Why Be Natural?

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Abstract. Naturalness, as a guiding principle for effective field theories (EFTs), requires that there be no sensitive correlations between phenomena at low- and high-energy scales. This essay considers four reasons to adopt this principle. The first three are that it has been empirically successful, it is quantifiable, and it is consistent with what Williams (2015) calls a "central dogma" of EFTs; namely, that phenomena at widely separated scales should decouple. I argue that these are not compelling reasons: First, the modest empirical success of naturalness must be balanced by spectacular empirical failures; second, measures of naturalness are highly subjective and risk begging the question; and third, a distinction between two types of EFTs, Wilsonian and continuum, suggests that while decoupling may be a central dogma of EFTs, naturalness is not. On the other hand, a fourth reason to be natural is that it underwrites a non-trivial notion of emergence. Thus to the extent that one desires to interpret EFTs as describing emergent phenomena, one should be natural.

1. Introduction
In effective field theories (EFTs), naturalness is a requirement that there be no sensitive correlations between phenomena at low- and high-energy scales. Instances of its failure in the Standard Model include the Hierarchy Problem, the Cosmological Constant Problem, and the Strong CP Problem. That these are taken as problems indicates the extent to which naturalness has come to be viewed as a guiding principle in the construction of EFTs. This essay considers four reasons for adopting this principle. Section 2 first reviews the steps involved in the construction of an EFT. Section 3 then considers three reasons to be natural: it has had modest empirical success, it is quantifiable, and it is consistent with what Williams (2015) calls a "central dogma" of EFTs; namely, that phenomena at widely separated scales should decouple. I argue that these are not compelling reasons: the modest success of naturalness must be balanced by spectacular failures, measures of naturalness are highly subjective and risk begging the question, and a distinction between two types of EFTs, Wilsonian and continuum, suggests that while decoupling may be EFT dogma, naturalness is not. Section 4 applies this last lesson to a fourth reason to be natural; namely, that it underwrites a non-trivial notion of emergence. Naturalness can be thought of as requiring that phenomena described by an EFT exhibit robust dynamical independence with respect to phenomena at high energies, and some authors have considered this to be a necessary characteristic of emergence. Thus to the extent that one desires to interpret EFTs as describing emergent phenomena, one should be natural.

2. How to Construct an Effective Field Theory
This section reviews the steps involved in the construction of a Wilsonian EFT. Given an action $S[\phi, \partial \phi]$ that is a functional of a field variable and its derivatives, the first step is to divide the field into high and low momenta parts $\phi = \phi_H + \phi_L$ with respect to a cutoff $\Lambda$. The next step is to integrate out the high momentum field. Formally, this is expressed as a path integral over $\phi_H$:

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1. In this essay by an EFT I mean an effective quantum field theory. Some authors use the term effective theory in a broader sense (e.g., Wells 2012).
2. The following exposition is based on Polchinski (1994). A second type of EFT known as a continuum EFT will be discussed below in Section 3.
3. In general, $\Lambda$ is an energy cutoff that separates high-energy "heavy" fields from low-energy "light" fields.
\[ e^{iS_{\Lambda}[\phi_L]} = \int D\phi_H e^{iS[\phi_L, \phi_H]} \]  

(1)

where \( S_{\Lambda}[\phi_L, \partial\phi_L] \) is the Wilsonian effective action that depends only on \( \phi_L \) and its derivatives. In practice, for weak interactions, \( S_{\Lambda} \) is expressed as a perturbative expansion:

\[ S_{\Lambda} = S_0 + \int d^D x \sum_i g_i O_i \]  

(2)

where \( D \) is the spacetime dimension, each operator \( O_i[\phi_L, \partial\phi_L] \) consists of powers of \( \phi_L \) and/or its derivatives, and the coupling constants \( g_i \) encode the effect of integrating out \( \phi_H \). The weak interaction assumption makes the expansion (2) possible, and it requires the \( g_i \) to be sufficiently small. It also identifies the 0th order term \( S_0 \) as the free action.

