Scientific Realism Made Effective

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Abstract

I argue that a common philosophical approach to the interpretation of physical theories – particularly quantum field theories – has led philosophers astray. It has driven many to declare the quantum field theories employed by practicing physicists, so-called "effective field theories," to be unfit for philosophical interpretation. In particular, such theories have been deemed unable to support a realist interpretation. I argue that these claims are mistaken: attending to the manner in which these theories are employed in physical practice, I show that interpreting effective field theories yields a robust foundation for a more refined approach to scientific realism in the context of quantum field theory. The paper concludes by briefly sketching some general morals for interpretive practice in the philosophy of physics.

1 Introduction

There are two central strands of contemporary philosophy of science which sit in tension. On the one hand, there is the increasing desire of philosophers of science to ensure that their philosophical commitments are grounded in our most successful scientific theories. This is often considered part and parcel of adopting a 'naturalistic' approach to philosophical investigation[1]. On the other hand is a currently widespread approach to the interpretation of physical theories. According to this approach, the central interpretive task of the philosopher is to answer the following counterfactual question: "if this theory provided a true description of the world in all respects, what would the world be like?" Given what we know about the restricted validity of the descriptions of the world provided by even our best physical theories, this sits uneasily with the interpretive question that follows more naturally from paying heed to scientific practice[2]: "given that this theory provides an approximately true description of our world, what is our world approximately like?"

My aim in this paper is to offer one way of resolving this tension. In the context of quantum field theory, I distinguish these two interpretive projects and argue that adopting the modern understanding of quantum field theories as 'effective theories' renders the prevailing counterfactual approach to theory interpretation at best unmotivated, and at worst misleading. Fortunately, effective quantum field theories provide philosophers with a superior starting point for interpretational questions, even according to the criteria that purportedly motivate prevailing interpretive practice. In particular, they enable one to answer in the affirmative the question that (Ruetsche [2011]) takes to be binding on any purported interpretation of a physical theory: "does this interpretation allow the theory to discharge all of its scientific duties?" In fact, in the context of quantum field theory it is only by attending to effective theories that one can satisfy this criterion.

It is especially profitable to attend to effective theories in order to answer questions about the ontological implications of quantum field theories. Since a number of philosophers of physics view effective theories as an *ad hoc* solution to certain mathematical problems in quantum field theory, or merely as tools for extracting empirical predictions which convey no ontological guidance (for example, (Halvorson and Müger [2006]), (Fraser [2009]), (Kuhlmann [2010]), (Fraser [2011]), and (Butterfield and Bouatta [2015], section 5.2)), I will argue for this position at some length in section 3.

The plan of the paper is as follows. In section 2, I review what I deem the Standard Account of theory interpretation before providing reasons to be dissatisfied with it. Section 3 is a detailed discussion of the virtues that interpreting effective theories promises for scientific realism. I argue that it yields a more robust and scientifically informed set of realist commitments than the Standard Account. I conclude in section 4 with some

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[1] For example, naturalism of a particularly appealing sort is exemplified by (Maddy [2007]) or (Wimsatt [2007]), or many papers in (Ross *et al.* [2013]).

[2] This phrasing can be found in (Fraser [2011]), where it is used to describe the preferred interpretive question of (Wallace [2011]). It is also endorsed by (Baker [2015], section 2), although I disagree with Baker about the sense in which quantum field theory can rightly be called "approximately true" in a way that leaves me unconvinced by the argument he goes on to give in section 2 of that paper.

brief, general comments on interpretive practice in the philosophy of physics.

Finally, a brief terminological note. Effective quantum field theories (EFTs) are quantum field theories that become inapplicable beyond some short distance scale, and that incorporate this inapplicability into their mathematical framework. Throughout the paper I will use the phrase "effective quantum field theory" in a slightly broader sense than sometimes displayed in the physics literature. The only significance of this here is that quantum field theories given a mathematically exact definition on a spacetime lattice will be labeled as EFTs, in addition to those that incorporate their limited domain of applicability into their perturbative approximation[3].

2 The Standard Account of Theory Interpretation

Philosophers of physics occasionally offer remarks about what it means to give an interpretation of a physical theory, but more frequently they get to the business of interpreting without a metaphilosophical preamble. In this section my aim is to extract a handful of principles that strike me as shared ground among many philosophers of physics regarding what it means to interpret a physical theory. These make up what I label the Standard Account, or Standard Interpretation, and its practitioners I call Standard Interpreters. I should note that I do not have in mind any particular author or set of authors as perfect examples of Standard Interpreters. The Standard Account is meant to reflect a set of assumptions that are at least tacitly assumed by many working in the philosophy of physics; in any given paper those authors might exhibit many (but not necessarily all) of the principles that I group together under the heading of the Standard Account. That said, after outlining the Standard Account, I will substantiate it with a representative sample of quotations from philosophers of physics addressing the question of what it means to interpret a physical theory.

The ingredients I take to be integral to the Standard Account are[4]:

1. The theory to be interpreted is assumed to provide a true and exhaustive description of the physical world in all respects, including at all length scales.
2. A theory is to be interpreted in isolation. It is illicit to appeal to, say, quantum mechanics to shed light on interpretational questions in classical physics, or to the

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[3] See (Georgi [1989]), (Duncan [2012]), or (Petrov and Blechman [2015]) for accessible introductions to EFTs, or (Williams [2015], section 2) for a much briefer introduction aimed at philosophers.

[4] What I call the Standard Account has some overlap with what (Ruetsche [2011]) calls 'pristine interpretation'. I hasten to add that Ruetsche does not endorse the practice of pristine interpretation, and in its stead offers an account of theory interpretation that requires interpreters to be engaged with how physical theories are employed in practice.

inevitability of gravitational effects at short distances to resolve an interpretational difficulty in quantum field theory[5].

3. An interpretation of a theory consists of the set of all worlds nomologically possible according to that theory.

4. This set of possible worlds is determined by generic structural features of the theory in question. These may include its dynamical laws, certain kinematical constraints (the symmetries of its space of physically allowed states, for example), and so on. Information about empirical applications of the theory – how it is employed in scientific practice – are largely or entirely ignored

5. The goal of interpreting a physical theory is to identify and characterize its *fundamental* ontological features.

Now for some evidence. Consider the following descriptions of theory interpretation offered by philosophers of physics:

- (Earman [2004], p. 1234): "Whatever else it means to interpret a scientific theory, it means saying what the world would have to be like if the theory is true."

- (Van Fraassen [1991], p. 242): "*Hence we come to the question of interpretation*: Under what conditions is the theory true? What does it say the world is like? These two questions are the same."

- (Belot [1998], p. 532): "To interpret a theory is to describe the possible worlds about which it is the literal truth. Thus, an interpretation of electromagnetism seems to tell us about a possible world which we know to be distinct from our own."[6]

- (Fraser [2009], p. 558): "By 'interpretation' I mean the activity of giving an answer to the following hypothetical question: 'If QFT were true, what would reality be like?' "

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[5] This is really a corollary of principle 1 – how could a physical theory that is assumed to provide a true and complete description of the world be consistently interpreted in anything but isolation? I list it as a separate principle merely for the sake of emphasis.

