Open systems across scales

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Abstract

The view that our best current physics deals with effective systems has gained philosophical traction in the last two decades. A similar view about open systems has also been picking up steam in recent years. Yet little has been said about how the concepts of effective and open systems relate to each other despite their apparent kinship—both indeed seem at first sight to presuppose that the system in question is somehow incomplete. In this paper, I distinguish between two concepts of effectiveness and openness in quantum field theory, which provides a remarkably well-developed theoretical framework to make a first stab at the matter, and argue that on both counts, every realistic effective system in this context is also open. I conclude by highlighting how the discussion opens novel avenues for thinking of systems as open across scales.

1 Introduction

Many of us have been used to thinking of physical systems as fundamental and closed during our physics training, be it through simple equations that apply in principle everywhere or elementary models that depict freely floating entities. This habit, however, quickly loses its sway once we confront it with the way real systems are treated in current physics practice. Physicists have indeed found remarkable theoretical and empirical benefits in conceiving of and theorizing physical systems as effective and open during the last decades, be it through the use of master equations, coarse-graining methods, or effective theories. They have, in fact, developed a large variety of new techniques to this effect, with successful applications in areas ranging from post-Newtonian and atomic physics to inflationary cosmology and high-energy physics (e.g., Davidson et al., 2020; Burgess, 2021; Calzetta and

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Hu, 2023). And these techniques have, in turn, reinforced the belief that the seemingly fundamental and closed character of a system is often the result of a drastic series of idealizations and approximations, whether we speak of negligible dissipative effects for the unitary time-evolution of a quantum system or irrelevant high-energy effects for a renormalizable dynamics. As Daniel Lidar summarizes it to his quantum mechanic apprentices in the case of open systems:

> [...] the idealization of an isolated quantum system obeying perfectly unitary quantum dynamics is just that: an idealization. In reality every system is open, meaning that it is coupled to an external environment. (Lidar, 2020, p. 5)

Philosophers have also found many benefits in treating physical systems as effective and open. In particular, the concepts and methods of effective field theories (EFTs) have been used in the last decade to flesh out epistemically more reliable pathways to extract the content of our best current physics (e.g., J. D. Fraser, 2018; Williams, 2019; Rivat, 2021b; Miller, 2023; Koberinski and D. Fraser, 2023; Dougherty, forthcoming). The foundational and conceptual value of open systems approaches in physics has also been more systematically investigated in recent years (e.g., Cuffaro and Hartmann, 2023b; 2024; Gryb and Sloan, 2024; Ladyman and Thébault, forthcoming). Yet little has been said about how these various ways of theorizing fit together. Perhaps even more crucially for philosophers, little has been said about how the concepts of effective and open systems *even* relate to each other. This is unfortunate. In their most common acceptation, both concepts indeed point to a form of incompleteness: (i) an effective system is a coarse-grained part of a more fundamental system; (ii) an open system is a system that interacts with some external system. But their exact relationship remains rather obscure. To make the matter even worse, the concepts of effective and open systems are themselves rather ambiguous. We might for instance wonder about how to understand them when the system description does not make any explicit reference to any other item than the system studied.

This paper aims to make a first stab at these general issues by examining them from the perspective of quantum field theory (QFT), which provides a remarkably well-developed theoretical framework to clarify both concepts and their relationship. More precisely, I will extract two concepts of effectiveness and openness from this framework and argue that on both counts, every realistic effective quantum field system is also open. Sections 2-3 outline the distinction for each kind of system, tracing it back in each case to two different ways of constructing a dynamics. Section 4 provides preliminary reasons to believe that realistic effective quantum field systems are open by sketching, in particular, how the standard EFT framework generalizes to an open EFT framework (e.g., Lombardo and Mazzitelli, 1996; Calzetta and Hu, 2023). Yet, despite the existence of a well-established abstract framework and a variety of successful models, this generalized framework has not yet been concretely implemented for the entire content of our best current theories in contrast to the standard EFT framework (e.g., Brivio and Trott, 2019; Donoghue, 2023). This motivates the search for more principled reasons to believe that every realistic effective quantum field system is also open. Section 5 provides two versions of a general argument to support this claim, one for each concept of effectiveness. As we will see, substantial assumptions regarding the existence of interactions between realistic systems and our ability to formulate successful theories about them are required for the argument to go through. And although I will frame both versions in general terms to simplify the discussion and lay the ground for future work, I will only provide reasons to believe that they hold within the context of QFT, in line with the idea of taking it as a case study to probe the relationship between effective and open systems. Section 6 concludes with general remarks on the concept of open system across scales.