One next performs dimensional analysis on (2) to determine how its terms behave at low energies \( E<<\Lambda \) that represent the scale of experimental interest. In units in which \( \hbar = c = 1 \), \( S_{\Lambda} \) is dimensionless, contributing \( E^{\delta_i} \) units of energy. If \( O_i \) has units \( E^{\delta_i} \), then \( g_i \) has units \( E^{D-\delta_i} \), where \( \delta_i \) is determined by \( S_\Lambda \). The \( g_i \) are dimensionful and, by assumption, encode the high-energy degrees of freedom. This suggests they are of order \( \Lambda^{D-\delta_i} \), and this allows the introduction of dimensionless couplings \( \lambda_i \), defined by

\[ \lambda_i = \Lambda^{D-\delta_i} g_i \]  

(3)

and assumedly of order 1. This assumption about the order of the couplings is important: arguably, it underwrites an intuition that naturalness is built into the formulation of a Wilsonian EFT, as I will argue below in Section 3.2.

By solving (3) for \( g_i \), and then substituting back into (2), one finds that the \( i \)th term in (2) is of order \( \lambda_i (E/\Lambda)^{D-\delta_i} \). Three types of term can now be identified: An irrelevant term is characterized by \( \delta_i > D \), hence decreases as \( E \rightarrow 0 \); a relevant term is characterized by \( \delta_i < D \), hence increases as \( E \rightarrow 0 \); and a marginal term is characterized by \( \delta_i = D \), hence remains constant as \( E \rightarrow 0 \). To the extent that the \( g_i \) encode high-energy effects, irrelevant terms indicate an insensitivity to these effects at low energies, whereas relevant and marginal terms indicate a sensitivity to them. Thus if a Wilsonian EFT is viewed as a low-energy version of a full theory that is insensitive to the latter, irrelevant terms might be considered ideal, whereas relevant and marginal terms might be worrisome.

As an example, consider a weakly self-interacting scalar field \( \Phi \) for \( D=4 \) with a symmetry \( \Phi \rightarrow -\Phi \) for simplicity.\(^4\) The effective action is given by a sum of all possible terms involving powers of the low momenta field \( \Phi_L \) and/or its derivatives that are consistent with the symmetry:

\[ S_{\Lambda}[\Phi_L] = \frac{1}{2} \int d^4 x (\partial_\mu \Phi_L)^2 + \int d^4 x \left[ \lambda_2 \Lambda^{-4} + \lambda_0 \Lambda^2 \Phi_L^4 + \lambda_2 \Phi_L^4 + \lambda_4 \Lambda^{-2} \Phi_L^6 + \ldots \right] \]

\[ + \int d^4 x \left[ \sum_{n=0} \lambda_n^{\Lambda^{-n}} (\partial_\mu \Phi_L)^2 \Phi_L^n + \sum_{n=0} \lambda_n^{\Lambda^{-n}} (\partial_\mu \Phi_L)^4 \Phi_L^n + \ldots \right] \]  

(4)

\(^4\) This example is discussed in Duncan (2012, 547) and Williams (2015, 84).
where $n$ is even (due to the symmetry), and the first term is the free action. The latter entails that the dimension of $\Phi_\tau$ is 1. There are thus two relevant terms: an additive term in which no field variable appears, with coupling $\lambda_\tau \Lambda^4$ that is quartically dependent on $\Lambda$; and a mass term containing the product of two fields, with coupling $\lambda_0 \Lambda^2$ that is quadratically dependent on $\Lambda$. If a Wilsonian EFT is thought of as a low-energy restriction of a full theory that is insensitive to the high-energy degrees of freedom of the latter, then these terms may appear worrisome: a slight change in the high-energy theory will produce a large (quartic or quadratic dependent) change in the low-energy theory.

