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From dressed electrons to quasiparticles: The emergence of emergent entities in quantum field theory

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ABSTRACT

In the 1970s, the reinterpretation of renormalization group techniques in terms of effective field theories and their subsequent rapid development led to a major reinterpretation of the entire renormalization program, originally formulated in the late 1940s within quantum electrodynamics (QED). A more gradual shift in its interpretation, however, occurred already in the early-to-mid-1950s when renormalization techniques were transferred to solid-state and nuclear physics and helped establish the notion of effective or quasi-particles, emergent entities that are not to be found in the original, microscopic description of the theory. We study how the methods of QED, when applied in different contexts, gave rise to this ontological reinterpretation.

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1. Introduction

While philosophers of science have written extensively about the topic of reduction and emergence in the physical sciences,[1] historians of science have only scarcely addressed the history of physicists' (and philosophers') debates surrounding this question.[2] The present paper is a step towards historicizing these debates.

At a first glance, the historians' neglect of questions of reductionism and emergence in physics might appear rather surprising. These questions, after all, played an important role in many theories of modern physics post ca. 1970 and also affected (and still affect) physicists' and philosophers' stances towards the relationship between different theories, or between different models. They also influenced physicists' views on the status and hierarchy—both social and intellectual—between different subdisciplines of physics, like high-energy and condensed-matter physics, and thus ultimately their views on the unity of their discipline.[3] The debates about reductionism in physics had appreciable effects, beyond the mere content and interpretation of physical theory, on the historical dynamics of people, practices, research fields, institutions, and even science policy, such as in the debates on building (or not building) the superconducting supercollider (Kevles, 1995, pp. ix–xlii).

At a second glance, then, the fact that debates about reduction and emergence in physics only took off during the 1970s already partially explains the comparable restraint historians of physics have shown so far in tackling the history of these debates. Historians, unfortunately but irresolvably, tend to lag behind by several decades, as important primary sources become available only

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[1] See, e.g., Kim (1999), Hartmann (2001), Batterman (2002), Morrison (2006), Butterfield (2011a,b), and Falkenburg & Morrison (2015).

[2] Exceptions include, among others (Cat, 1998; Howard et al., 2007; Schweber 1993a,b; Schweber, 2015). Also note the documentation of the project "The Physics of Scale" at http://www.authors.library.caltech.edu/5456/1/hrst.mit.edu/hrs/renormalization/public/index.html.

[3] See, e.g., Anderson (1972), Galison (1996), Hacking (1996), Cat (1998), Morrison (2000), Coleman (2003), Howard et al. (2007), and Darrigol (2008).

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piecemeal over time. As the emphasis of historical research on twentieth-century physics moves slowly but steadily forward in time, the time seems ripe to soon tackle in detail the important developments in theoretical physics during the 1970s when a reconceptualization of renormalization, first and foremost of the renormalization group, put questions of reduction and emergence on the table, both for physicists and for philosophers of physics.

Renormalization had been developed in the late 1940s as the culmination of a twenty-year attempt to remove the infinite results that were generally obtained in calculations based on quantum electrodynamics (the microscopic theory describing the interaction between matter and light) and had fundamentally called into question the internal consistency of any quantum theory of fields.[4] Renormalization consisted of a set of techniques with which these infinities could be isolated, mathematically manipulated, and then absorbed into a small number of parameters of the theory. These formally infinite quantities could then instead be specified by their empirically observed (and finite) values. As the infinities could be viewed as arising from the contribution of high-energy particles, renormalization was a way to black-box the actual high-energy behavior, which one hoped would someday turn out to be well-behaved and finite.

Around 1970, these formal black-boxing techniques were reinterpreted, following the work of Kadanoff (1966) and Wilson (1971, 1975)[5]: the neglect of high-energy contributions was now interpreted physically in terms of a coarse graining, i.e., an averaging over the effects of microscopic structure. This led to an understanding of physical (quantum field) theories at different scales as being related by such coarse-graining procedures and the notion of an effective field theory (Castellani, 2002; Hartmann, 2001; Kadanoff, 2013). The precise dynamics of an effective field theory, and even its interpretation in terms of physical entities, could then be discussed largely independently of an underlying microscopic theory. In its most extreme form, this new reading led to a conceptualization of the physical world as consisting of a potentially infinite number of layers of reality, each described by its own effective field theory (Cao & Schweber, 1993; Laughlin & Pines, 2000; Schweber, 2015).