Three additional clarifications before I begin. (i) I use 'realistic system' to refer to any kind of system that can give rise to observational effects and is amenable to empirically successful scientific theorizing. The motivation is to exclude highly idealized toy models and include the set of empirically successful QFTs that we may find, say, beyond the standard model (SM) of particle physics. (ii) I will only provide justification for the claim that every realistic effective quantum field system is open. But it is worth noting that the converse may not hold. Although unlikely, the universe could well be made of fundamental fields governed by a dissipative yet non-effective dynamics. Or, to put it in more technical terms, we may well come up with an empirically successful open QFT of gravity and matter with fixed points at low and high energies. (iii) I will have little to say here about how the open EFT framework affects existing philosophical discussions related to standard EFTs (e.g., Bain, 2013; Rivat and Grinbaum, 2020; Williams, 2023). As open and standard EFTs have a similar dynamical structure overall, I suspect that the same lessons about scientific realism and reduction go through in both cases. But I will not have the space to explore this here.

2 Effective systems

I will start with the concept of effective system. As new theoretical developments, philosophical discussions, and historical outlooks make it increasingly clear, there is much diversity about how to construct and understand effective theories and models (e.g., Rivat, 2021a; Bechtle et al., 2022; Koberinski and D. Fraser, 2023). Yet it is common amid this diversity to distinguish between two main approaches in QFT.

On the top-down approach, the effective theory of interest is derived, perhaps only partially, from a more fundamental theory, and the effective system is thus specified in a "reductive" manner by reference to a more fundamental system (e.g., Petrov and Blechman, 2016, chap. 4; Burgess, 2021, chap. 2). The simplest Wilsonian version involves three steps, using the path integral for a single massive scalar field $\phi(x)$ with a quartic self-interaction term as my main toy example in what follows (see, e.g., Polchinski, 1999, lecture 1, for a classic reference):

(1) Split the variables of the system into a low-energy and a high-energy set, say, $\phi(x) = \phi_L(x) + \phi_H(x)$, where $\phi_L(x)$ and $\phi_H(x)$ correspond to the slowly and rapidly varying configurations of $\phi(x)$ across space-time relative to some arbitrary separation scale Λ;

(2) Coarse-grain the system, i.e., eliminate the high-energy part and take into account its average effect on the low-energy part (by computing the path integral over ϕ_H);

(3) Approximate the average low-energy effect of the high-energy part (which typically takes the form of non-local contributions) by means of a local covariant expansion in the field variable ϕ_L, its derivatives, and the separation scale Λ.

In its most complete form, the resulting effective theory typically involves arbitrarily complicated local interaction terms organized according to the importance of their relative contributions to predictions across energy scales:

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial\phi_L)^2 - \frac{1}{2}m^2\phi_L^2 - g_0\phi_L^4 - \frac{g_2}{\Lambda^2}\phi_L^6 - \frac{g_4}{\Lambda^4}\phi_L^8 - ..., \tag{1}$$

where the effective theory is expressed here in terms of its Lagrangian density $\mathcal{L}_{\text{eff}}$, with m the mass of the field and g_i coupling parameters ($i \geq 0$). Higher-order interaction terms ($i \geq 2$) typically give rise to inconsistent probabilistic predictions for sufficiently high energies beyond Λ.[1]

Despite its conceptual simplicity, coarse-graining a system by "integrating out" high-energy variables in the path integral remains a very taxing if not impracticable business in most cases. Instead, physicists tend to ignore the high-energy variables ϕ_H of a given theory $\mathcal{L}[\phi_L, \phi_H]$, i.e., $\mathcal{L}_L[\phi_L] := \mathcal{L}[\phi_L, 0]$, or even directly start with a different low-energy theory,

[1]Note that the notion of (perturbative) unitarity violation in the S-matrix setting is distinct from the notion of non-unitary dynamical evolution. In particular, standard non-unitary dynamical maps are trace-preserving, i.e., they preserve the sum of probabilities associated with the states of the target system.

and constrain it by imposing "matching conditions" between the (renormalized) correlation functions obtained from the effective and the full theory (relative to some reference scale Λ and up to some order of approximation).