This sensitivity manifests itself in other ways, too. For instance, the relation between the "physical" mass coupling (i.e., what is measured in experiments) and the dimensionless coupling is $m_{\text{phys}}^2 = \lambda_0 \Lambda^2$. The physical mass is the mass of the scalar field at energies $E \ll \Lambda$; thus the dimensionless parameter $\lambda_0$ cannot be of order 1. The sensitivity of the mass term in (4) to high energy effects is thus encoded in a dimensionless parameter that is not order 1. Moreover, if one includes higher order corrections to the mass term, one finds that they are proportional to $\Lambda^2$; namely, $m_{\text{phys}}^2 = m_{\text{bare}}^2 + \kappa \Lambda^2$, for constant $\kappa$, and this requires a fine-tuning of the (non-renormalized) bare mass $m_{\text{bare}}$ to guarantee the small measured value for $m_{\text{phys}}$ (in the context of the Higgs scalar mass, see, e.g., Giudice 2008, 161; Dine 2015, 47). Thus the sensitivity of the mass term to high energy effects is also encoded in the necessity of fine-tuning the corresponding bare parameter.

3. Why Be Natural?
The criterion of naturalness is supposed to make the concerns at the end of the preceding section explicit. After Williams (2015, 82), I will take naturalness be the requirement that there should be no sensitive correlations between low- and high-energy phenomena in the context of an EFT. Other formulations of naturalness that appear in the physics literature include:

(a) There should be no parameters with quadratic (or higher power) dependence on the cutoff.
(b) There should be no dimensionless parameters that are not of order 1, unless they are protected by a symmetry.
(c) There should be no bare parameters that require fine-tuning.

The symmetry formulation (b) is motivated by the fact that fermion masses in the Standard Model are small relative to the appropriate cutoff, and hence the corresponding dimensionless parameters are not of order 1; but because of the form of the mass term in a fermion theory, setting a fermion mass to zero restores a chiral symmetry to the theory. This symmetry affects the form of the higher-order corrections to the mass term with the result that no fine-tuning of the bare mass is needed to be consistent with the small value of the physical mass. There can be

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5 The first term, being dimensionless, contributes $E^0$ energy units. The $d^4x$ part of it contributes $E^{-4}$ units and the $\delta_i^2$ part contributes $E^2$ units. If the contribution of $\Phi_\tau$ is $E^6$, then $E^0 = E^{-4}E^2E^{2\delta}$, hence $\delta = 1$.
6 These are discussed in Williams (2015) who argues that they all have the sensitivity prohibition in common.
7 This is ultimately a result of the fact that fermions are typically represented mathematically by spinor (as opposed to scalar or tensor) fields, and the former have a "built-in" chiral symmetry. The symmetry formulation of naturalness was introduced by 't Hooft (1972).
other ways of avoiding such fine-tuning besides an explicit symmetry; hence, in general, one might maintain that apparent violations of naturalness signal the presence of new physics (i.e., new symmetries or interactions) that occurs between the low-energy scale $E$ and the cutoff $\Lambda$. In other words, when low-energy phenomena appear to be sensitive to high-energy phenomena, we should look for new physics, the effect of which is to remove the apparent sensitivity.

3.1. Modest Empirical Success

Why insist that low-energy phenomena must not be sensitive to high-energy phenomena? One reason is that naturalness has had modest empirical success in the context of effective quantum field theories. Indeed, most parameters in the Standard Model are natural, and the failure of a parameter to be natural has on three occasions signaled the presence of new physics; namely, the existence of the charm quark, the positron, and the $\rho$-meson.

(a) Gaillard and Lee (1974) predicted the mass of the charm quark to be $\sim1.2$ GeV on the basis of the smallness of the difference in masses of the neutral kaons $K^0$ and $\bar{K}^0$ ($\sim7 \times 10^{-15}$), and the appropriate cutoff for kaon physics; namely, $\Lambda < 2$ GeV. The existence of a new interaction mediated by the charm quark at an energy less than 2 GeV explained the apparent sensitivity of the kaon mass difference to high-energy effects.

(b) In the positron case, one observes that the electron radius $r$ should satisfy $r > \alpha/m_e$, where $\alpha$ is the fine constant and $m_e$ the electron mass; but this is much larger than what is observed; hence the electron self-energy correspondingly is smaller than what is observed. If the appropriate cutoff is on the order of $1/r$, this suggests new physics no later than 70 MeV, and this is born out by the existence of the positron.

(c) In the $\rho$-meson case, the observed smallness of the difference in masses of the charged and neutral pions with respect to the appropriate cutoff suggests a new interaction no later than $\sim850$ MeV, and this is born out by the existence of the $\rho$-meson with mass 770 MeV.