[6] In the same paper, Belot does offer an account of how one can learn about our own world by examining the interactions between theories we know to be merely effective, but that we have interpreted as true in all respects. His account hinges on a recommendation I heartily endorse – examining the relations between theories which we know to be merely effective – but I do not see how his account can be consistent. In particular, I do not see how one can consistently interpret theories as literally true in all respects while advocating comparisons between theories in the domains in which the two are taken to break down. It seems that strict commitment to the former rules out the possibility of the latter.

- (Ruetsche [2008], p. 199): "To interpret a physical theory is to say what the world would be like, if the theory were true. A realist about a theory believes that theory to be true."

- (Arntzenius [2014], p. 4): "So, what is it that I am doing when I discuss what the structure of space and time is according to classical mechanics, according to quantum mechanics, and so on? What I am doing is discussing what we should take the structure of the world to be if the phenomena were as classical mechanics, or quantum mechanics, or...says they are. [...] On the other hand, it has to be said that while it seems quite reasonable to expect that future science will have a huge predictive overlap with current science, it is not so obvious that it will have a huge overlap concerning the kind of *fundamental structure* that is the concern of this book" (emphasis mine).

Consider two corollaries of the Principle 1. The first corollary is that one must also banish other theories from consideration: to interpret some theory *T* is to interpret *T* in isolation. It is illuminating to see how this corollary affects philosophical practice, and the following discussion in (Fraser [2009], p. 552) provides a helpful example. She notes that physicists and philosophers often appeal to the fact that quantum field theory will be succeeded by a (currently-unknown) theory of quantum gravity at short distance scales as one way of giving physical content to the short-distance cutoff present in EFTs, and that some theories of quantum gravity suggest that spacetime may have a discrete structure. She then argues that it would be mistaken to think that appeals to such theories of quantum gravity could possibly do any interpretational work in EFTs because "even if these claims are borne out, the fact that quantum gravity indicates that space is discrete would not help settle the question of how to interpret the cutoff variant of QFT *because gravitational considerations are external to QFT*" (emphasis mine). The conclusion she draws is that EFTs are unfit for interpretation, in part due to difficulties she sees related to interpreting the short-distance cutoff.

The second corollary is that the theory to be interpreted must have a rigorous mathematical description at all length scales. That is, after all, a necessary condition for assuming a theory to be true in all respects (and being able to assume the theory's truth down to arbitrarily small length scales is necessary for interpreting the theory as making claims about fundamental metaphysical structure). Acceptance of this mathematical precondition for interpretation is what leads Halvorson, for instance, to state that "[i]n the absence of some sort of mathematically intelligible description of QFT, the philosopher of physics has two options: either find a new way to understand the task of interpretation, or remain silent about the interpretation of quantum field theory" (Halvorson and Müger [2006], p. 731). Standardly Interpreting a physical theory, then, requires that it be mathematically well-behaved even in domains where it fails *qua* physical theory: that is, even in domains where we expect this mathematical description to fail to describe any properties of the actual world.

Principle 5 identifies another recurrent attitude one encounters in Standard Interpretations of physical theories, closely related to the assumption that the theory being studied is true in all respects: the focus on identification of the fundamental structure of the physical theory being interpreted[7]. In such investigations, this is commonly identified with the structure present in a theory at the smallest length scales, and in many cases this seems to be uncritically assumed to capture the structure that is common to all length scales. This emphasis on identifying fundamental structure means that the focus is often on the ontology of the theory at arbitrarily small length scales, precisely the physical domain in which one has good reasons to distrust the ontological information contained in any extant physical theory[8]. For example, consider (Fraser [2008], p. 857), where she argues that if particles do not exist at some fundamental level in quantum field theory, then "QFT does not furnish grounds for regarding particlelike entities as constituents of reality." This is defended on the grounds that in order to take particles to be constituents of reality, "the cogency of the distinction between fundamental and less fundamental entities must be defended and a case must be made for admitting additional, non-fundamental entities into our ontology" (p. 858). Similar claims are made by (North [2009], p. 23), where she states that "if our world's fundamental physical theory were the theory of classical particles, we should conclude that the structure of the mathematical space in which to best represent the theory, and of the world according to that theory, has *only* symplectic structure" (my emphasis). These exemplify the Standard Interpreter's emphasis on fundamental structure, as well as the tendency to equivocate between a theory's ontological content at the fundamental level and that content at all distances scales.

Surveying the principles of Standard Interpretation, one is impressed by the degree to which they require a starting point for interpreting quantum field theories that differs from the conceptual and mathematical framework that characterizes the modern understanding of quantum field theories as EFTs. In fact, Standard Interpreters' insistence on treating a theory as true in all respects – in particular, at all length scales – has restricted them to studying toy quantum field theories formulated in two or three dimensional spacetimes, or features of the axiomatic framework in which those models are constructed. These toy theories are furthermore quite structurally distinct from the quantum field theories we know to be empirically successful in the real world[9]. One reason this restriction is

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[7] This is fairly common in philosophy of physics and ubiquitous in the analytic metaphysics literature, but even within the small subfield of the philosophy of quantum field theory it is on display in (among other places) (Healey [2007]), (Fraser [2008]), (Baker [2009]), (Baker [2010]), (Baker and Halvorson [2010]), (Arntzenius [2014]), and the discussion in (Butterfield and Bouatta [2015], section 5.2)

[8] Thus the emphasis on identifying fundamental structure is also closely tied up with Standard Interpreters' demand that a physical theory have a rigorous mathematical description at all length scales. My thanks to an anonymous referee for pressing this point.

[9] In particular, even in two or three spacetime dimensions these toy models are

so remarkable is that it is commonplace for physicists to describe the recognition that all quantum field theories break down at short distances, and the associated development of the RG and the EFT framework, as the most significant conceptual advance in the understanding of quantum field theory in the second half of the twentieth century[10]: as (Rivasseau *et al.* [2014], p. 4) put it in their recent review of the RG, "the theory of renormalization...that initially might have appeared as a computational trick, is now understood to be the heart of QFT." Physicists generally regard the inevitable breakdown of any EFT at short distances not as a disaster, but as offering profitable physical insight. Among other advantages, it provides insight into the length scales at which physical processes not included in the particular EFT they are working with become important, and thus at which length scales their theory must be modified or replaced entirely.

Before turning to the vices of the Standard Account, I want to emphasize that I am not suggesting that Standard Interpreters fail to recognize that classical mechanics, or general relativity, or quantum field theory do not provide valid descriptions of our world at short distances. They unquestionably do know this. This is part of what makes Standard Interpretive practice so odd: they uniformly set this knowledge aside in order to pursue Standard Interpretation, and then frequently double-down on the oddity by focusing their philosophical attention on the identification of the theory's ontology in precisely those short-distance regions where one knows the theory's description to be inadequate.

2.1 Vices of the Standard Account

> The theoretical results currently available fall into two categories: rigorous results on approximate models and approximate results on realistic models.
> – (Wightman and Glance [1989])

Here I describe three serious problems with Standardly Interpreting quantum field theory. I will be brief, for two reasons. First, because much of this ground has been covered at length in (Wallace [2006]) and (Wallace [2011]), with whom I am almost entirely in agreement. Second, because section 3 consists of a positive argument that interpreting EFTs grounds ontological commitments that are more reliable than those any Standard Interpretation of quantum field theory can provide, and I hope this argument will be more persuasive than any purely critical discussion.