Let me mention one philosophically important yet underappreciated technical point here (e.g., Bain, 2013, pp. 9-10). In principle, matching the full sets of low-energy off-shell correlation functions obtained from low-energy and high-energy generating functionals $\mathcal{Z}_{\text{eff}}[J_L]$ and $\mathcal{Z}[J_L, J_H]$ is equivalent to imposing $\mathcal{Z}_{\text{eff}}[J_L] = \mathcal{Z}[J_L, 0]$ and thus assuming that $\mathcal{Z}_{\text{eff}}[J_L]$ is obtained by integrating out high-energy variables in $\mathcal{Z}[J_L, 0]$, with J_L and J_H some low-energy and high-energy external currents. In practice, there is also little difference between the "matching" and "integrating out" procedures, even if the full theory bears no similarity to the low-energy one. For one thing: renormalizing a low-energy theory with a finite cut-off typically requires introducing all the terms compatible with its principles and thus all the terms typically obtained by integrating out high-energy variables. For another: imposing matching conditions fixes the parameters of the low-energy theory up to some order of approximation in the same way as integrating out high-energy variables does. I will assume in the sequel that this overall equivalence is sufficient for us to speak at least of a "partial" derivation in the matching case.

Then, this top-down approach naturally leads us to a "reductive" concept of effective system.

Effective system (reductive sense): System E_R characterized by a restricted set of degrees of freedom associated with a limited range of scales.

To be clear again, I am expressing this concept and subsequent ones in general terms to simplify the discussion and lay the ground for a more general analysis. But I take the conceptual distinctions and the claims I make out of them to be justified only within QFT in what follows.

Keeping this in mind, several clarifications are in order. (i) The restricted set of degrees of freedom characterizing E_R may form either a proper or a coarse-grained subset of a given set of physical degrees of freedom. In both cases, what matters is that some physical degrees of freedom are missing: e.g., the degrees of freedom represented by the "fine-grained" difference variable $(\phi_1(x) - \phi_2(x))/2$ if we keep only the "coarse-grained" average variable $(\phi_1(x) + \phi_2(x))/2$, for some scalar fields $\phi_1(x)$ and $\phi_2(x)$. (ii) The effective theory representing E_R has a limited range of applicability across scales. There is, again, much to be said here (see Rivat, 2021b, for more detail). I will endorse the rather weak interpretation that its predictions become inconsistent beyond this range. (iii) The effective theory is derived, perhaps only partially, from a more fundamental theory, both in terms of scope and variables. Although the underlying notion of reduction at work here is compatible with various philosophical models, I will understand it exclusively in terms of the standard mathematical operations used for effective theories (e.g., integrating out variables in the path integral formalism). (iv) This reductive concept does *not* presuppose that E_R interacts with a more fundamental system. We may indeed match an effective and a high-energy theory without using (or knowing whether there is) any interaction term between low-energy and high-energy variables. This will be the most crucial difference with the reductive concept of open system introduced in section 3.

Despite its generality, this reductive concept of effective system still fails to capture a large class of effective systems, which cannot, either in practice or in principle, be specified via the (partial) derivation of an effective theory from a more fundamental and empirically successful theory (e.g., the various effective versions of the SM). In such situations, physicists rather tend to follow a bottom-up approach, in which the effective theory of interest is derived from first principles and the effective system is thus specified in an "autonomous" manner without reference to a more fundamental system (e.g., Donoghue et al., 1994, chap. 4; Petrov and Blechman, 2016, chap. 8). The most popular Weinbergian version involves two steps (see Weinberg, 1979, for a classic reference):

(1) Start with a reference theory defined by means of a set of variables, principles, and constraints (e.g., a local, real, Lorentz invariant, and Z_2-invariant Lagrangian functional density $\mathcal{L}$ for a massive scalar field $\phi(x)$ with a standard kinetic term, a quartic self-interaction term, and trivial boundary conditions);

(2) Formulate the most complete version of the reference theory that is compatible with its variables, principles, and constraints (e.g., include arbitrary even local covariant polynomial interaction terms in the field variable $\phi(x)$ and its derivatives with arbitrary real-valued coefficients in $\mathcal{L}$).

