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Essay review

The Higgs mechanism and superconductivity: A case study of formal analogies

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ABSTRACT

Following the experimental discovery of the Higgs boson, physicists explained the discovery to the public by appealing to analogies with condensed matter physics. The historical root of these analogies is the analogies to models of superconductivity that inspired the introduction of spontaneous symmetry breaking (SSB) into particle physics in the early 1960s. We offer a historical and philosophical analysis of the analogies between the Higgs model of the electroweak (EW) interaction and the Ginsburg–Landau (GL) and Bardeen–Cooper–Schrieffer (BCS) models of superconductivity, respectively. The conclusion of our analysis is that both sets of analogies are purely formal in virtue of the fact that they are accompanied by substantial physical disanalogies. In particular, the formal analogies do not map the temporal, causal, or modal structures of SSB in superconductivity to temporal, causal, or modal structures in the Higgs model. These substantial physical disanalogies mean that analogies to models of superconductivity cannot supply the basis for the physical interpretation of EW SSB; however, an appreciation of the contrast between the physical interpretations of SSB in superconductivity and the Higgs model does help to clarify some foundational issues. Unlike SSB in superconductivity, SSB in the Higgs sector of the Standard Model (without the addition of new physics) is neither a temporal nor a causal process. We discuss the implications for the 'eating' metaphor for mass gain in the Higgs model. Furthermore, the distinction between the phenomenological GL model and the dynamical BCS model does not carry over to EW models, which clarifies the desiderata for the so-called 'dynamical' models of EW SSB (e.g., minimal technicolor). Finally, the development of the Higgs model is an illuminating case study for philosophers of science because it illustrates how purely formal analogies can play a fruitful heuristic role in physics.

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1. Introduction

The Higgs mechanism, and the application of spontaneous symmetry breaking (SSB) in particle physics more widely, has historical origins in condensed matter physics. According to the Bardeen–Cooper–Schrieffer (BCS) model of superconductivity, low-temperature superconductivity occurs when the ground state of a metal has a lower symmetry than the solid itself (at sufficiently low temperatures), and when the metal is in this state, electrons condense together to form bound states (Cooper pairs). Nambu noticed (in 1960) the formal similarities between the BCS model and the Dirac equation, and so borrowed the concept for what turned out to be an effective theory of quantum chromodynamics (QCD). With this move, SSB became a valuable heuristic tool in particle physics. It was employed by Higgs, Englert, Brout, and others in 1964 to introduce massive gauge bosons into quantum field theory. The Higgs mechanism ended up being a key ingredient in the renormalizable theory produced by the Glashow–Weinberg–Salam (GWS) electroweak (EW) unification (1967).

The aim of this paper is to determine what analogies to superconductivity reveal about the physical interpretation of the Higgs mechanism. While there is a tradition of using analogies to condensed matter physics to explain the Higgs mechanism and the Higgs boson to a lay audience and to physics students, there has

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been a recent resurgence in such explanations with the celebrated discovery of the Higgs boson at the Large Hadron Collider. One of the best analogies of this type is David Miller's from 1993, for which he won a bottle of champagne in a competition from then UK Minister of Science William Waldegrave (and which played a role in the UK's approval of funding for the Large Hadron Collider). Miller draws his analogy between three domains: British politics, solid state physics, and the Higgs model. A room full of politicians evenly distributed is taken as the analogue of the Higgs vacuum. As a noteworthy politician enters the room, the distribution of people distorts to cluster around her, providing resistance to her motion through the room. The politician is the analogue of a W or Z boson, the people clustering around her represent the interaction between a particle and the Higgs field, and the resisted motion is the analogue of the acquisition of mass. Likewise, a rumor of scandal can cause clustering in the room, and this cluster travels as the rumor spreads amongst the politicians. The cluster occurs without an external politician (particle) present, and these clusters in the politician 'field' are the analogues of the Higgs boson (Miller, 1993). Analogies such as this help the public and physics students gain intuitive understanding of the formal framework of the Higgs mechanism. Whether the analogies also convey information about the physical interpretation of the formalism depends on a more detailed analysis of the types of analogies that have been successfully employed. Our main analytical tool will be to clearly distinguish formal analogies between superconductivity and EW SSB from material and physical analogies. We argue that the Higgs model demonstrates that purely formal analogies can play a fruitful heuristic role in physics; this is a case in which formal analogies are not underwritten by a further physical or material analogy, yet have proven to be very useful.