These are "modest" successes to the extent that only (a) counts as a prediction, whereas (b) and (c) should be taken to be postdictions. Moreover, these successes must be balanced by three spectacular failures:

1. The first takes the form of The Hierarchy Problem, which is the failure of the Higgs mass in the Standard Model to be natural. Indirect observations at the Large Hadron Collider have assigned the Higgs mass a value of 125 GeV. For the Standard Model, the Planck mass $M_{\text{Pl}} \sim 10^{19}$ GeV is taken as a cutoff; hence, the corresponding dimensionless parameter for the Higgs mass is given by $\lambda_0 = m_{\text{Higgs}}^2/M_{\text{Pl}}^2 \sim 10^{14}/10^{38} = 10^{-24}$, which is a very small number, certainly not of order 1. Alternatively, in order for the physical Higgs mass to be 125 GeV, given that higher-order corrections are on the order of $M_{\text{Pl}}^2$, the bare Higgs mass must be fine tuned to one part in $10^{-34}$.

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8 Admittedly, naturalness as a constraint on effective theories in general has had much more empirical success than its restricted application to effective quantum field theories (see, e.g., Wells 2012). (Thanks to Sebastian Rivet for making this point.)

9 Details of these examples may be found in Giudice (2008, 168-9).
2. Another failure of naturalness is exhibited by the cosmological constant \( \Lambda_C \) (not to be confused with a generic cutoff \( \Lambda \)), if it is understood as an additive term in the effective action for general relativity. Observational constraints put the value of \( \Lambda_C \) at \( < 10^{-47} \) GeV\(^4\), and if the Planck mass is again taken as a cutoff, the corresponding dimensionless parameter is on the order of \( \Lambda_C^4/M_{Pl}^4 = 10^{-47}/10^{76} = 10^{-120} \).

3. Finally, the Strong CP Problem is the failure of a parameter \( \theta \) associated with a CP-violating term in the Lagrangian for quantum chromodynamics to be of order 1. One can show\(^{10} \) that \( \theta < 10^{-10} \). This would be consistent with 't Hooft's notion of naturalness if setting \( \theta \) to zero restored a CP symmetry, but this is not the case.

In all three cases naturalness might be upheld if there was new physics that would explain the sensitivity of the low-energy phenomena. In the Higgs case, new physics has been proposed most prominently in the form of supersymmetry, in the cosmological constant case, new physics has been proposed in the forms of various candidates for dark matter, and in the CP-violating parameter case, new physics has been proposed in the form of gauge bosons known as axions. These and related exotica have yet to be observed. Of course this doesn't necessarily mean they, or something similar, won't be discovered in the future, but the current experimental constraints on such exotica make the detection of most of them highly unlikely.

3.2. Quantifiability

A second reason to be natural is that naturalness is quantifiable. Measures of naturalness fall broadly into two categories:

(a) Measures of the sensitivity of low-energy parameters to high-energy parameters.
(b) Measures of the likeliness of fine-tuned values of bare parameters.

Granted, that a property is quantifiable in this sense does not necessarily entail that it exists, or that it is a relevant way to characterize a theory. On the other hand, quantifiability in this sense might be considered a necessary condition for taking the corresponding property seriously. Thus if we are to be natural, then we might legitimately require that we be able to measure the degree to which our theories possess the property of naturalness. In any event, even this weak understanding of quantifiability as a necessary condition for being natural is problematic, as I will now argue.

With respect to (a), a sensitivity measure involves specifying a set of low-energy and high-energy parameters (with the former functions of the latter), and then defining a sensitivity parameter \( \Delta \) in terms of the maximum value of derivatives of the low-energy parameters with respect to the high-energy parameters. As Williams (2015, 90) notes, this is supposed to measure how the low-energy parameters react to changes in the high-energy parameters. A