Once again, the resulting effective theory $\mathcal{L}_{\text{eff}}$ typically takes the form of a local covariant expansion in some scale Λ (introduced to ensure that the coefficients are dimensionless) and its predictions typically become inconsistent for sufficiently high energies beyond Λ. In fact, if all the terms are included and their dimensionless couplings are of order $O(1)$, these predictions do break down around Λ.[2]

This bottom-up approach, in turn, naturally leads us to an "autonomous" concept of effective system.

[2]Note that the reference theory should not be overly constrained: e.g., renormalizability in the power-counting sense is not assumed here (see, e.g., Rivat, 2019, sec. 4, for more detail).

Effective system (autonomous sense): System E_A governed by an effective law of nature, i.e., a law that is irreducibly expressed as a local covariant expansion in some scale Λ.

I use 'law of nature' to keep again the discussion at a general level. But we may speak more specifically of a Lagrangian (or Hamiltonian) density in the standard EFT framework.[3]

I should emphasize that the reductive and autonomous concepts of effective system are independent of each other, strictly speaking. Agreed: in practice, they appear to coincide in the case of empirically successful QFTs. We typically obtain a local covariant expansion in some scale Λ when we restrict the variables of a QFT to a limited range $[0, \Lambda]$, whether we integrate out high-energy variables or renormalize the theory with a finite cut-off Λ. We also typically find that QFTs that take the form of a local covariant expansion in some scale Λ and whose predictions break down at high energies fail to account for high-energy degrees of freedom beyond Λ. But the two concepts are still extensively and intensionally distinct. On the one hand, many effective systems in the reductive (resp. autonomous) sense are indeed not effective in the autonomous (resp. reductive) sense. For instance, integrating out high-energy degrees of freedom in a non-interacting QFT does not give rise to arbitrarily complicated local interaction terms. On the other hand, these two concepts provide two different (and valuable) ways of identifying an effective system: roughly, (i) as a coarse-grained part of a more fundamental system; (ii) as a system governed by a generalized scale-dependent dynamics, independently of its relation to any other system. I will thus keep them separate in what follows.

3 Open systems

A strikingly similar divide arises for open systems. There is, to be sure, much diversity about how to construct and understand theories and models of open systems too (e.g., Breuer and Petruccione, 2002; Calzetta and Hu, 2023). But it is again common to distinguish between two main approaches in the quantum setting, which I will call the "standard" and "general" approaches following Cuffaro and Hartmann (2023a; 2024). For simplicity, I will restrict myself to separable Hilbert spaces here and lift this restriction in the next section.[4]

[3]If needed, we may also relax the constraint of locality and allow for non-local covariant expansions in some scale.

[4]If we put mathematical and foundational subtleties aside, the standard approach below directly extends to the non-separable case. I will thus appeal to it in section 5 when moving from 'open' in the reduction sense to 'open' in the autonomous sense. The extension of the general approach to the non-separable case is more contentious, and I will

Both approaches start with the assumption that density operators $\rho = \sum_i p_i |\phi_i\rangle\langle\phi_i|$ provide a more general characterization of quantum states than state vectors $|\phi\rangle$, where p_i is usually interpreted as the probability of finding the system in the state $|\phi_i\rangle\langle\phi_i|$. Density operators indeed encode any kind of information about arbitrary mixed states (in the sense of Gleason's theorem and its generalizations) and return exactly all the information encoded in state vectors in the limiting case of pure states $\rho = |\phi\rangle\langle\phi|$. Density operators also provide a basis-independent and thus somewhat less arbitrary characterization of quantum states than state vectors.

Now, on the standard approach, the temporal evolution of an open system is derived from that of a more comprehensive closed system composed of the open system and its environment, and the open system is thus specified in a "reductive" manner by reference to some external system, in close analogy with the top-down approach to effective theories. There are usually three steps involved in this case (e.g., Lidar, 2020, sec. III-VI, IX):

(1) Split the Hilbert space $\mathcal{H}$ of the closed system into a subsystem space $\mathcal{H}_S$ and an environment space $\mathcal{H}_{\text{env}}$, i.e., $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_{\text{env}}$;

(2) Coarse-grain the closed system, i.e., eliminate the environment and take into account its average effect on the temporal evolution of the subsystem S (by taking the partial trace of the density operator $\rho(t)$ of the closed system over $\mathcal{H}_{\text{env}}$ and thereby defining a reduced density operator for S, i.e., $\rho_S(t) = \text{Tr}_{\text{env}}[\rho(t)]$);

(3) Specify further the temporal evolution of S by imposing additional constraints.