The Higgs mechanism is a remarkably good case study of the heuristic use of analogies in contemporary physics because it is widely recognized that there are two models of superconductivity—the BCS and Ginzburg–Landau (GL) models—which support different types of analogies. The BCS model is a *dynamical* model that offers a dynamical mechanism for the transition from 'normal' to superconducting states (i.e., the formation of Cooper pairs). In contrast, the GL model, first proposed by Ginzburg and Landau prior to the BCS model, is (merely) a *phenomenological* model because it does not offer a dynamical mechanism for superconductivity. Formally, the Higgs model is clearly a closer analogue to the GL model than the BCS model. The analogies to the two models of superconductivity are widely recognized in historical accounts of the discoveries. For example, in his Nobel prize address, Higgs explains that "Nambu's models were inspired by the Bardeen, Cooper, and Schrieffer theory (Bardeen, Cooper, & Schrieffer, 1957), based on Bose condensation of Cooper pairs of electrons: Goldstone used scalar fields, with a "wine bottle" potential to induce Bose condensation, as in the earlier Ginzburg–Landau theory" (2014, p. 851).[1] There are also good treatments of analogies to both models in the contemporary physics textbook and review article literature. (For example, Marshak, 1993; Quigg, 2007; Witten, 2007 offer clear presentations.) The success[2] of the analogies to superconductivity in providing a heuristic for formulating the Higgs model set another program in motion: the program of devising a new model for electroweak interactions that is more closely analogous to the BCS model than the GL model. A number of such dynamical SSB models have been proposed, including the quark composite model, the electroweak perturbation model, and different versions of technicolor.

The first part of the paper is devoted to a historical and philosophical analysis of the types of analogies that hold between the Higgs model and the GL and BCS models, respectively. For this purpose, we distinguish between three types of analogies: formal, physical and material. We use Hesse's (1966) account of analogies to frame our discussion. Roughly, formal analogies map similar elements of the mathematical formalisms of the models; physical analogies map elements of the models with similar physical interpretations; and material analogies map the causal structures of the models. In Section 3 we give brief expositions of the GL model, the BCS model, and the Higgs model. After identifying the formal analogies between the BCS and GL models, respectively, and the Higgs model in Section 4, we turn to the prospects for physical and material analogies between the models in Section 5. The formal analogical mappings do not map the temporal, modal, or causal structures of the superconductivity models to temporal, modal, or causal structures in the Higgs model. We argue that these crucial differences between the physical interpretations of the analogues rule out material and physical analogies between the BCS and GL models, respectively, and the Higgs model. Furthermore, the distinction between phenomenological and dynamical models gleaned from the GL and BCS models is not applicable to the Higgs model. The material and physical disanalogies between the superconductivity models and the Higgs model also entail that neither the BCS model nor the GL model supplies a guide for the physical interpretation of the Higgs field or the Higgs boson.

Our treatment of the Higgs mechanism is for the most part orthogonal to one of the dominant strands in the philosophical literature. Earman (2002) draws attention to the problem that, according to standard presentations of the Higgs mechanism in the contemporary physics literature, particles gain mass as a result of choosing a particular gauge; this is at odds with philosophical accounts according to which a gauge symmetry is supposed to represent "descriptive fluff," a mere redundancy in the mathematical representation without physical content. Earman thus demands that an adequate account of the Higgs mechanism be gauge invariant in order to determine its physical interpretation. Our discussion of the Higgs mechanism is for most part orthogonal to these issues because we focus on historical presentations of the Higgs model. Analogies to superconductivity were most influential in the development of the EW component of the Standard Model c.1960-6. At this time gauge invariant presentations of SSB were current (Struyve, 2011). As a result, the analogies examined here do not hinge on the choice of a particular gauge. The mass gain metaphor will be discussed in its historical context in Section 5.4.

While our main conclusion is the negative one that models of superconductivity do not help to inform the physical interpretation of the Higgs mechanism, the points of contrast with superconductivity do serve to clarify some foundational issues, particularly regarding the role of time in the Higgs model. We emphasize that the scope of our arguments in Sections 3–5 (i.e., excluding Section 6) is limited to the Higgs mechanism *as presented in the Standard Model of particle physics*. We take it that this focus on the theoretical presentation of EW SSB in the Standard Model is in keeping with most of the philosophical discussion of EW SSB to date. To clarify, questions about the physical interpretation of SSB in the Higgs sector of the Standard Model are questions about the possible world described by the Higgs model. This possible world may well not be the actual world. In particular, one of the main points that we want to stress to our philosophical audience is that—unlike SSB in superconductivity—SSB in the

[1] In the historical literature, Brown and Cao opine that "Nambu's approach is 'microscopic', and comparable to the BCS-Bogoliubov theory" whereas "Goldstone's is 'macroscopic', in the sense of 'phenomenological', comparable to the Landau–Ginzburg theory" (Brown & Cao, 1991, p. 232).

In his Nobel prize lecture, Nambu notes that "[t]he [Weinberg–Salam theory of electroweak unification] resembles the Ginzburg–Landau description of superconductivity, which was shown to follow from the BCS theory by Gor'kov" (Nambu, 2008, p. 62).

[2] At least conceptually; the direct empirical success of the Higgs model of course took much longer to establish.