The central vice of Standard Interpretation, illustrated by the quote from (Halvorson and Müger [2006]) cited earlier, is that it declares essentially all empirically applicable quantum field theories to be unfit for interpretation. This is because no mathematically

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unable to accommodate the local gauge symmetries that are necessary for formulating the Standard Model of particle physics.

[10] For example, see (Weinberg [1983]), (Gross [1999]), (Weinberg [1999]), (Zinn-Justin [1999]), (Banks [2008]), (Zee [2010]), (Duncan [2012]), (Cardy [2013]), and many of the papers in (Baaquie *et al.* [2015]).

rigorous version of the Standard Model – indeed, of any interacting QFT in four spacetime dimensions – has ever been constructed, and a rigorous mathematical model of a physical theory is a precondition for providing a Standard Interpretation[11]. Quantum field theories that satisfy the preconditions for Standard Interpretation are known to exist only in two or three spacetime dimensions, and lack many of the crucial structural features that characterize the quantum field theories which describe our world, such as invariance under local gauge symmetries. This means that in quantum field theory, the question the Standard Interpreter aims to answer is actually worse than the counterfactual starting point I attributed to Standard Interpretation at the outset of the paper. In quantum field theory, the Standard Interpreter sets out to answer the following nested counterfactual: "If we lived in a world with two (or three) spacetime dimensions, and if that world could be described by a theory that we know is structurally incapable of describing our world, and if that theory provided a complete and exhaustive description of that two (or three) dimensional world in all respects, what would that world be like?" The answer to this question is then purported to offer insight into the ontology of the world in which we do, in fact, reside.

A second vice stems from this inability to Standardly Interpret empirically applicable quantum field theories. The manner in which a physical theory is employed in real-world applications offers valuable guidance about which elements of that theory's mathematical framework play a genuinely representational role and which are likely just mathematical artifacts. The absence of applications for the quantum field theories preferred by Standard Interpreters thus makes their proposed interpretations even less reliable. Again, this is not just in the general sense that one may reasonably have more confidence in the approximate truth of empirically successful theories, but also in the more specific sense that their preferred toy theories lack an important tool for providing a fine-grained separation of ontological wheat from mathematical chaff. Explaining how this works in EFTs is addressed in detail in section 3.

The rectitude of Standard Interpretation is not always just assumed. There have been arguments presented in its favor – in particular, arguments for ignoring EFTs in favor of attempting to extract ontological information by answering the nested counterfactual given above (for example, (Fraser [2009]), (Kuhlmann [2010]), (Fraser [2011]), or (Baker [2013])). However, these arguments reveal a third vice of adhering to Standard Interpretive methodology: it can generate conclusions we have good reason to believe (at best) non sequiturs, and (at worst) false. As one example, consider the argument in (Fraser

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[11] By "rigorous mathematical model" I mean a model that satisfies the Wightman axioms (or some similar set of axioms). In the case of theories which are not asymptotically free (or asymptotically safe), there is positive reason to suspect that no rigorous mathematical model could ever be constructed (see for example (Rivasseau [1991])). For theories that are asymptotically free (or asymptotically safe), it is suspected such a mathematically consistent extension is possible, but no one knows how to provide one yet (Douglas [2004]).

[2009]) that the lack of a rigorous mathematical model of quantum field theory in four spacetime dimensions renders it unsuitable for interpretation. Fraser's argument takes the form of a *reductio ad absurdum*: she considers an EFT whose breakdown at some short distance L is captured by representing space as a lattice with lattice spacing L. Adherence to Standard Interpretational methodology (that the description of the world offered by the theory be treated as true and exhaustive, for instance) leads her to conclude that the theory assigns a lattice structure to physical space. Thus, she continues, since no one believes that quantum field theory entails that physical space has a lattice structure, EFTs are unfit for interpretation[12]. Of course, the upshot of any *reductio* is just that some set of assumptions is inconsistent; one then identifies the assumption(s) to be discarded based on whatever considerations are most appropriate within the context of the investigation. An alternative response to discovering that one's approach to theory interpretation generates a conclusion that no one believes is to conclude that it may be the approach to interpretation that is unfit for interpretive work, not the theory.

The three objections to Standard Interpretations of quantum field theories that I've offered are: (i) it requires replacing questions about the actual world (answerable by investigating empirically successful EFTs) with questions about remote counterfactual worlds, to be answered by interpreting toy quantum field theories; (ii) the lack of empirical applications of the quantum field theories preferred by Standard Interpreters weakens even further the realism such investigations can support; and (iii) it is prone to generating absurd ontological conclusions due to artifical restrictions on what information one is allowed to take into account when interpreting a physical theory.

One may worry that allowing the way a theory is applied in practice to inform its interpretation in the fashion I am encouraging makes the endeavor troublingly pragmatic, and so threatens to undercut any strongly realist interpretation of quantum field theory. I think that it strengthens our realist commitments, and it is to that issue that I turn now.

3 A More Effective Realism

Adopting EFTs as an object of interpretation necessitates an approach distinct from Standard Interpretation. Most obviously, it requires giving up the assumption that the theory provides a true and complete description of the world in all respects. It is part and parcel of treating a physical theory as effective to accept that it does not provide such a description. The emphasis on characterizing the fundamental ontology of the EFT also becomes unmotivated, since the fact that the theory offers no reliable information about

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[12] Fraser doesn't consider any of the myriad ways of incorporating the short-distance breakdown of EFTs that don't involve formulating the theory on a spatial lattice, but her argument is easy to extend to such cases. For example, it is also the case that no one believes our world has a non-integer number of spacetime dimensions, so EFTs whose breakdown is incorporated through dimensional regularization are unsuitable for interpretation. And so on.

our world at ‘fundamental’ length scales is built directly into the formalism. Furthermore, in some cases (though not all) one will have to develop a stomach for interpreting physical theories that fail to live up to mathematicians’ standards of mathematical rigor[13]. Finally, interpreting the theory in isolation becomes unmotivated as well, since appeals to (currently unknown) short-distance physics are integral to understanding the physical significance of the short-distance breakdown of EFTs. What philosophical payoffs can EFTs offer to justify these required departures from prevailing interpretational practice?

In this section I argue that an approach to scientific realism that has become popular over the last 20 years or so falls naturally out of an attempt to interpret EFTs. Originally born out of attempts to respond to the pessimistic meta-induction, this approach to realism focuses on particular scientific theories and attempts to identify a subset of the entities and structures in the theory that can be expected to survive future episodes of theory change[14]. One can identify two prongs to this approach, which (Psillos [1999]) labels the ‘divide and conquer’ strategy: (i) attend to the details of a theory’s empirical applications to distinguish those entities and structures that play an essential or ‘active’ role in the theory’s empirical success from those that are merely ‘idle constituents’; and (ii) identify those theoretical elements that are stable and “robust” (in a sense to be made more precise in a moment).

The many empirical applications of EFTs and the availability of the RG play crucial roles in carrying out this divide and conquer strategy in quantum field theory. In doing so, they provide a corrective to a common attitude of Standard Interpreters that (Stachel [1993], p. 149) calls ‘the fetishism of mathematics’[15]: “the tendency to assume that all the mathematical elements introduced in the formalization of a physical theory must necessarily correspond to something meaningful in the physical theory and, even more, in the world that the physical theory purports to help us understand.” At least within the context of quantum field theory, they also offer one avenue of response to perhaps the most significant challenge facing the divide and conquer strategy: the need for a criterion that can be applied now “to pick out those parts or features of our own theories we may safely regard as accurate descriptions of the natural world” (Stanford [2006], p. 169).