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\(^{10}\) See, e.g., Dine (2015, 48). This upper limit is based on experimental limits on the electric dipole moment of the neutron, which can be derived as a function of \( \theta \).
typical sensitivity parameter for the weak sector of the Standard Model takes the following form:

$$\Delta[a_i] = \frac{\partial \ln m_Z^2}{\partial \ln a_i^2}, \quad \Delta = \max_i \Delta[a_i]$$

where $a_i$ are a set of high-energy parameters and $m_Z$ is the (low-energy) mass of the $Z$ boson. One can now impose a tolerance level for naturalness, so quantified, by choosing a particular value $\Delta_{\text{max}}$ and requiring $\Delta < \Delta_{\text{max}}$. As various authors point out, the problem with this method of quantifying naturalness is that it involves a high degree of subjectivity (Williams 2015, 90; Craig 2013, 7; Feng 2013, 365). First, there is an arbitrary aspect to the choice of low-energy and high-energy parameters within a given theory (as well as how these parameters are parameterized), and this choice can determine whether the theory is labeled natural or unnatural. Second, the definition of the sensitivity parameters $\Delta[a_i]$ varies among authors, with alternatives including $\Delta[a_i] = \frac{\partial \ln m_Z^2}{\partial \ln a_i}$ and $\Delta[a_i] = \frac{\partial \ln m_Z}{\partial \ln a_i^2}$ (Feng 2013, 367). How one defines these parameters again determines whether or not a given theory is labeled natural. Finally, Craig (2013, 7) reports that the choice of tolerance level $\Delta_{\text{max}}$ has changed over the years from $\sim10$ to 1000. These and other problems lead Craig to claim that "...it is clear that measures of tuning have no intrinsic meaning" (pg. 7).

With respect to (b), Hossenfelder (2018, 10) points out that any measure of the likeliness of a value of a parameter requires the introduction of a probability distribution, and this raises the risk of begging the question that the particular value of a fine-tuned parameter is intrinsically unlikely to begin with. In particular, if we answer the question "Why be natural?" by referring to the unlikeliness of a fine-tuned value of a parameter with respect to a particular probability distribution, this raises the further question, "Why that particular probability distribution?" And if we answer this latter question by referring to its naturalness (i.e., that it makes fine-tuned values of parameters unlikely), we've entered a vicious circle of justification. Of course, one may exit this circle by attempting to justify the adoption of a particular probability distribution independently of the criterion of naturalness, but Hossenfelder's point is that such justifications do not appear in the physics literature.

Norton (2010) raises a more fundamental concern with any attempt to define a fine-tuning measure in terms of a probability distribution. According to Norton, a fine-tuning measure is characterized by a claim that has completely neutral support from current evidence, insofar as current theories take the value of a bare parameter as a brute fact. A probability distribution is required to be additive, and, according to Norton, additivity represents the complementary between favorable and unfavorable evidence, and "...leaves no place in the representation for neutrality" (Norton 2010, 504). Norton's concern then is that adopting a probability distribution as a measure of the likeness of a fine-tuned value of a parameter risks conflating neutral evidence (i.e., data that is neutral with respect to the value of the parameter) with

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11 Craig (2013, 6), Feng (2013, 365).
12 Craig (2013, 7) also reports that sensitivity measures can make intuitively incorrect judgements, labeling theories in which small energy scales are set by dynamical processes as unnatural.
13 Given $n$ mutually exclusive and exhaustive outcomes $A_1, ..., A_n$, and the conditional probability $P(A_i|B)$ of outcome $A_i$ given background evidence $B$, additivity requires $\sum_{i=1}^n P(A_i|B) = 1$. Norton interprets this as meaning that $B$ can favor one outcome or set of outcomes only if it disfavors others.
disfavoring evidence. For Norton, then, to justify the use of a probability distribution to represent a fine-tuning measure first requires providing an account how the current evidence is not neutral with respect to a particular fine-tuned value. Thus both Hossenfelder and Norton claim that fine-tuning measures require justification. For Hossenfelder, this involves justifying a particular probability distribution over others; for Norton, this involves justifying the use of a probability distribution in the first place.