Even without venturing into the period of the 1970s and beyond, history of science can contribute to, and historicize, the debates about reduction and emergence that began during the 1970s and 1980s and gained steam during the 1990s and 2000s. The connection between renormalization and the emergence of new physical entities not present in the original microscopic description, which became an essential part of the later notion of an effective field theory,[6] was already being explored 20 years earlier: During the 1950s, renormalization methods were transferred to the treatment of many-body systems in solid-state and nuclear physics, such as metals or heavy nuclei. It provided solid-state and nuclear physics with new concepts and techniques for describing interacting many-body systems in terms of emergent entities, so-called "effective particles" or "quasiparticles," and even provided a master narrative for how they emerged from the underlying microscopic theory. Our historical investigation provides an opportunity, also for philosophers of science, to study questions of reduction and emergence outside of the framework of post-1970s renormalization group techniques, which, for all its elegance, does tend to convey a generic, and almost algorithmic, understanding of the construction of effective field theories. In particular, as we will show, empirical knowledge played an important role in constructing and interpreting emergent entities in physics, and both motivated and legitimized the mathematical techniques employed in a non-trivial manner.

Our paper is structured as follows: first, we present the development of renormalization methods in quantum electrodynamics (Section 2). The focus will be on how already here these methods involved the introduction of emergent entities, most notably the dressed electron, consisting of a bare electron surrounded by its own radiation field. Second, we will present the transfer of these methods to the study of solids and how this led to a first conceptualization of the notion of emergent entities (Section 3). We present our conclusions in Section 4.

2. QED

The extension of quantum mechanics to a quantum theory of fields was beset from the very beginning with grave difficulties. This "very beginning" follows almost immediately after the development of quantum mechanics in the mid-1920s, as it was clear from the outset that the quantum theory describing the "mechanical" behavior of microscopic particles would have to be complemented with a quantum theory of the electromagnetic field, quantum electrodynamics, or QED for short.[7]

We will focus on two of these problems, in particular on how these problems related to the ontology of the theory. Here we mean ontology in a very simple (and maybe simple-minded) manner. This is not about the discussions concerning the interpretation of quantum mechanics, not about wave-particle duality. These questions were famously debated at the 1927 Solvay conference, whose title was "Electrons and Photons." This choice of title can be understood as the least common denominator, agreed upon by all the involved physicists: the world consists of electrons, charged matter particles, and photons, quanta of electromagnetic radiation. But even this simple-minded basic ontology was problematized by the new QED.

We will first tackle the problem of the photon. Maxwell's electrodynamics covers a lot more than just electromagnetic radiation. Rather, it was the historical success of Maxwell to have integrated the theory of radiation (and thereby optics) into a broader theory of electromagnetic fields, which also covered electrostatic effects, such as Coulomb's law. This unification had been undone in quantum theory: there was a successful theory of electromagnetic radiation based on photons, due to Paul Dirac (1927a,b). But what was lacking was a quantum theory of the whole electromagnetic field. In particular, the question was open how such a theory, which should also be able to describe static fields, would relate to the photon concept, which was intimately tied to the notion of a periodically oscillating electromagnetic wave.

This was the task undertaken by Werner Heisenberg and Wolfgang Pauli, beginning in 1927, and culminating in two massive papers (Heisenberg & Pauli, 1929, 1930). In the first of these papers they employed the following trick: they introduced additional terms to their theory, which turned the non-periodic solutions into periodic ones. One could then perform calculations as if the entire electromagnetic field consisted of photons, and then only in the end result set the additional terms to zero. More

[4] On the history of renormalization, see, e.g. Brown (1993) and Schweber (1994).

[5] See also Niss (2011).

[6] It is a danger, of course, that one whiggishly projects later categories back in time. We have attempted to carefully avoid this fallacy, and leave it to the reader to critically assess whether we have succeeded.

[7] For the early history of quantum field theory, see, e.g. Cini (1982), Darrigol (1982a, 1982b) and the first two chapters of Schweber (1994). The difficulties of early quantum field theory are discussed in Rueger (1992). An overview that places the development of quantum field theory in the larger context of the development of quantum mechanics can be found in a chapter by Christoph Lehner and one of the authors (AB) in a forthcoming volume on the genesis of quantum mechanics.