Philosophy of Science Made Effective: Realism, Reduction, and the Renormalization Group in Quantum Field Theory

Dissertation Abstract

The unifying theme of my dissertation is the use of the renormalization group (RG) to address philosophical questions in relativistic quantum field theory (QFT). QFT is the theoretical framework that unifies quantum mechanics and special relativity and which underlies some of our most successful physical theories (such as the Standard Model of particle physics); the RG is a centrally important theoretical tool that relates physics at different length scales. Virtually all of the tremendous empirical successes that we associate with quantum field theories have been achieved by studying them through the lens of the RG. In this dissertation I demonstrate that the RG can also afford us with powerful insight into philosophical questions that arise in quantum field theory. In particular, I argue that it underwrites a uniquely robust approach to scientific realism, offers deep insight into intertheoretic relations, and provides the physical content of a controversial heuristic for theory development that has guided theoretical particle physicists since the 1970s.

The first chapter of my dissertation describes the historical development of the RG, beginning with the development of the early renormalization procedure in the 1940s and concluding with the introduction of the RG into QFT by Kenneth Wilson in the 1970s. My focus is on tracking the conceptual changes that physicists' understanding of the foundations of QFT underwent as a result of this history. I conclude that the development of the RG involved far more than just a mathematical breakthrough – it required a deep philosophical reconceptualization of what QFTs are and of the role we expect them to play in our description of nature. In particular, the success of the RG leads very naturally to the view that QFTs are effective theories – theories which are not fundamental, but necessarily provide valid descriptions of nature only over a restricted range of length scales.

My second chapter takes up the question of how to interpret these effective theories. In opposition to standard interpretational practice, I argue that effective theories provide an improved interpretive starting point. Using the RG one can precisely capture how physics at very short length scales beyond the domain of the effective theory – representing future theoretical developments in physics – will affect the ontological structure of the effective theory. I illustrate how one can employ an RG analysis to demonstrate that new developments at short length scales will leave the higher-level structures virtually unperturbed. I conclude that the ontological stability ensured by the RG allows one to give effective field theories a robustly realist interpretation. Among the benefits of this ‘effective realism’ are that (i) it clarifies the notoriously opaque notion of ‘approximate truth’ that is ubiquitous in discussions of scientific realism and (ii) affords ontological commitments that will remain stable in the face of future theory change.
The third chapter takes up the question of intertheoretic relations. The RG dramatically shifts the context in which questions about reduction and emergence are typically asked, from selected pairs of theories to a mathematical space containing all QFTs. The RG naturally provides a ‘dynamics’ describing how different QFTs in this space relate. Within this context, I focus on two contributions of the RG to ongoing debates among philosophers of science. First, the RG illustrates that recent accounts which treat emergence and reduction as irreconcilably opposed, in particular the respective accounts of Robert Batterman, Margaret Morrison, and Tian Yu Cao and S.S. Schweber, are unsatisfactory in a variety of respects. Second, I argue that a better characterization can be had using a particular notion of “autonomy” which I make precise. This positive account offers a more rigorous notion of emergence than commonly available in many standard investigations of intertheoretic relations, and also demonstrates that reduction and emergence are capable of peaceful coexistence in quantum field theory.

My final chapter provides a physically transparent characterization of a concept that has been at the heart of theory construction in theoretical particle physics for the last forty years, the notion of naturalness. Numerous dissonant descriptions of the meaning of naturalness exist in the physics literature, which has led some physicists to question its physical content. I use the RG to provide a unified account of the physical meaning of naturalness, illustrating that it is best understood as a demand that physical phenomena at long and short distance scales be effectively insensitive to one another. I conclude by arguing that the failure of naturalness in the Standard Model, as strongly suggested by recent data from the Large Hadron Collider, has important ontological consequences for our understanding of the relative autonomy of physical phenomena at different length scales in particle physics.