The criterion that suggests itself as a response to Stanford’s challenge is Wimsatt’s

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[13] Although pursuing it would take me too far afield, it is worth noting that I think many philosophers underestimate the extent to which this standard fails to be met in many other domains of physics as well, especially once one attends to the mathematical trickery needed to extract empirically adequate predictions from those theories.

[14] Varieties of this approach can be found in (Kitcher [1993]), (Psillos [1999]), and (Chakravartty [2007]), among other places. I consider the “local” realism of (Wimsatt [2007]) also to be a realism of this sort, though his motivations have nothing to do with the pessimistic meta-induction.

[15] Related concerns have recently been raised by (Curiel [2016]), (Weatherall [2016]), and (Lehmkuhl [forthcoming]) concerning certain interpretive strategies in the philosophical literature on general relativity.

notion of ‘robustness’[16]. Wimsatt offers a criterion for ontological commitment that I will adopt going forward: one should include in one’s ontology those entities, properties, or relationships which are ‘robust’: “accessible (detectable, measurable, derivable, definable, producible, or the like) in a variety of independent ways” (Wimsatt [2007], p. 95). I will argue that the host of empirical applications and the use of the RG play powerful roles in determining which properties, entities, and structures in a given EFT are robust. Before making that argument, a brief example may be helpful for getting a feel for Wimsatt’s robustness criterion. A paradigmatic instance of a robustness argument for the reality of some entity is Jean Perrin’s argument for the existence of molecules in the early twentieth century. Perrin performed a variety of different experiments that yielded independent but convergent calculations of Avagadro’s number, which represents the number of (then-hypothetical) molecules needed in a substance such that its mass in grams equals its molecular mass (what one now calls a mole of the substance). Perrin then concluded that

> Even if no other information were available as to the molecular magnitudes, *such constant results would justify the very suggestive hypotheses that have guided us* [including that molecules exist], and we should certainly accept as extremely probable the values obtained with such concordance for the masses of the molecules and atoms...The objective reality of the molecules therefore becomes hard to deny. – (Perrin [1916], p. 106) (quoted in (Achinstein [2002], p. 473); emphasis in original)

On the basis of the stability of his experimental and calculational results across distinct and independent physical conditions, Perrin thus concludes that molecules are elements of reality. This captures the general structure of robustness arguments well[17].

There are several ways in which EFTs can enhance the reliability of our realist commitments. First, they contribute to the advancement of the divide and conquer strategy by clarifying the sense in which quantum field theories are “approximately true”. EFTs do this by (i) explicitly incorporating into their mathematical framework the length scales beyond which they become unreliable, making explicit the physical domains in which one can trust the theory to deliver reliable ontological information; and (ii) using the RG to provide a means of identifying elements of EFTs that are invariant across independent and distinct choices about how to model the physics at the short distances where the theory is empirically inapplicable. These are two senses in which the RG identifies ‘robust’ structures in EFTs, thereby offering guidance about which structures in that EFT represent physical content and which are just mathematical artifacts.

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[16] Wimsatt’s description of his own ‘local’ realism based on robustness is (in brief) (Wimsatt [2007], p.95) and (at length) (Wimsatt [2007], chapter 4).

[17] To my knowledge, the earliest use of Perrin’s argument by a philosopher in support of scientific realism is (Salmon [1984]). My thanks to an anonymous referee for bringing Salmon’s use of Perrin’s argument to my attention.

Second, focusing on elements of EFTs that the RG shows to be robust reveals a rich, layered ontology that is hidden if one shares Standard Interpreters' focus on fundamental structure (of non-fundamental theories, remember!). The RG reveals that the ontology that Standard Interpretations generate is impoverished, presenting a misleading picture of the structures and entities that populate the actual world. Indeed, I will argue that for certain quantum field theories a Standard Interpretational ontology renders them unable to discharge their scientific duties, thereby violating the requirement for interpretational success suggested by (Ruetsche [2011]). The following two subsections substantiate and expand on these claims.

I should note before proceeding that the belief that EFTs provide more reliable realist commitments is at odds with a widespread attitude of the philosophy of physics community[18]. This attitude is captured well by the remark of (Butterfield and Bouatta [2015], p. 25) that studying EFTs "suggests a rather opportunistic or instrumentalist attitude to quantum field theories. [...] Meanwhile...results showing some quantum field theories' good [mathematical] behaviour at arbitrarily high energies [= at arbitrarily short length scales] foster a less opportunistic or instrumentalist attitude." A similar attitude is espoused in (Halvorson and Müger [2006]), (MacKinnon [2008]), (Fraser [2009]), (Kuhlmann [2010]), (Ruetsche [2011]), and (Fraser [2011]). Undermining this attitude is the aim of the following two subsections.

3.1 Approximate Truth

> Although this may seem a paradox, all exact science is dominated by the idea of approximation. When a man tells you he knows the exact truth about anything, you are safe in inferring that he is an inexact man. – (Russell [1931])

The notion of 'approximate truth' employed in most traditional formulations of scientific realism is both (i) of central importance, since we know our current scientific theories aren't exactly true, and (ii) sufficiently opaque as to function as little more than an acknowledgment of this fact. The divide and conquer strategy aims to improve this by identifying elements of a theory that are crucial to its empirical success (as opposed to the 'idle posits' of the theory that are not), and by identifying robust entities and structures that are likely to survive episodes of theory change; ideally these two sets will have considerable overlap. In this section I highlight several ways in which EFTs represent a significant improvement on this situation[19].

First, they provide explicit guidance about the domains in which one is warranted in believing claims made by the theory. Consider the most general case: the expected

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[18] Though see (Wallace [2006]), (Wallace [2011]), and (Fraser [2016]).

[19] I encourage the reader to consult (Fraser [2016]) for a discussion of this topic complementary to the one here.

breakdown of the entire theoretical framework of quantum field theory itself. It is well known that quantum field theory has not provided and probably cannot provide a consistent theory of quantum gravitation, and it is generally believed that the entire theoretical framework of quantum field theory itself becomes inapplicable at the length scales where quantum effects of gravity become significant (generally thought to be near the Planck scale)[20]. A very general appeal of EFTs is that they explicitly incorporate this inevitable breakdown of their theoretical framework. EFTs thus provide formal signposts delineating the physical domains in which one should and should not trust the theory to provide reliable ontological guidance. By making explicit that the theory becomes inapplicable beyond a given length scale, EFTs provide some measure of refinement and clarification of the sense in which quantum field theory is 'approximately true'; by studying a given EFT in an entirely 'internal' fashion, one can learn that its claims about the properties of and interactions between its degrees of freedom in one domain – their symmetries, dynamics, allowed final states in scattering experiments, and so on – are not a reliable guide to the world once one pushes the theory beyond a specified length scale. As physicist Tony Zee puts it in a discussion of EFTs, "I find it sobering and extremely appealing that theories in physics have the ability to announce their own eventual failure and hence their domains of validity" (Zee [2010], p. 172). This is one unique way in which EFTs offer a more precise handle on the sense in which quantum field theories are "approximately true".