3.3 The "Central Dogma"
Williams (2015, 87) suggests a third reason to be natural: "...the reason that failures of naturalness are problematic is that they violate a 'central dogma' of the effective field theory approach: that phenomena at widely separated scales should decouple." This section will argue that decoupling, understood in the EFT context, does not entail naturalness; hence, a failure of naturalness does not entail a failure of decoupling. Moreover, while it seems reasonable to view decoupling as a central dogma of EFTs, it is less clear that naturalness should be viewed in a similar way. I will attempt to establish these claims by considering two distinct types of EFTs. The first type are Wilsonian EFTs which were described in Section 2. The second type is what Georgi (1993) calls "continuum" EFTs. My claim is that, while decoupling is common to both types, naturalness is more in the spirit of Wilsonian EFTs and less so for continuum EFTs. Thus while decoupling might be considered part of the internal logic of EFTs, naturalness should not.

The two types of EFTs are based on a distinction between two types of renormalization scheme. A renormalization scheme involves a method of regularizing divergent integrals, and a method of absorbing the corresponding infinities in a systematic way. Wilsonian EFTs employ mass-dependent renormalization schemes that use the cutoff $\Lambda$ to regularize divergent integrals, and then absorb the divergent parts into renormalized parameters. One result of this process is that the latter are mass-dependent, hence the name. Continuum EFTs employ mass-independent renormalization schemes that use dimensional regularization to tame divergent integrals. One result of this choice is that renormalized parameters on this approach are mass-independent.

Ultimately, the choice of renormalization scheme has no empirical significance: the values of physical parameters come out to be the same regardless of scheme. Thus Wilsonian and continuum EFTs are empirically indistinguishable. However, the choice of renormalization scheme does affect the way high-energy degrees of freedom are encoded in low-energy phenomena; hence, Wilsonian and continuum EFTs are conceptually distinct in how they treat high-energy effects. For instance, a mass-dependent renormalization scheme is a necessary ingredient in the proof of Appelquist and Carazzone's (1975) Decoupling Theorem:

**Decoupling Theorem**: In a perturbatively renormalizable theory with two widely separated mass scales, there is always a mass-dependent renormalization scheme by means of which the effects of the heavy masses can be encoded in the parameters of an effective theory in which only the light masses appear.

On the other hand, the Decoupling Theorem fails under a mass-independent renormalization scheme. The notion of decoupling in this theorem involves not just the removal of high-energy effects...
degrees of freedom, but in addition, the encoding of their effects in low-energy dynamics. Decoupling thus entails that low-energy phenomena are sensitive to high-energy phenomena, to the extent that the latter are encoded in the former. Naturalness, on the other hand, is a constraint on this sensitivity: it requires that the dependence of the effective couplings that encode high-energy effects cannot be too large. Thus a failure of naturalness does not signify a failure of decoupling. Indeed, the examples in Section 3.1 of EFTs that fail to be natural all exhibit decoupling in the sense that they are given by effective actions that are functionals only of the light fields and are such that the effective couplings of the light fields encode the effects of the heavy fields. Their failure to be natural involves a failure of the sensitivity expressed by this encoding to be small enough.

In a Wilsonian EFT, the Decoupling Theorem guarantees decoupling if there is a high-energy theory that is perturbatively renormalizable; and even when this doesn't hold, decoupling is guaranteed in practice via the steps outlined in Section 2 in which an effective action (2) is constructed by including all local operator terms consistent with symmetries. Part of this procedure involves assuming a fixed cutoff $\Lambda$ that informs the order of the effective couplings; in particular, one assumes the couplings $g_i$ both encode high-energy effects and are sufficiently small. This then suggests they are of the order of positive powers of $1/\Lambda$, and this suggests the naturalness criterion, for instance in the form of a requirement that dimensionless couplings be of order 1. Thus both decoupling and naturalness seem part of the internal logic of Wilsonian EFTs. I will now claim that, while decoupling also seems to be a part of the internal logic of a continuum EFT, naturalness is not.

