingenuity in characterizing new kinds of physical structure that are preserved (i.e., accommodating our metaphysics to a new world-view). Of course, there is nothing that stands in the way of adherent of this stripe of ontic structural realism pursuing this research program. But bear in mind that this position is being introduced to rescue the NMA for scientific realism; therefore, scientific realism cannot be assumed. At a minimum, this research program would have to be successfully completed in order to yield an argument for scientific realism.

6 Conclusion

The main conclusion defended in this chapter is that getting some fact about the world essentially correct is not always a candidate explanation for success in science, which runs contrary to the spirit and the letter of the NMA. Evidence in support of this conclusion is furnished by the instrumentally successful use of purely formal analogies in the development of the Higgs model.

This is a case of successful theory development that is not underwritten by approximately veridical representation. The analogies drawn between the GL model of superconductivity and the Higgs model for the electroweak interaction are purely formal. They are not accompanied by physical analogies. In particular, the analogical mappings do not map temporal structure, causal structure, or modal structure in the GL model to structure of the same physical kind in the Higgs model. As a result, this case study undermines both Psillos' Refined Explanationist Defence of Realism and the NMA-inspired premise of the Argument from the History of Science for structural realism. In the former case, the success of the method of purely formal analogical reasoning cannot be explained by appeal to causal relations or even to approximate truth. In the latter case, the Higgs case study blocks the inference from the preservation of formal structure to the formal structure approximately encoding physical structure. Nevertheless, the construction of the Higgs model is not an example of the miraculous success of science. The explanation for the successful use of purely formal analogies in this case is that this was a suitable method for solving the problem that particle physicists had mistakenly ruled out mathematical models that in fact were mathematically or logically possible. The target of the arguments in this chapter is the NMA for scientific realism, not scientific realism itself. The adoption of separate (i.e., not related by the analogies) realist interpretations of the GL and Higgs models is not precluded, as long as the NMA is not invoked.

In response to these arguments, a scientific realist could concede the point and give up on the NMA. This would of course entail reliance on other arguments to support scientific realism. There are several other potentially viable lines of response for scientific realists who wish to hang on to the NMA. One response, mooted in Sec. 5.1, would be to adopt a variant of ontic structural realism which takes as its starting point the commitments that the formal structures in a theory represent the structure of the world and that one aspect of the project of interpreting the theory is to (if necessary) revise our ontology to accord with the formal structures. Of course, how compelling this approach is would hinge on the details of how the ontological structure gets spelled out.

A third response to this counterexample to the NMA would be to concede that the blanket intuition behind the NMA does not hold universally, and to revise the argument accordingly. That is, the scientific realist could concede that approximate truth only explains the success in science in a restricted set of cases. However, this would be a substantial concession. The worry is that weakening the NMA in this way would leave the NMA vulnerable to other lines of objection. The argumentative strategy in this chapter is to raise a counterexample in which the proposed best explanation for the instrumental success of science is not even a candidate explanation. This is in contrast to the more popular strategy for arguing against the NMA, which is to contend that rival candidate explanations for the instrumental success of science are actually superior to the best explanation proposed by the NMA. For example, Ruetsche (this volume) draws on analysis of the use of renormalization group methods in particle physics to argue for humble empiricism, which denies that approximately true representation of the world (at all energy scales) is the best explanation for the instrumental success of renormalization group methods in particle physics (at low energy scales). If the NMA were modified to include a restriction on its scope, then it would become more difficult to fend off arguments such as this. If it is possible to have instrumental success without approximate truth in some cases, why should the best explanation for instrumental success be approximate truth in other cases (i.e., cases within the intended scope of restricted NMA)?