A second way EFTs can refine the notion of "approximate truth" is that one can examine the roles different elements of the theoretical framework play in empirical applications in order to evaluate their physical significance. This is apiece with the divide and conquer approach to scientific realism sketched at the outset of this section, and the RG plays an important role in this endeavor. I will focus on one especially salient example of the role that EFTs can play in distinguishing physical significance from mathematical artifact. This takes place in the context of lattice quantum field theory: the short-distance physical breakdown of the theory around some length scale, which I will denote here by a, is incorporated by placing a quantum field theory on a four-dimensional spatiotemporal lattice with lattice spacing a (instead of a continuum spacetime). Most commonly it is EFTs that are invariant under a non-abelian gauge symmetry that one formulates this way – especially quantum chromodynamics (QCD), the theory of the strong interactions – and for concreteness I will focus on that case. My goal is to illustrate how combining the RG with applications of lattice QCD allows one to distinguish theoretical structures with genuine representational content from mere mathematical artifacts. Again for concreteness, I will restrict attention to two particular examples: (i) the way one can use the

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[20] However, there is an active research program dedicated to determining whether a quantum field theory of gravitation may be asymptotically safe: in such a scenario, the gravitational interaction would obtain a fixed, finite strength at some short distance and maintain that strength down to arbitrarily short length scales. See (Niedermaier and Reuter [2006]) for a fairly recent review.

RG to establish that so-called ‘mirror fermions’ that arise when one formulates an EFT on a spacetime lattice are mere mathematical artifacts and (ii) how the RG demonstrates the general physical irrelevance of the specific method chosen for formally incorporating the breakdown of an EFT[21].

Case 1: Mirror Fermions: Mirror fermions arise whenever one attempts to represent the breakdown of a quantum field theory containing fermions, like electrons or quarks, with a spacetime lattice[22]. A well known theorem, the Nielsen-Ninomiya theorem, proves that any attempt to place a quantum field theory that (i) satisfies a set of physically reasonable conditions and (ii) contains fermion fields on a d-dimensional spacetime lattice runs into trouble: the ‘latticized’ EFT necessarily contains 2^d more fermionic degrees of freedom than the theory intended to describe[23]. For instance, if one sets out to give a quantum field theoretic description of a single, non-interacting fermion field propagating on a four-dimensional spacetime and attempts to ‘latticize’ the theory, the result is an EFT on the lattice that now describes 16 fermions! One could reasonably ask how an EFT containing 15 more fermionic degrees of freedom than the theory intended to describe could possibly be a source of reliable ontological information. And indeed, a Standard Interpretation of such an EFT seems to result unavoidably in the conclusion that the theory’s ontology includes 16 species of fermion – a clear indication, it would seem, that such a theory is unfit for interpretation[24].

I think this attitude is mistaken, and that one can extract reliable ontological information as follows. Start by adopting one of several less naive approaches to putting fermions on a lattice[25], which isolate the undesired ‘mirror’ fermions from the physical fermion(s) one wanted to describe in the first place. After employing a more sophisticated method for ‘latticization’[26], the action $\mathcal{S}$ (which contains all the theory’s dynamical information) has the following form:

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[21] For more details than I can provide in what follows, and for further examples, see (Kronfeld [2002]) or (Gattringer and Lang [2009]).

[22] The problem is unique to this particular way of representing the breakdown of the EFT. The use of a spacetime lattice is very useful for both performing computations and mathematically rigorously defining EFTs, so physicists have been forced to grapple with the consequences of the Nielsen-Ninomiya theorem.

[23] See (Friedan [1982]) for a proof of the theorem, and (Montvay and Munster [1997], Chapter 4.4) for discussion.

[24] If one doubts that this would be the result of a Standard Interpretation of the lattice EFT, I ask them to recall the conclusion of (Fraser [2009]) that an EFT whose breakdown was represented by a spatial lattice was committed to an ontology according to which physical space itself has a lattice structure.

[25] ‘Wilson fermions’ and ‘Kogut-Susskind’ (or ‘staggered’) fermions are two widespread approaches. See (Montvay and Munster [1997], chapter 4) for details.

[26] The strategy employed here is called ‘Symanzik improvement’; see (Gattringer and Lang [2009], chapter 9).

$$\mathcal{S}_{lattice} = \mathcal{S}_{continuum} + (a^p)\mathcal{S}_{mirror}$$

where $\mathcal{S}_{mirror}$ is proportional to some positive power p of the lattice spacing a. The unwanted mirror fermions are sequestered into a term proportional to the lattice spacing a, while the physical fermion(s) are contained in $\mathcal{S}_{continuum}$, which is independent of a and dynamically decoupled from the mirror fermions[27] By the lights of the divide and conquer strategy, there is excellent reason to withhold ontological commitment from them (and other lattice artifacts of similar ilk), even within the EFT framework. The justification for this goes as follows.

The Standard Interpreter's claim in this case is that since mirror fermions appear in the formalism being interpreted, one is committed to including them in the theory's ontology. As mentioned above, the mirror fermions are sensitive to the specific choice of the lattice spacing a, while the physical fermions contained in $\mathcal{S}_{continuum}$ are not. This means that while they do appear in the formalism, they do so as part of the short distance, cutoff-scale physics that one discards in an EFT on principled grounds, since the theory is not trustworthy in that physical domain. One can cash this out in more detail using the notion of robustness, our criterion for ontological commitment, as follows.

One lesson of the RG is that choosing a specific value for the cutoff length a is somewhat arbitrary – one can choose any number of different lattice spacings $a' < a$ without affecting the empirical predictions of the theory. Furthermore, there are several different and independent methods for 'latticizing' quantum field theories that contain fermions. Each of these methods produces mirror fermions that manifest differently in the lattice dynamics $\mathcal{S}$, but in all cases they are dynamically decoupled from $\mathcal{S}_{continuum}$ and proportional to the lattice spacing. The mirror fermions thus depend on an arbitrary choice of modeling scheme in a way that genuinely representational quantities in physical theories do not. On the other hand, in each of these 'latticization' schemes the physical dynamics $\mathcal{S}_{continuum}$ are insensitive to the specific physical details of the chosen modeling scheme – in particular, the cutoff length and latticization method – and so remain invariant across a broad variety of independent methods. Of course, in the terminology used above, this is just to say that they are robust.

Recalling the two prongs of the divide and conquer strategy, one can say that while mirror fermions may remain present in the mathematical formalism of lattice QCD (or any EFT describing fermions on a lattice), they are neither (i) stable and robust elements of the theory, since they are sensitive to arbitrary choices of the length a of the lattice spacing and the chosen method of 'latticization' in a way that the genuinely physical fermion(s) are not, and (ii) they do not play an essential role in the empirical success of the theory. As such, there is little reason to believe that they are candidates for representing anything ontologically interesting.

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[27] It is worth noting that $\mathcal{S}_{mirror}$ may contain other lattice artifacts as well; for a general treatment of lattice artifacts see (Weisz [2011]).