One disadvantage of mass-independent renormalization schemes is that heavy field terms appear in a dimensional-regularized action, an indication of the failure of the Decoupling Theorem. Georgi's (1993, 227–8) notion of a continuum EFT is meant to address this. To construct a continuum EFT, one starts with a dimensionally regularized action $S = S[\phi_L^0] + S_H[\phi_L, \phi_H]$ that is a functional of a set of light and heavy fields at some energy scale $\mu$. However, unlike the Wilsonian approach, the next step does not involve a formal integration over the heavy fields. Rather, in the continuum approach, one evolves the action to lower energies, $\mu \to \mu - d\mu$, via the renormalization group. When the energy scale gets below the mass of a heavy field, the action is replaced with an effective action $S_{\text{eff}} = S[\phi_L] + \delta S[\phi_H]$ that is a functional only of the light field plus a correction $\delta S[\phi_H]$ obtained by a matching condition. The matching condition is supposed to guarantee that high-energy observables match low-energy observables across the threshold characterized by the heavy mass. This matching condition takes the place of the path integral in the Wilsonian approach, and is meant to achieve the same goal; namely, to encode the effects of the heavy field in the light field interactions. In both approaches, this encoding is performed on the effective couplings, but the exact form of the encoding, which depends on the type of renormalization scheme one adopts, differs. The end result, however, is the same measured values for the couplings.

Thus decoupling occurs in both Wilsonian and continuum EFTs. In fact, the matching condition in the latter is called "decoupling by hand" (Georgi 1993, 225). Thus it seems reasonable to view

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15 Assumedly, the term "continuum EFT" refers to the absence of a physical cutoff in a mass-independent scheme.

16 These observables can take the form of scattering amplitudes, for instance.
decoupling as a "central dogma" of EFTs: an EFT is a way of removing high-energy variables by encoding their effects in low-energy interactions. On the other hand, while naturalness seems to be part of the internal logic of Wilsonian EFTs, this is not the case for continuum EFTs. In the latter, the renormalization scale \( \mu \) plays the demarcation role that the cutoff \( \Lambda \) plays in Wilsonian EFTs. But whereas in Wilsonian EFTs the presence of a fixed \( \Lambda \) suggests that the effective couplings be of a certain order, thus constraining their sensitivity to high-energy effects, in a continuum EFT the presence of a variable \( \mu \) is not suggestive of how insensitive the effective couplings produced by a matching condition should be. Rather than encoding aspects of the high-energy physics in the order of the effective couplings, a matching condition is better understood as guaranteeing empirical adequacy across a mass threshold.

To sum up so far, whereas decoupling seems built into the conceptual framework of both Wilsonian and continuum EFTs, naturalness is built into the conceptual framework of Wilsonian EFTs alone. Thus, while Wilsonian EFTs might be considered naturally biased, continuum EFTs perhaps are better thought of as naturally agnostic. Indeed, Georgi (1993, 219) suggests that fine-tuning bare parameters is perfectly reasonable if it is understood as a matching condition that guarantees empirical adequacy over a given mass threshold; and so long as we understand that an EFT does not commit us to anything that goes on at energies much larger than this threshold.

4. Naturalness and Emergence
I'd now like to consider a fourth reason to be natural; namely, that it underwrites a non-trivial notion of emergence. I take emergence to be a characteristic of the ontology associated with a physical system, call it the emergent system, with respect to another physical system, call the latter the fundamental system. Crowther (2015, 429) has suggested two necessary criteria for emergence, so conceived, to be applicable. The first, "Dependence", is the requirement that the emergent system be ontologically determined, in some sense, by the fundamental system. The second criterion is "Independence", which requires that the emergent system be novel with respect to the fundamental system. The task in articulating a non-trivial notion of emergence is to resolve the tension between Dependence and Independence: an emergent system must be both dependent on, and sufficiently independent of, a fundamental system. My suggestion is that phenomena described by a natural EFT accomplish this task.\(^{17}\)

Bain (2016, 28) suggests that Dependence and Independence be cashed out in terms of microphysicalism and novelty, respectively. Microphysicalism requires that an emergent system be composed of microphysical systems that comprise the fundamental system and that obey the fundamental system's laws. This captures the intuition that an emergent system cannot completely float free of a fundamental system. Novelty requires that the emergent system exhibit robust dynamical independence with respect to the fundamental system. Thus, while the micro-constituents of an emergent system obey the fundamental system’s laws, the emergent system itself does not; rather, it exhibits novel dynamical behavior. Moreover, this behavior should be robust in the sense that it should be insensitive to slight changes in the dynamics of the fundamental system. The failure of such robustness would indicate that the dynamical

\(^{17}\) Authors who have suggested emergence be associated with EFTs include Crowther (2015) and Bain (2013, 2016).
independence exhibited by the emergent system is only apparent, or accidental, as opposed to an essential feature.