The closed system is usually assumed to evolve unitarily over time, i.e., $\rho(t) = U(t)\rho(0)U^{-1}(t)$. To keep track of the entanglement pattern generated by the dynamics alone, S and its environment are also usually assumed to be uncorrelated at some initial time, i.e., $\rho(0) = \rho_S(0) \otimes \rho_{\text{env}}(0)$. Then, if S interacts with its environment and $\mathcal{H}_{\text{env}}$ is non-trivial, i.e., at least two-dimensional, the temporal evolution of S is guaranteed to be non-unitary:

$$\rho_S(t) = \sum_\alpha K_\alpha(t)\rho_S(0)K_\alpha^\dagger(t), \tag{2}$$

where the so-called "Kraus operators" $K_\alpha(t)$ satisfy the general constraint $\sum_\alpha K_\alpha(t)K_\alpha^\dagger(t) = 1$, which ensures that probabilities are conserved. Finally, it is common to assume that S is Markovian, i.e., that its state at a given

thus use it here only to motivate the autonomous concept of open system. See Earman (2020) for a philosophical discussion of the "tug-of-war" between the separable and the non-separable in quantum physics.

time depends only on its state at the previous time. In this case, it can be shown that S must be governed by a master equation called the "Lindblad equation," which irreducibly includes dissipative terms (e.g., Lidar, 2020, sec. IX). In general, S indeed exchanges at least information with its surroundings, in the sense that its von Neumann entropy $S_{VN} = -\operatorname{Tr}(\rho_S \ln \rho_S)$ varies over time.

This standard approach naturally leads us again to a "reductive" concept of open system.

Open system (reductive sense): System O_R characterized by a set of degrees of freedom coupled to those of some external system.

We encountered this popular concept in Lidar's quote in the introduction. An open system defined in this way has again a restricted set of degrees of freedom. But in contrast to the reductive concept of effective system, what makes a system open is not its scale-relative character but rather its interaction with some non-trivial external system and thus its ability to exchange information, energy, matter, or some other characteristic quantity with it. We may thus say that a system is open in the reductive sense if and only if it is not isolated (from any other system).[5]

The notion of characteristic quantity can be further clarified as follows: S has a characteristic quantity Q if and only if Q is invariant when S does not interact with any other system.[6] The von Neumann entropy of S passes the test since it remains invariant when S does not interact with its environment (and thus evolves unitarily under the assumption that the full closed system does). But the amplitude of a field is typically not a characteristic quantity for instance. As we will see below, the notion of characteristic quantity is harder to pin down in the absence of external systems.

Now, physicists also follow a general approach, in which theories and models are derived from first principles and open systems are thus specified in an "autonomous" manner without reference to any external system, in close analogy with the bottom-up approach to effective theories. The construction involves again two steps in this case (e.g., Breuer and Petruccione, 2002, sec. 3.2; Alicki and Lendi, 2007, chap. 1):

(1) Specify the state of a given system S with a density operator $\rho_S(t)$ defined on some Hilbert space $\mathcal{H}_S$;

(2) Impose general principles on the dynamical map $\mathcal{M}$ specifying the temporal evolution of S.

[5]The notion of reduction at work here is again to be understood exclusively in terms of the partial trace procedure used to derive the temporal evolution of an open quantum system. I will provide more detail about the notion of interaction in section 5.1.

[6]A quantity that remains invariant independently of whether the system is isolated also counts as a characteristic quantity.

It is common to impose three principles besides requiring $\mathcal{M}$ to preserve linearity, positivity, hermiticity, and trace: (a) continuous evolution, i.e., the dynamical map is a continuous function of some parameter t; (b) Markovian evolution; (c) complete positivity, i.e., the dynamical map and any of its extensions on a larger Hilbert space map positive operators to positive operators (see, e.g., Cuffaro and Hartmann, 2024, for a philosophical discussion; Alicki and Fannes, 2001, sec. 8.4, for more technical detail). Then, if the system S is specified by a separable Hilbert space and a bounded time-evolution generator, it is possible to show that S is governed by a Lindblad equation and is thus irreducibly dissipative (see esp. Lindblad, 1976; Gorini et al., 1978). Many realistic infinite-dimensional systems beyond this can also be shown to display the same kind of non-unitary dissipative dynamical behavior (e.g., Breuer and Petruccione, 2002; Calzetta and Hu, 2023). But to the best of my knowledge, there is not yet any general result for non-separable Hilbert spaces or unbounded time-evolution generators.

