Studies in History and Philosophy of Modern Physics 51 (2015) 82–96

Contents lists available at ScienceDirect

Studies in History and Philosophy of Modern Physics

journal homepage: www.elsevier.com/locate/shpsb

Naturalness, the autonomy of scales, and the 125 GeV Higgs

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ARTICLE INFO

Article history:
Received 3 February 2014
Received in revised form
8 May 2015
Accepted 26 May 2015
Available online 17 June 2015

Keywords:
Quantum field theory
Effective field theory
Naturalness
Renormalization
Inter-level relations
High-energy physics

ABSTRACT

The recent discovery of the Higgs at 125 GeV by the ATLAS and CMS experiments at the LHC has put significant pressure on a principle which has guided much theorizing in high energy physics over the last 40 years, the principle of naturalness. In this paper, I provide an explication of the conceptual foundations and physical significance of the naturalness principle. I argue that the naturalness principle is well-grounded both empirically and in the theoretical structure of effective field theories, and that it was reasonable for physicists to endorse it. Its possible failure to be realized in nature, as suggested by recent LHC data, thus represents an empirical challenge to certain foundational aspects of our understanding of QFT. In particular, I argue that its failure would undermine one class of recent proposals which claim that QFT provides us with a picture of the world as being structured into quasi-autonomous physical domains.

1. Introduction

This paper is an analysis of a conceptual problem that has been at the center of high-energy physics research for approximately 40 years: the problem of “naturalness”. I introduce the effective field theory framework in which the problem arises, survey the many faces of naturalness in the physics literature with an eye toward clarifying its (oftentimes misunderstood) physical significance, and discuss the implications that a failure to solve the naturalness problem would have for the ontology of quantum field theory. This latter issue is particularly pressing after the first run of the LHC: the discovery of the Higgs boson with a mass of 125 GeV and no additional particles not predicted by the Standard Model has put significant pressure on proposed solutions to the main problem of naturalness in the Standard Model, the Hierarchy Problem (for details see “Supersymmetry: Theory,” “Supersymmetry: Experiment,” and “Dynamical Symmetry Breaking: Implications of the *H*” in Olive et al. (2014)).[1] The motivation for and significance of naturalness in quantum field theory is a hotly contested topic, with some claiming it to be ill-motivated or a mere theorists' prejudice[2]; I argue that, to the contrary, naturalness is essentially a prohibition of sensitive correlations between widely separated physical scales. I further argue that this is an expectation which is well-motivated within the effective field theory framework, justified on both theoretical and empirical grounds. The fact that the prospects for naturalness appear dim in light of the discovery of the 125 GeV Higgs, then, constitutes an empirical challenge to our current understanding of certain foundational features of quantum field theory (QFT).

The structure of the paper is as follows. I begin by introducing the notion of an effective field theory (EFT), since it is in this context that the naturalness problem arises. In Section 3, I use 2 simple models – a massive Yukawa theory and a scalar field theory– to illustrate the essential features of the naturalness problem. This then leads to a survey of the physics literature on naturalness, where there is a remarkable discordance of opinion. In Section 4, I draw on general features of the structure of effective field theories as well as particular

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[1] This is not the place for a detailed discussion of Beyond the Standard Model phenomenology at the LHC, so I refer the reader to Craig (2013), Feng (2013), Bertuzzo (2013), and Giudice (2013) for further discussions of the status of solutions to the Hierarchy problem after the first run of the LHC. For a pedagogical introduction to the phenomenology of such supersymmetric solutions, see Murayama (2000).

[2] See, for example, Wilson (2005), Richter (2006), or from a slightly different angle Arkani-Hamed & Dimopolous (2005).

http://dx.doi.org/10.1016/j.shpsb.2015.05.003
1355-2198/

examples of past successful realizations of naturalness in particle physics to present a physically transparent characterization, arguing that naturalness is best understood as a prohibition of correlations between widely separated physical scales. This understanding of naturalness has existed in the physics literature for quite some time; indeed, it is clearly stated in some of the earliest discussions of the concept in the late 1970s.[3] However, over time a variety of technical conditions for ensuring naturalness have developed and the understanding of naturalness has shifted in a direction that obscures its physical content (for a historical overview, see Grinbaum (2012)). I argue that understanding naturalness in the proposed way illustrates that these superficially discordant technical understandings of naturalness in the physics literature are simply diverse attempts to formalize a shared unease about correlations between widely separated physical scales. This understanding of naturalness then forms the basis of an argument that naturalness is a well-motivated expectation in particle physics whose apparent failure requires a significant revision of our understanding of the effective field theoretic description of nature. Section 5 discusses one such revision: I examine how such a failure affects recent proposals that quantum field theory supports an ontological picture on which our world consists of a hierarchy of quasi-autonomous physical domains.

2. Effective field theory

Problems of naturalness arise in effective field theories. An effective field theory (EFT) is a quantum field theory which is known to become inapplicable above some energy scale Λ. This energy scale is called the *ultraviolet cutoff*[4] of the EFT. There are both conceptual and pragmatic reasons for treating QFTs as EFTs. I postpone the technical details of naturalness to Section 3; in this section, my aim is to introduce core conceptual and technical features of EFT. In particular, I claim that the severity of naturalness problems is amplified by the fact all empirically applicable QFTs are best understood as EFTs, and provide a short argument to that effect.