The use of purely formal analogies in the Higgs case—and plausibly more widely in the development of quantum theories—reveals that quantum theories carry new implications for the scientific realism–anti-realism debate. The underlying reason is that the debate has been informed by historical case studies, such as the use of analogies in the development of electromagnetism, which use different methods. For scientific realists, an additional consequence of the Higgs case study is that the use of purely formal analogies affects how one fixes an interpretation for a theory. For example, in the Higgs case, the fact that the analogies to superconductivity are purely formal means that it is not licit to export the physical interpretation of SSB from superconductivity to particle physics (e.g., genuine mass in the Higgs model does not have the same physical interpretation as effective mass in the GL model, there is no causal process in which mass is gained in electroweak systems). It is tempting to export the physical interpretation from the superconductor model to the electroweak model because there is a clearer physical picture behind the superconductor model. However, this temptation needs to be resisted—not only in the Higgs case, but also in other cases in which the analogies linking models are purely formal. Scientific realists need to be alert to the possibility of purely formal analogies in order to properly interpret theories.

Another broader moral for the scientific realism–anti-realism debate is that quantum theories exhibit different patterns of development than their precursors, which affects where one should look for relevant case studies. Participants in the debate have primarily been interested in the history of science as a source of evidence for either continuity in theories over time (approximately, in some respects) or else discontinuity in theories over time. This has focused attention on diachronic sequences of theories for a single domain. For example, in the domain covered by what is now known as condensed matter physics (which includes, e.g., phase transitions in superconductors), a relevant diachronic sequence of theories is classical statistical mechanics, non-relativistic quantum mechanics (including many-body quantum theory), and quantum statistical mechanics. To take another example, in the domain covered by what is now known as particle physics (which includes, e.g., scattering phenomena) one of the diachronic sequences of theories that is of interest is classical particle mechanics, non-relativistic quantum mechanics, and relativistic quantum field theory. While case studies of theoretical change in a single domain are interesting and important for the scientific realism debate, this focus excludes a prominent pattern of historical development in quantum theories in the twentieth century: the formulation of new theories (or models) based on *synchronic* relations between theories that apply to *different domains*. Reasoning by analogy has served as a mechanism for transferring concepts and frameworks from one domain to another. This pattern of theory development deserves more attention in the scientific realism–anti-realism debate.

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References

Abrikosov, A. A., L. P. Gorkov, and I. E. Dzyaloshinski (1975). *Methods of quantum field theory in statistical physics.* Dover Publications, Inc., New York. Republication, with corrections, of the revised English edition (1963), Translated from the Russian and edited by Richard A. Silverman.

Bacciagaluppi, G. and J. Ismael (2015). Essay Review: David Wallace, The Emergent Multiverse. *Philosophy of Science 82*(1), 129–148.

Bardeen, J., L. N. Cooper, and J. R. Schrieffer (1957). Theory of superconductivity. *Phys. Rev. (2) 108*, 1175–1204.

Bartha, P. F. (2010). *By Parallel Reasoning: The Construction and Evaluation of Analogical Arguments.* Oxford University Press, Oxford.

Blum, A. S. and C. Joas (2016). From dressed electrons to quasi-particles: The emergence of emergent entities in quantum field theory. *Studies in the History and Philosophy of Modern Physics 53*, 1–8.

Boyd, R. (1990). Realism, approximate truth, and philosophical method. In C. W. Savage (Ed.), *Scientific Theories*, pp. 355–391. University of Minnesota Press.

Fraser, D. (forthcoming). The development of renormalization group methods for particle physics: Formal analogies between classical statistical mechanics and quantum field theory. *Synthese*. DOI: 10.1007/s11229-018-1862-0.

Fraser, D. and A. Koberinski (2016). The Higgs mechanism and superconductivity: A case study of formal analogies. *Studies in the History and Philosophy of Modern Physics 55*, 72–91.

French, S. (2014). *The Structure of the World: Metaphysics and Representation.* OUP Oxford.

Frigg, R. and I. Votsis (2011). Everything you always wanted to know about structural realism but were afraid to ask. *European Journal for Philosophy of Science 1*(2), 227–276.

Ginzburg, V. L. and L. D. Landau (2009). On the Theory of Superconductivity. In *On Superconductivity and Superfluidity: A Scientific Autobiography*, pp. 113–137. Berlin, Heidelberg: Springer Berlin Heidelberg.