This will not be a concern for us here (see Rivat and Hartmann, 2024, for a discussion). What matters is the autonomous concept of open system that naturally follows again from this general first-principles approach.

Open system (autonomous sense): System O_A governed by a dissipative law of nature, i.e., a law whose expression irreducibly implies that some characteristic quantity of the system is not conserved.

Again, I use 'law of nature' to keep the discussion at a general level. But we may speak more specifically of the dynamical map governing the temporal evolution of an open quantum system, or even of the Lagrangian density defining the dynamics of an open quantum field system in the double path integral formulation (cf. section 4).

As advertised above, the notion of characteristic quantity is hard to pin down in the absence of any external system. We could perhaps identify for each model a minimal dynamical core, say, the usual kinetic term in the Lagrangian density of a QFT, and select invariant properties accordingly (e.g., energy-momentum). But this does not appear to be a good solution. Take for instance the conserved particle number in the non-interacting version of a QFT (in Minkowski space-time). This number fails to be conserved once we introduce self-interaction terms. Yet this does not seem to be sufficient to interpret the system as dissipative.

We could perhaps appeal instead to the set of conserved quantities associated with the symmetries typically displayed by the class of systems under consideration. But again, this just seems to postpone the issue. We might indeed wonder about the relevant set of symmetries, whether global symmetries associated with distinct particle numbers like lepton and baryon numbers count, and, if so, whether it is appropriate to speak of dissipative systems if these numbers fail to be conserved.

All things considered, we may as well choose a set of characteristic quantities commonly associated with systems in each theoretical context (see Ladyman and Thébault, forthcoming, for a similar outlook). For instance, we may safely take onboard energy-momentum and entropy in QFT. But we should certainly not include field amplitude and total particle number, and probably not specific particle numbers like lepton and baryon numbers. Fortunately, the rest of the discussion does not require making any precise cut and I will assume for simplicity that information variation (in the von Neumann entropy sense) is a sufficient and necessary condition for a quantum field system to count as dissipative.

Let me close this section with three comments. First, the reductive and autonomous concepts of open system are again independent of each other, strictly speaking. In principle, we can always couple any given quantum system to a trivial quantum system with a one-dimensional Hilbert space. Interaction terms are trivial in this case and the open system is guaranteed to evolve unitarily if the combined system does. Inversely, it is conceivable that a system does not interact with any other system and still displays dissipative effects (see, e.g., Cuffaro and Hartmann, 2023a; 2024, for a discussion). Since trivial quantum field systems are of little physical interest, I will go rather quickly from 'open' in the reductive sense to 'open' in the autonomous sense in section 5.

Second, following Ladyman and Thébault's distinction (forthcoming, pp. 3-4), I use 'autonomous' in the "formal mode" to characterize a system description that does not make any explicit reference to some external system. I also use the term in the "material mode" to highlight a particular property of the system—for instance, that it is governed by a dissipative law of nature—without presupposing that it instantiates some other seemingly related property—for instance, that it interacts with some external system. But I am not associating 'autonomous' with any more specific mathematical feature of the system description or any deeper metaphysical assumption about the structure of the world across scales (see, e.g., Ladyman and Thébault, forthcoming; Wallace, forthcoming; Weinberger et al., forthcoming, for a discussion).

Now, I agree that many realistic effective (resp. open) systems are largely independent of their counterpart across scales (resp. environment). I also agree that this metaphysical fact underwrites the success of many different kinds of approximation methods employed in the course of theorizing about effective (resp. open) systems. But I do not think that this fact is constitutive of our ability to treat systems as effective (resp. open). For one thing: there are notable examples of empirically successful theories for which the effective (resp. open) system of interest depends significantly on its counterpart across scales (resp. environment). The naturalness problem provides a plausible case in the context of QFT (e.g., Williams, 2015). For another:

the frameworks outlined above (and below) are perfectly applicable to systems with highly-dependent component parts. Take for instance the case of effective systems. We can always integrate out the high-energy part of any system decomposable across energy scales in the path integral formalism. We may not be able to perform a local expansion for the non-local contributions that typically arise out of the procedure. But we can usually use some other approximation method or simply replace these non-local contributions by "brute force" with more tractable expressions. Either way, the important point is that it does not require much of a system to formulate a self-standing effective theory of its low-energy part. We only need to be able to decompose the system across scales.