The central obstacle to formulating a QFT that is a plausible candidate for describing our world up to arbitrarily high energies is gravity. All matter fields couple to the gravitational field. At low energies the effects due to this coupling are negligibly weak but gravity becomes strong when considering physical processes occurring at energies on the order of the Planck scale Λ_{Pl}. This means that while one can ignore gravity when doing particle physics at relatively low energies – such as those energies currently being probed at the LHC – gravitational effects must be taken into account at higher energies. Now, it is well known that a quantum field theoretic description of gravity is not perturbatively renormalizable. New divergences arise at each order of perturbation theory and in order to describe gravitational processes occurring up to arbitrarily high energies, eliminating these divergences would require considering an infinite number of parameters in the Lagrangian. The upshot of these two features of gravity is that while gravitational effects must be incorporated as we experimentally probe higher energies, it appears that quantum field theory is not the appropriate framework for doing so.[5] The fact that no quantum field theoretic description of gravitation is available in the regime where it is needed most, then, leads one to conclude that any QFT which aims to describe the world should not be trusted at energies above, at the highest, the Planck scale.

For the general class of QFTs that possess non-abelian gauge symmetries[6] gravity is the only clear obstacle to treating them as fundamental. In particular, there is no clear mathematical obstacle to treating such theories as fundamental. These theories are called *asymptotically free*; the interactions get weaker at higher energies, ultimately going to zero as the ultraviolet cutoff is taken arbitrarily large. This is quite different from QFTs which are *not* non-abelian gauge theories, such as quantum electrodynamics (QED) or the ϕ^4-theory. When formulated on a background spacetime of dimension greater than or equal to 4, the strength of interactions in these theories gets stronger at higher energies, eventually diverging at some finite energy scale. These singularities are known as Landau poles, and indicate that these theories are not mathematically consistent to arbitrarily high energies – at some finite energy scale, they break down on purely mathematical grounds.[7]

These two cases cover theories that describe physics at low energies but which are incapable of being extended above some very high energy scale. However, the use of EFTs also has a strong pragmatic motivation. Very commonly one wants to study physics at a relatively *low* energy scale but possesses a theory that describes physics up to some much higher scale. Typically, the high energy theory includes degrees of freedom distinct from those that are dominant at the low scale; in quantum chromodynamics (QCD), for example, the dominant degrees of freedom at low energy are hadrons that do not even appear in the Lagrangian of the high energy theory describing quarks and gluons. Similarly, given a theory of atomic physics and a desire to study some low-energy process like ocean wave propagation, the dominant degrees of freedom are not those found in the high energy theory; the atomic constituents of the sea can be neglected in providing an accurate description of the propagation of ocean waves. In that case, one employs an effective hydrodynamical theory describing ocean waves as disturbances in a continuous fluid, ignoring the underlying atomic structure of the ocean. In these cases, the main benefit of EFTs is essentially a pragmatic one. One could in principle describe the low-energy phenomena using the full theory (or at least many think we could; I doubt whether anyone has actually tried to study ocean wave propagation using the Standard Model). The central issue is that not only is doing calculations in the full theory more complicated, it also generally yields a *less* informative qualitative description of the phenomena in question. Degrees of freedom appropriate for vastly different scales become mixed up and a tractable understanding of the physics becomes much more difficult.[8] Effective field theories provide a better understanding of which degrees of freedom are dominant at different energy scales and of the relationship between the dominant physical processes that at these different scales.

The upshot of this discussion is that, due mathematical inconsistency or the inability to incorporate gravitational degrees of freedom (or both), all quantum field theories that purport to describe the world come with an ultraviolet cutoff beyond which they become inapplicable. For physics below this scale, however, these theories provide the most accurate agreement between theory and experiment in scientific history. I turn now to the technical details of effective field theories.

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[3] See Susskind (1979), t Hooft (1979), or Ovrut & Schnitzer (1980).

[4] In what follows, unless otherwise noted all usages of Λ will stand for a generic ultraviolet cutoff whose particular value is not of central importance.

[5] It is worth noting that there is an active research program predicated on the possibility that gravity may be a consistent quantum field theory to arbitrarily high energies after all, in the sense that the renormalization group equation describing the behavior of the gravitational coupling at different energy scales hits a fixed point as we consider the coupling's behavior at higher and higher energies. This is called "asymptotic safety"; see Niedermaier & Reuter (2006) for a review.

[6] To be precise, they must also not contain too many matter fields since large numbers of these fields can spoil the asymptotic freedom of the theory. In QCD, for example, the theory is only asymptotically free if it includes 16 or fewer quark flavors.

[7] For discussion in both perturbative and nonperturbative contexts, see Aizenman (1982), Callaway (1988), Montvay & Munster (1997), or Rivasseau (1991).

[8] For a philosophical discussion of the difficulties of modeling systems over many scales of length, see Batterman (2013).