Harman, P. (1998). *The Natural Philosophy of James Clerk Maxwell.* New York: Cambridge University Press.

Hesse, M. B. (1966). *Models and Analogies in Science.* University of Notre Dame Press, Notre Dame, IN.

Higgs, P. W. (2014). Nobel lecture: Evading the Goldstone theorem. *Rev. Mod. Phys. 86*, 851–853.

Holyoak, K. J. and P. Thagard (1995). *Mental Leaps: Analogy in Creative Thought.* MIT Press, Cambridge, MA.

Jona-Lasinio, G. (1964). Relativistic field theories with symmetry-breaking solutions. *Nuovo Cimento 34*, 1790–1794.

Jona-Lasinio, G. (2002). Cross fertilization in theoretical physics: The case of condensed matter and particle physics. In A. e. a. Fokas (Ed.), *Highlights of Theoretical Physics*, pp. 143–152. Providence, RI: Americal Mathematical Society.

Kojevnikov, A. (1999). Freedom, collectivism, and quasiparticles: Social metaphors in quantum physics. *Historical Studies in the Physical and Biological Sciences 29*(2), 295–331.

Laudan, L. (1981). A confutation of convergent realism. *Philosophy of Science 48*(1), 19–49.

LeBellac, M. (1996). *Thermal Field Theory.* New York: Cambridge University Press.

Matsubara, T. (1955). A new approach to quantum-statistical mechanics. *Progress of Theoretical Physics 14*(4), 351–378.

Maxwell, J. C. ([1861] 1890). On physical lines of force. In W. Niven (Ed.), *The scientific papers of James Clerk Maxwell*, Volume I, pp. 452–513. Cambridge: Cambridge University Press.

Maxwell, J. C. ([1873] 1954). *A treatise on electricity and magnetism* (3rd ed.). New York: Dover.

Peskin, M. E. and D. V. Schroeder (1995). *An introduction to quantum field theory.* Reading, MA: Addison-Wesley Publishing Company Advanced Book Program. Edited and with a foreword by David Pines.

Post, H. R. (1971). Correspondence, invariance and heuristics: In praise of conservative induction. *Studies in History and Philosophy of Science Part A 2*(3), 213–255.

Psillos, S. (1999). *Scientific Realism: How Science Tracks Truth.* Routledge.

Psillos, S. (2011). The scope and limits of the no miracles argument1. In D. Dieks, W. Gonzalo, T. Uebel, S. Hartmann, and M. Weber (Eds.), *Explanation, Prediction, and Confirmation*, pp. 23–35. Springer.

Ruetsche, L. (2011). *Interpreting quantum theories.* New York: Oxford University Press.

Saatsi, J. (2005). Reconsidering the Fresnel–Maxwell theory shift: How the realist can have her cake and eat it too. *Studies in History and Philosophy of Science Part A 36*(3), 509–538.

Stein, H. (1989). Yes, But... Some Skeptical Remarks on Realism and Anti-Realism. *Dialectica 43*(1-2), 47–65.

Struyve, W. (2011). Gauge invariant accounts of the Higgs mechanism. *Studies in the History and Philosophy of Modern Physics 42*, 226–236.

Tegmark, M. (2008). The mathematical universe. *Foundations of Physics 38*(2), 101–150.

Thagard, P. (2012). *The Cognitive Science of Science: Explanation, Discovery, and Conceptual Change.* MIT Press.

Wells, J. D. (2018). Beyond the hypothesis: Theory's role in the genesis, opposition, and pursuit of the Higgs boson. *Studies in History and Philosophy of Modern Physics 62*, 36–44.

Wilson, K. G. and J. Kogut (1974). The renormalization group and the ϵ expansion. *Physics Reports 12*, 75–200.

Worrall, J. (1989). Structural realism: The best of both worlds? *Dialectica 43*(1-2), 99–124.