Bain (2016, 29) claims that the phenomena described by an EFT can be interpreted as emergent to the extent that they exhibit both microphysicalism and robust dynamical independence with respect to the corresponding high-energy theory. Microphysicalism applies insofar as the field variables that enter into an effective action are simply the low-energy degrees of freedom of the high-energy phenomena. In more provocative terms, the low-energy phenomena are ontologically determined by the high-energy phenomena insofar as the former are derivative of the latter. With respect to robust dynamical independence, Bain observes that the effective action is formally distinct from the high-energy action, and this entails that the corresponding equations of motion are formally distinct, too. Hence, if dynamical laws are encoded in equations of motion, the low-energy phenomena obey different dynamical laws than the high-energy phenomena, and this suggests dynamical independence. But is robustness necessarily an aspect of this independence in the context of EFTs? Examples of EFTs that fail to be natural suggest otherwise. In these examples, while the low-energy effective dynamics is formally distinct from the high-energy dynamics, robustness fails in the sense that there are effective low-energy parameters (the Higgs mass, the cosmological constant, etc.) that depend sensitively on the high-energy dynamics: in Wilsonian EFTs, for instance, a slight change in the cutoff Λ will produce large changes in low-energy physical scalar masses.

Of course there is an easy remedy to this difficulty in Bain's analysis. We can simply modify the claim that EFTs in general describe emergent phenomena to the claim that natural EFTs describe emergent phenomena. The distinction between decoupling and naturalness described in Section 3.2 suggests a way of making this more precise. Decoupling in an EFT underwrites dynamical independence tempered by dependence. It involves dynamical independence to the extent that an effective action is formally distinct from a corresponding high-energy action; hence, if dynamical laws are encoded in equations of motion, the low-energy phenomena described by an effective action obey different dynamical laws than the high-energy phenomena described by a corresponding high-energy action. But decoupling also involves a degree of dynamical dependence, insofar as the effects of high-energy phenomena are encoded in the interactions of the low-energy phenomena. Moreover, decoupling by itself does not guarantee robust dynamical independence. Only naturalness guarantees this. Again, in a natural EFT, the dependence of low-energy interactions on high-energy degrees of freedom is sufficiently small so that slight changes in the latter do not induce large changes in the former.

5. Conclusion

18 There are examples of EFTs for which this claim is problematic. For instance, in a "top-down" EFT in which there is a clear distinction in the high-energy theory between light fields and heavy fields, and the high-energy degrees of freedom (consisting of the heavy fields and the high-energy dynamics of the light fields) are represented in the effective Lagrangian as corrections to the low-energy dynamics of the light fields, the sense in which the low-energy dynamics is independent of the high-energy dynamics is fairly weak. Dynamical independence seems better motivated by examples of "top-down" EFTs for which there is no initial clear distinction between "heavy" and "light" degrees of freedom, and examples of "bottom-up" EFTs for which the high-energy degrees of freedom remain unknown.

19 Williams (2015, 95) mounts a similar criticism of Bain (2013a).
Why be natural? I've argued that we should not be natural because it is empirically warranted, or because it is quantifiable, or even because it underwrites a central dogma of EFTs. Rather, we might be natural because it helps to underwrite a non-trivial notion of emergence associated with EFTs. More generally, as an empirical hypothesis with limited empirical support, one should be cautious in using naturalness as a guiding principle; and one should be cognizant of where it occurs as an assumption in theoretical frameworks (Wilsonian EFTs, for instance). But as an ontological principle, there is nothing wrong with the project of examining what the world would be like if it were true, or how current theories might be extended if it were true.

References

Bain, J. (2013a) "Effective Field Theories", in B. Batterman (ed.) The Oxford Handbook of Philosophy of Physics, Oxford University Press, 224.

Bain, J. (2013b) "Emergence in Effective Field Theories", European Journal for Philosophy of Science 3, 257.


