Formal analogies in the development of electromagnetism and the Higgs model

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A heuristic for theory development in physics is to draw formal analogies to theories applied in different physical domains. Perhaps the first use of this strategy in the history of physics was William Thomson's use of formal analogies to Fourier's theory of heat in his development of a mathematical theory of electrostatics in the 1840s. Since then, there have been many examples in which formal analogies have been the basis for developing a theory in one physical domain by applying a mathematical framework articulated in the context of a theory applied in a different physical domain. This paper will consider the example of analogies to theories of low-temperature superconductors in solid state physics that were the basis for the development of the Higgs model in particle physics in the 1960s. I will briefly argue that the development of electromagnetism by Thomson and James Clerk Maxwell (among others) in the nineteenth century and the development of the Higgs model in the twentieth century are both examples of the successful application of the heuristic strategy of drawing formal analogies to theories in different physical domains. I will focus on two respects in which this illuminates the Higgs model case study: (1) the analogy with superconductivity does not supply a physical interpretation for the Higgs field or the Higgs boson in the same way that the analogies with theories of fluids and mechanical systems did not underwrite a physical interpretation of a luminferous ether in electromagnetism, and (2) formal analogies were useful in developing both electromagnetism and the Higgs model because physicists lacked physical intuitions about the subject matter of the theories. The electromagnetism case study is better understood than the Higgs model case study, in part because historical distance allows philosophers, historians, and physicists the benefit of hindsight and because there has been more opportunity for analysis. This is why integrated HPS is a fruitful approach to understanding the Higgs model.

Maxwell's investigations of electromagnetism leading up to his formulation of Maxwell's equations were inspired by Thomson's analogies. His early work on electromagnetism introduced a model of an incompressible fluid ([1856] 1890, 155); in later work he developed a mechanical model for electromagnetism that employs molecular vortices in an ether connected by idle wheels ([1861] 1890, [1873] 1954). Maxwell did not believe any of these models accurately represented the mechanism for the production of electromagnetic phenomena, but he did take his models to be a sort of proof of concept' that there is some mechanical model that represents the production of electromagnetic phenomena (Maxwell [1873] 1954, 416-7; Harman 1998, 118-9). Similarly, when contemporary physicists are pressed to explain the Higgs mechanism to their students or the general public they often rely on analogies to a condensed matter system (e.g., Miller 1993). The historical basis for these explanations is the analogies to models of superconductivity that introduced spontaneous symmetry breaking into particle physics. The order parameter in models of superconductivity is the analogue of the order parameter in the Higgs model. The analogue of the Higgs field is the condensate wave function, which represents the collection of superconducting electrons. Based on an analysis of physical disanalogies, I argue that the same conclusion we reached about the physical interpretation of electromagnetism also applies to the physical interpretation of the Higgs mechanism: we should not invest the successful formal analogies with physical significance. There is no mechanical ether; the Higgs field is not the same kind of entity as a collection of superconducting electrons and the W and Z bosons do not acquire mass by a similar physical mechanism to the gain of effective mass in superconductors.

If one inclines towards one of many variants of scientific realism, one might worry that the success of formal analogies is inexplicable if they are not underwritten by physical analogies. In the course of presenting his early model of the force as lines of incompressible fluid, Maxwell offers the following insight: The substance here treated of...is not even a hypothetical fluid which is introduced to explain actual phenomena. It is merely a collection of imaginary properties which may be employed for establishing certain theorems in pure mathematics in a way more intelligible to many minds and more applicable to physical problems than that in which algebraic symbols alone are used. ([1856] 1890, 160)

This insight also applies to the Higgs model case study. Formal analogies to superconductivity were useful because solid state physicists had a much clearer physical interpretation of the physics underlying superconductivity phenomenology than particle physicists did of that underlying particle phenomenology. Having an intuitive picture that goes along with a mathematical formalism can aid with manipulating the mathematical formalism. Ultimately, the intuitive fluid and mechanical models were abandoned, but the lessons about the abstract Maxwell equations were retained. Similarly, the intuitive picture of the physical processes in superconductivity is inapplicable to particle physics, but was still helpful in enabling physicists to grasp the range of consequences of the mathematical formalism (e.g., the possibility of massive gauge bosons).