Case 2: Recovering Spacetime Symmetries: A related (but distinct) way in which the RG can identify 'robust' physical quantities in an EFT is by demonstrating the differential sensitivity of structures in the theoretical framework to the specific way one chooses to model the physics at the scale of the short-distance breakdown scale[28]. This was integral for denying ontological significance to lattice artifacts like mirror fermions, but this function of the RG is entirely general. In fact, it is one of the essential virtues of the RG that it provides a tool for determining how changes in the structure of the theory at the scale of the short-distance breakdown affect physics at longer distances where the theory is empirically reliable. What the RG shows is that the 'fundamental' short-distance structure with which Standard Interpreters are so concerned is largely irrelevant to the physical content of an EFT in the domain where we have any reason to consider it empirically reliable. This includes changes in the way we model physics at the scale of the short-distance breakdown – which includes modeling schemes as diverse as carrying out calculations in a non-integer number of spacetime dimensions or introducing fictional 'particles' at the scale of the breakdown[29] – but is not limited to this. The RG also demonstrates that the long-distance structure of the theory is stable across variations of many physical conditions: one can add (say) (i) a variety of additional (hypothetical) particles at short distances, including novel interactions between those particles and the particles included in the EFT; or (ii) vary the strengths of the physical couplings in the theory; or (iii) incorporate symmetries present at the 'fundamental' scale that differ from those present in the theory at longer length scales, all while leaving unperturbed the structure of the theory in the physical domains in which it can be subjected to experimental tests, and has been shown empirically reliable. An EFT at long distances is 'robust' in a way that the the short distance 'fundamental' theory is demonstrably not: its entities and structures at that scale are "accessible (detectable, measurable, derivable, definable, producible, or the like) in a variety of independent ways," and so are candidates for being included in the ontology of that EFT.

In what follows I provide a single, less frequently discussed example which might be surprising for those inclined to equate a theory's fundamental ontological structure with its structure at all scales: the recovery of an EFT whose dynamical equations are Lorentz invariant even though the dynamics of that same EFT at short distances (i.e. the 'fundamental' level) strongly violate those symmetries.

For concreteness[30], consider a simple EFT describing a single scalar field Φ that has

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[28] I encourage the reader to consult (Fraser [2016], chapter 5), which contains a discussion of effective spacetime symmetries in QFT I take as complementary to mine. It is also worth noting that this is a topic worthy of further philosophical examination, as is illustrated by (for example) (Collins *et al.* [2004]).

[29] The former is called "dimensional regularization" and the latter "Pauli-Villars" regularization. See (Schwartz [2014], Appendix B) or (Duncan [2012], chapter 16.5) for a sampling of the many ways to incorporate the short-distance breakdown of EFTs.

[30] This discussion follows (Moore [2003], pp. 7-8). The switch from QCD to scalar

been placed on a four-dimensional lattice spacetime, with lattice spacing a. The structure of the lattice violates Lorentz invariance in multiple ways – for instance, special relativistic spacetimes are symmetric under arbitrary spatial rotations, but on a spacetime lattice one can only carry out spatial rotations in integer multiples of 90 degrees. The action for this theory is:

$$\mathcal{S}_{lattice} = \int d^4x \left((\partial\Phi)^2 + \frac{g_1}{a^2}\Phi^2 + \Phi^4 + \sum_i a^{\dim(O_i)+4} g_i O_i \right)$$

Only a subset of the interactions in the action violate the symmetries of special relativity: those multiplied by positive powers of a, all of which are sequestered into the summation on the right hand side. Starting with this action, one can use the RG to examine how the structure of the theory changes at length scales L that are long compared to the lattice spacing a, i.e. in the domain where the theory is empirically adequate. One finds that the interactions in the summation die off at a rate proportional to $(a/L)^p$ for some positive integer p. For illustration, let a be the Planck length 10^{-35} meters and L be the scale at which quarks and gluons become confined into hadrons, $L \sim 10^{-15}$ meters. The symmetry-violating interactions then decay at a rate of $(10^{-20})^p \approx 0$; in practice, one often allows $L \to \infty$ since this proves a perfectly reasonable approximation for $L \gg a$. The result is that in the physical domain $L \gg a$ where the EFT actually provides reliable ontological guidance, the only interactions that remain in its dynamics are those invariant under Lorentz transformations. Thus, beginning with an EFT that contained interactions at the 'fundamental' level that violate the symmetries of special relativity, one obtains a fully Lorentz invariant theory in the long-distance domain where one expects the theory to be physically trustworthy[31].

Recall that the primary purpose of this particular example was to illustrate that the RG

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field theory is motivated by the fact that ϕ^4 theory is infrared free, i.e. the couplings go to zero as the length scales at which we are examining the the structure of the theory get arbitrarily long. This allows us to maintain analytic control over the theory (and over the RG flow) at the long distance scales where the irrelevant operators that break Lorentz invariance die off and an "effective" or "emergent" Lorentz invariance is restored. In the case of QCD, the couplings get larger at long distances, eventually leading to the confinement of the quark and gluon degrees of freedom. This is a region of QCD over which we do not have particularly good analytic control, and have to resort to computers and numerical methods. My thanks to an anonymous referee for pushing me to clarify this choice.

[31] To be mathematically precise, one actually 'latticizes' the theory in Euclidean spacetime for reasons of mathematical tractability, and then recovers invariance under the group of four-dimensional rotations O(4), the Euclidean spacetime analogue of the Lorentz invariance of special relativity. Full Lorentz invariance is recovered by then analytically continuing the theory from Euclidean spacetime back to Minkowski spacetime.

can refine and clarify the notion of "approximate truth" by identifying which theoretical entities and structures in a quantum field theory are 'robust' and which are likely mere mathematical artifacts. It also suggests two further conclusions. First, it functions as a response to those such as (Fraser, Fraser [2009, 2011]) who want to assign physical significance to the fact that (some) methods of representing the short-distance failure of EFTs violate the symmetries of special relativity. Fraser argues that one cannot confine the ontological significance of such violations to physical domains in which the theory is empirically inadequate anyway – they affect the physical content of the theory at all distance scales. As she puts it in (Fraser [2009], p. 560), "[c]utting off the theory at some short-distance scale has the effect of changing the content of the theory as a whole, including its description of long-distance scales." I take the examples presented here to go some way toward demonstrating this is mistaken: as long as one is not in the grip of Standard Interpretation, they are justified in denying that mathematical artifacts at the scale of an EFT's breakdown carry any ontological significance.

The second conclusion these examples suggest is that we can be misled about the reliable ontological information provided by a quantum field theory by interpreting only its empirically unreliable 'fundamental' structure and conflating that with its structure at all scales. It is a mistake to think that one can simply read a quantum field theory's ontology off its 'fundamental' mathematical structure. The next section develops in more detail the implications this has for our interpretational practice and for the ontological commitments of EFTs.

3.2 Scales and Ontology

In section 3.1, I argued that by interpreting EFTs one has resources to make fine-grained distinctions between mathematical artifice and physical significance, which supports a 'divide and conquer' approach to ontological commitment. I contrasted this with an excessively egalitarian approach to ontological commitment: Standard Interpreters treat all of the entities and structures of a theory's mathematical framework (at least those at the 'fundamental' level) as on more or less equal ontological footing. This is one symptom of the 'fetishism of mathematics' diagnosed earlier by Stachel.

In this section, I argue that attending to EFTs also makes clear that for many quantum field theories, any interpretation that enables those theories to 'discharge their scientific duties' must include higher-level entities in its ontology[32]. This is particularly true of their explanatory duties, and it is on these that I will focus here[33]. The contrast again is

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[32] This section touches on a number of issues that are contentious in the mainstream metaphysics literature. In particular, the discussion may benefit from more direct engagement with the ongoing discussions of fundamentality and grounding there; length constraints prohibit pursuing this engagement here, but I thank an anonymous referee for flagging the issue.