Third, the concepts of effective and open systems may arguably be interpreted as admitting degrees.[7] For instance, E_R may be thought of as more or less fundamental depending on the extent to which it is restricted across scales and excludes physical degrees of freedom.[8] The dynamics of E_A may be thought of as more or less close to the dynamics of a putatively fundamental system depending on the value of its higher-order dynamical terms.[9] O_R may be thought of as more or less interacting with its environment depending on the value of their interaction parameters. And O_A may be thought of as more or less dissipative depending on the extent to which its characteristic quantities are not conserved.

Clarifying these gradual notions of effectiveness and openness and examining how they are related to each other certainly constitutes an important project. But I will not undertake it here for two main reasons. (i) The relationship between these gradual notions is rather complicated and would require a much more extensive discussion that I can provide here. For instance, a system approximately closed in the reductive sense may be far from being approximately closed in the autonomous sense depending on the circumstances. To take a simple example, the *range* of variation of the von Neumann entropy of a qubit interacting with another one does not depend on the value of their interaction parameters (see, e.g., Lidar, 2020, pp. 40-2, for the expression of the reduced density operator). (ii) The relationship between the absolute notions of effectiveness and openness is already far from trivial even for realistic systems. On the one hand, and as already emphasized, the whole universe may well be open in the autonomous sense and yet non-effective in any sense of the term. On the other hand, for all we know, the most fundamental law of nature known at a given time may

[7] I am thankful to a reviewer for pressing me on this point.

[8] Note that this may, but need not, be tied to the existence of a relation of determination or dependence between increasingly fundamental systems (see, e.g., McKenzie, forthcoming, for a related discussion).

[9] Typically, in the context of QFT, most of these higher-order terms need to vanish for the dynamics to display a UV fixed point and thus count as putatively fundamental.

well involve every physical degree of freedom and still be best expressed in terms of a covariant expansion in some scale with no dissipative term (cf. option (2b) in section 5.3). This suggests that there is still some substantial argumentative work to be done to make the claim that realistic effective systems are open (besides the conceptual work done so far).

4 Open effective field theories

Let us then turn to the relationship between effective and open quantum field systems. To get a handle on the matter, we first need to realize that standard EFTs, whether top-down or bottom-up, are designed to account for idealized physical situations and thus offer in general an overly constrained setting to specify the dynamics of effective systems. (It goes without saying that standard EFTs still cover with unprecedented success the vast majority of the most fundamental ongoings we can reliably account for at the moment.)

The idealized physical situations I have in mind consist of interaction and decay processes involving incoming and outgoing free low-energy particles prepared and detected in the infinite past and future. This presupposes that: (i) these low-energy particles are in a pure state far away from the region of interaction at $t = \pm\infty$; (ii) the high-energy part of the system (if any) is in a non-interacting vacuum state at $t = \pm\infty$; (iii) the temperature T of the system is null at these stages. We may accordingly specify the initial and final states of the system in terms of product states $|p_1, ..., p_n\rangle_L \otimes |0\rangle_H$ and $|q_1, ..., q_m\rangle_L \otimes |0\rangle_H$, with momenta p_i and q_i ($n, m \geq 1$).

There are, of course, other assumptions involved here (see, e.g., Duncan, 2012, chap. 9, for more detail). But (i)-(iii) are already sufficient to make it palatable that the usual effective dynamics of low-energy systems is overly constrained. Recall first that experimental quantities like cross sections and decay rates are computed from S-matrix elements. S-matrix elements are, in turn, obtained via the LSZ formula from the vacuum expectation value $\langle\Omega|\mathrm{T}\{\phi(x_1)...\phi(x_{n+m})\}|\Omega\rangle$ of the relevant products of field operators $\phi(x_i)$ relative to some initial and final asymptotic product states $|p_1, ..., p_n\rangle_L \otimes |0\rangle_H$ and $|q_1, ..., q_m\rangle_L \otimes |0\rangle_H$, with T the usual time-ordering operator and $|\Omega\rangle$ the vacuum state of the interacting theory. Although these vacuum expectation values involve field correlations at arbitrary space-time points x_i, the interpolating procedure used to relate them to initial and final asymptotic states requires that the system is ultimately in its free vacuum state $|0\rangle$ in the infinite past and future. At the level of the generating functional used to compute these quantities, this requirement is equivalent to imposing trivial asymptotic boundary field configurations. At the level of the path integral, this amounts to defining it in terms of a transition amplitude between pure vacuum states in the infinite past and future. And insofar as the low-energy system is specified by integrating out high-energy field configurations in this kind of path integral, we should expect (i)-(iii) to have a significant impact on the form of its effective dynamics.