[33] I do not have any particular account of scientific explanation in mind. All that I

with Standard Interpretation: while its insufficiently discriminating approach to a theory's mathematical structure leaves it open to too much ontological commitment, its focus on only the 'fundamental' structure of quantum field theories leaves it prone to committing simultaneously to too little.

As an example, consider[34] (Fraser [2008], p. 856) in which a theory's ontology is straightforwardly equated with its fundamental ontology: "[t]he point at issue is whether entities with certain properties – particlelike properties – exist. More precisely, does QFT support the inclusion of particlelike entities as fundamental entities in our ontology?" After answering 'no', Fraser entertains the response that "quanta are not part of the ontology of fundamental entities described by QFT, but...that nevertheless quanta do exist according to QFT." Her response epitomizes the 'fundamentalism' I have attributed to Standard Interpreters: "[f]or this to be a viable response, the cogency of the distinction between fundamental and less fundamental entities must be defended and a case must be made for admitting additional, non-fundamental entities into our ontology....*the important question* – which remains outstanding – is not the status of quanta, but what fundamental entities are allowed into our ontology by QFT" (pp. 857-8) (my emphasis).

As I stated above, focusing exclusively on fundamental ontology in this fashion leaves one with an interpretation unequipped to support the theory in the performance of its explanatory duties. By paying attention the applications of EFTs and the RG, it becomes clear that many explanatory affirmations made in the theory simply cannot be made true by including in one's ontology only those entities at the fundamental scale. I emphasize that as long as one grants that scientific explanations aim at providing an at least minimally illuminating and manageable account of their *explananda*, there is good reason to believe that the "cannot" in the previous sentence will not be eliminated by some "future complete physics" or "in principle" explanations in terms of the fundamental ontology. This belief can be in part motivated by considerations of the sort discussed in section 3.1, where we saw that the fundamental structure of a quantum field theory can be in many respects irrelevant for answering why-questions about its behavior at longer distances. I will focus on a specific example in quantum field theory, that of 'confinement', that I think makes the motivation for this belief especially salient. This story is itself rather general – the phenomenon of confinement is present in any quantum field theory which

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require in what follows is this, which I hope is relatively uncontroversial: whatever else they do, scientific explanations necessarily aim at providing practitioners with some sense of understanding of the *explanandum*. I should note, however, that there is an argument to be made that I require more than this: in particular, the recommendation of (Saatsi [2016]) that any explanationist argument for realism be situated within a particular articulated account of scientific explanation puts pressure on my lack of commitment to any such account here. I thank an anonymous referee for bringing Saatsi's paper to my attention.

[34] Recall also the quotes above from (Arntzenius [2014]) and (North [2009]), and the references in fn. 12.

is invariant under a non-abelian gauge symmetry – but for concreteness I will focus on an example of considerable physical import: the confinement of quarks and gluons into hadronic bound states in QCD at long distances[35].

At the shortest distances at which it is empirically valid[36], QCD describes the interactions of quark and gluon fields via the strong force. Consider a schematic version of the QCD dynamics:

$$\mathcal{S}_{QCD} = \mathcal{S}_{gluon} + \mathcal{S}_{quark} + \mathcal{S}_{interaction}$$

The physical degrees of freedom appearing in the dynamics of QCD at short distances are quarks and gluons, with the final term representing their interactions. When interactions between these fields are relatively weak, as they are in QCD at short distances, a description in terms of quark and gluon particles is available and explanatorily powerful. Calculations performed in the theory at this distance scale have played an enormous role in cementing QCD as the appropriate theory of the strong interaction[37], and it is these physical degrees of freedom that appear in the fundamental dynamics of the Standard Model of particle physics. It may therefore seem natural to conclude that an interpretation of QCD requires the admission of quark and gluon fields to one's ontology, but nothing more. This would almost surely constitute the Standard Interpretation of the ontology of QCD, at least[38].

Such an interpretation of QCD would leave it unable to discharge its explanatory duties, and thus fails *qua* interpretation by the standard of (Ruetsche [2011]) that I have adopted here. Studying the behavior of QCD at long distances, using the RG and techniques of lattice QCD, reveals that QCD has a rich, scale-dependent structure that is hidden from the perspective of the fundamental level. It also reveals that many physical processes involving these long-distance structures in QCD are not explicable purely using the dynamics and degrees of freedom present at the fundamental level. The feature of QCD responsible for this is that the strength of the interaction between quark and gluon fields increases as one considers the structure of the theory at longer distances. This

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[35] To be more precise: any non-abelian gauge theory is confining as long as it meets certain other fairly mild conditions – it must not have too many scalar or fermion fields, for instance.

[36] As a piece of mathematics QCD is mathematically consistent to arbitrarily short distances, in the sense that its interactions get weaker at short distances, reducing to a theory with no interactions at all in the continuum limit. It is, of course, still not physically reliable at those arbitrarily short distances.

[37] See (Collins [2011]) for a thorough presentation of QCD in this domain

[38] Presumably such an interpretation would then go on to question whether one must represent the quarks and gluons in the fundamental ontology as elementary particles, or only the corresponding quark and gluon quantum fields, or gauge-invariant Wilson loops, or something else entirely. Such questions, while interesting, are not my concern here.

gives rise to 'confinement', the phenomenon I think most clearly illustrates the scale-dependence of the ontology of QCD. Roughly, a quantum field theory is 'confining' if, beyond a certain length scale, the strength of the interactions between its short-distance degrees of freedom become so strong as to make explanations of phenomena in terms of particulate states of those fundamental fields intractable and (even if one could provide such a description) entirely unenlightening. In QCD, the fundamental quarks and gluons become confined into hadrons (particles like the proton and neutron, which are bound states of quarks and gluons), preventing particulate states at length scales longer than about 10^{-15} meters.

This is unlike other familiar bound states, such as a hydrogen atom, in the following sense. In those cases, bound states form under certain energetic conditions, but under other common conditions one can also scatter sufficiently energetic electrons off of a proton and let the two become separated by very long distances without a bound state being formed. The situation is different in the case of quarks and gluons. In that case, it is nomologically impossible to separate a pair of particulate states of quark or gluon fields by a distance of more than about 10^{-15} meters. Imagine a tiny experimentalist living inside of a hadron, attempting to pull quarks apart. She would discover, presumably after much exertion, that it is impossible to separate them to distances greater than the confinement scale.

This prevents these degrees of freedom from being dynamically active on length scales longer than the confinement scale, which means that they play neither an observational nor explanatory role in physical processes taking place above that scale[39]. Rather than quarks and gluons, the degrees of freedom appearing there are bound states: hadrons (like pions, protons, and neutrons) which have different properties (they lack the 'color charge' that quarks and gluons possess, for example), interact via dynamics with a different structure than the fundamental QCD dynamics, and which are invariant under different symmetries than is QCD at short distances.

It is true that starting from the fundamental QCD dynamics, one can derive that the fundamental degrees of freedom are confined into hadrons at around 10^{-15} meters[40]. However, if one wants to explain physical processes characterized by length scales longer than this – the binding of atoms into molecules, for example – it is a matter of physical law that one cannot 'zoom out' to those length scales without a description in terms of particulate states of quark and gluon fields becoming wildly intractable and devoid of

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[39] This isn't to deny that some properties of hadrons, like their masses, are best explained by the properties and interactions of their constituent quark and gluon fields. It is simply to state that the dynamics of quarks and gluons do not explain the hadronic dynamical behavior, and that one cannot explain hadronic behavior, such as proton-proton scattering, solely in terms of quark and gluon states.

[40] At least in the sense of 'derive' used in physical practice. A fully mathematically rigorous derivation remains elusive, although there is also overwhelming numerical evidence of confinement from computational studies of lattice QCD.

explanatory power, and one is required to replace such a description by one in terms of hadrons. Furthermore, the hadronic degrees of freedom play an integral role in a tremendous number of empirical applications and explanations of physical phenomena, such as those currently taking place at the LHC.

On this last point: due to the confinement of the quarks and gluons, the strongly-interacting particles that experimenters actually prepare, manipulate, and observe in particle physics experiments are hadrons, not quarks and gluons. Furthermore, experimenters and theorists also employ hadrons to explain the results of those experiments: almost every high energy scattering event at the LHC produces so-called ‘jets’ of hadrons which are then observed in particle detectors, and the details of their production are integral for explaining the scattering event (see for example (Schwartz [2014], Chapter 36)). As (Montvay and Munster [1997], p. 231) put it, “the transformation of the perturbative predictions at the parton (i.e. quark and gluon) level to the hadronic incoming and outgoing states *cannot be done* without some knowledge of...confinement phenomena” (my emphasis)[41] So in this very flat-footed sense, an interpretation of QCD that does not admit higher-level entities like hadrons into its ontology fails almost immediately its task of enabling the theory to discharge its scientific duties. In fact, this is a special case of a rather general principle about the explanation of experimental results: in the words of (Wimsatt [2007], p. 210),[42] “[t]he fact that most direct interactions of something at a level of organization will be with other things at that level means that detectors of entities at a level...will interact with it via properties characteristic of that level. [...] For these reasons, and for others, eliminative reduction is often not possible, necessary, or desirable – our very instruments anchor us...at the level we are observing.” In the case of QCD, Wimsatt’s principle is a corollary of the fact that any description of any strong-interaction process at distances longer than the confinement scale in terms of particulate states of the quark and gluon fields will be entirely devoid of explanatory power. So our guiding interpretive principle – that an interpretation enable a theory to discharge its scientific duties – entails that any interpretation of QCD had better include, at minimum, higher-level entities like hadronic bound states along with quarks and gluons in its ontology.

QCD thus provides a case in which even though one knows that some higher-level

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[41] The situation with the top quark is subtle. Top quarks do not live long enough to form hadronic bound states themselves, instead decaying semi-weakly (most commonly into a b-quark and a W-boson). The b-quarks do undergo hadronization and this is a source of theoretical and experimental uncertainty in the determination of top quark observables. So although top quarks themselves do not undergo hadronization, top quark phenomenologists are forced to deal with confinement phenomena; see (Olive *et al.* [2014]) for discussion. This has motivated the construction of top quark observables that minimize sensitivity to b-quark hadronization; see (Stieger [2016]) for a recent discussion. My thanks to an anonymous referee for encouraging me to investigate some of the subtleties of top quark phenomenology.

[42] A somewhat similar point is made in (Wallace [2012], chapter 2).

entities are composite states of more fundamental entities, one cannot explain the behavior of those higher-level entities solely in terms of the behavior of the fundamental level. Recall that this story about confinement of fundamental degrees of freedom at long distances has some generality: it will occur in any quantum field theory which is invariant under non-abelian gauge symmetries[43] – precisely the sort of theories which make up the Standard Model of particle physics. This is yet another way in which EFTs and the RG provide us with improved realist commitments: they reveal absolutely physical information that is obscured from the perspective of the Standard Interpreter.

I began by asking what sort of scientific realism could be grounded by EFTs, and I will close with a few remarks on that theme. It demands that we distinguish reliable ontological information from theoretical artifacts, and requires attending in detail to the way theories are applied in practice to do so, in line with my earlier advocacy for the divide and conquer strategy. The result is a more discerning sort of realism, and one that gives the lie to the idea that we can simply read a physical theory's ontological commitments off of its fundamental mathematical framework. I take this to be a feature, not a bug: the idea that one could responsibly do otherwise seems to me to always have been a mistake.

For this sort of realism it is important that a theory have a broad range of empirical applications[44]. However, this is not to say that the ontological commitments of an EFT are restricted to its "observable" content. It just emphasizes something that has come to be overlooked by philosophers of physics: examining in detail how a theory makes contact with the world offers important guidance in determining which features of the theory have a genuine representational function and which are excess structure. I should note that I don't believe that attending to empirical applications is the only method of sorting ontological wheat from theoretical chaff – I have emphasized the importance of the RG in the context of EFTs, and different theoretical contexts are likely to have similar 'locally' useful tools. I think it is in general, however, the most important method. Finally, I noted at the outset that one of the original motivations for the divide and conquer strategy was that the ontological commitments it entails are entities and structures that are likely to survive episodes of theory change. In the case of quantum field theory, such an episode is inevitable – the need for a theory of quantum gravity is almost certain to produce a theory describing physics at short-distances that differs dramatically from quantum field theory. In light of this virtual guarantee that theory change is on the horizon, I think the ability of EFTs and the RG to identify entities and structures that are robust and insulated against such short-distances changes should be appealing to would-be realists.

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[43] Again, as long as it satisfies certain other fairly mild conditions; see fn. 35.

[44] Arguably, any theory that doesn't isn't a physical theory at all.

4 Conclusion

> Our mistake is not that we take our theories too seriously, but that we do not take them seriously enough. It is always hard to realize that these numbers and equations we play with at our desks have something to do with the real world. – Steven Weinberg (Weinberg [1993])

> To be sure, Weinberg's remark has to be applied with care. Although his desk has played host to an inordinate amount of mathematics that has proved relevant to the real world, far from every equation with which we theorists tinker rises to that level. In the absence of compelling experimental or observational results, deciding which mathematics should be taken seriously is as much art as it is science. – Brian Greene (Greene [2011])

I have argued that a widespread approach to the interpretation of quantum field theories is misguided, and have proposed an alternative "effective" replacement. This approach offers a more discerning approach scientific realism that does not share the Standard Interpreters' quixotic focus on fundamental structure, and aims to identify robust structures that will survive future episodes of theory change. It is is well-grounded in both the theoretical framework and empirical applications of our best scientific theories.

In closing, I again want to forestall any misconception of an anti-metaphysical spirit on my part and emphasize that I agree with Weinberg that failing to take our theories seriously is a mistake; it is far from any brand of instrumentalism that I am endorsing here. Indeed, I take it that providing a corrective to the mistake that Weinberg diagnoses is part of the motivation of many philosophers of physics, myself included. However, I have argued here that such a corrective has come to be applied indiscriminately – Standard Interpreters are guilty of the opposite mistake of taking the mathematical structures of our theories too seriously. The pendulum has swung too far in the other direction. They have ignored the way these theories make contact with the real world and proceed as if every nook and cranny of the theoretical framework carries equal representational claim, overlooking the bit of wisdom captured by Greene's cautionary note. I think Greene is correct that determining the ontological implications of our physical theories, above and beyond their observational implications, contains considerable amounts of art as well as science, and it is a task well-suited for philosophers. I just think that, for the reasons I've outlined in this paper, the philosophical project of scientific realism will be better grounded, and more promising, if we introduce more attention to science into the state of the art.

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