Now, in real life, interaction and decay processes take place during a finite amount of time and at finite temperature $T \neq 0$, which means that the low-energy part of the system is typically entangled with its high-energy counterpart. In principle, we can extend the standard path integral formalism to determine the pure state of the *full* system at arbitrary times and temperatures. This was first done in the imaginary-time formalism in the context of thermal field theories for systems near equilibrium and is now widely believed to be best carried out in the real-time formalism for generic situations (e.g., Das, 1997; Kamenev, 2011). But this extended formalism still does not allow us to specify the effective evolution of the low-energy system into some arbitrary mixed state $\rho(t)$ at some time t.

As it turns out, physicists have developed methods to deal with this general type of situation before modern EFTs were even invented (see esp. Schwinger, 1961; Feynman and Vernon, 1963; Keldysh, 1965). These methods are, in fact, both at the basis of the real-time formalism mentioned above and the set of decoherence models more familiar to philosophers. But they have also been used more generally to develop an open EFT framework, which extends the scope of the standard EFT framework (e.g., Lombardo and Mazzitelli, 1996; Liu and Glorioso, 2018; Calzetta and Hu, 2023). I should emphasize that physicists have not attempted to reformulate the entire content of our best current EFTs in terms of open EFTs. It is also fair to say that this general framework is still under construction (see, e.g., Polonyi, 2014; Nagy et al., 2016; Nagy and Polonyi, 2022; Baidya et al., 2017; Baidya et al., 2019, for recent work on the UV and scale-dependent structure of open EFTs). But the core structural features of open EFTs are still sufficiently well-specified to provide at least preliminary reasons to believe that the dynamics of realistic effective quantum field systems should include dissipative terms.

Since this framework is less familiar to philosophers, I will summarize the top-down construction of open EFTs to further clarify the sense in which standard EFTs are overly constrained. The key idea is to treat the high-energy degrees of freedom of the system as an environment for its low-energy degrees of freedom and unwrap the dynamical structure of dissipative effects they generate at low energies:

(1) Start with a closed system evolving unitarily over time, i.e., $\rho(t) = U(t)\rho(0)U^{-1}(t)$, and represent its temporal evolution in terms of two path integrals, one for the unitary U and one for its inverse U^{-1}, after expressing $\rho(t)$ in some coordinate representation and sandwiching in twice a complete set of initial state vectors around $\rho(0)$. Note that

the path integral for U (resp. U^{-1}) is parametrized by a forward-propagating variable ϕ^+ (resp. backward-propagating variable ϕ^-).

(2) Divide the closed system into a low-energy part (the subsystem S) and a high-energy part (the environment) relative to some separation scale Λ as in section 2. It is again common to assume that S and its environment are uncorrelated at $t = 0$, i.e., $\rho(0) = \rho_S(0) \otimes \rho_{\text{env}}(0)$.

(3) Coarse-grain the closed system by tracing over the states of its high-energy part and computing the double path integral over its high-energy field configurations. Schematically, the resulting double path integral governing the effective time-evolution of S takes the following form:

$$\langle \phi_{L,f} | \rho_S(t) | \phi'_{L,f} \rangle = \int d[\phi_{L,i}] d[\phi'_{L,i}] \; \langle \phi_{L,i} | \rho_S(0) | \phi'_{L,i} \rangle \int d[\phi_L^+] d[\phi_L^-] e^{iS_{\text{open, eff}}[\phi_L^+, \phi_L^-]}, \tag{3}$$

with $\langle \phi_{L,f} | \rho_S(t) | \phi'_{L,f} \rangle$ and $\langle \phi_{L,i} | \rho_S(0) | \phi'_{L,i} \rangle$ the coordinate representations of the reduced density operator for S at the final time t and initial time $t = 0$ given some final and initial low-energy vector states $|\phi_{L,f}\rangle$, $|\phi'_{L,f}\rangle$, $|\phi_{L,i}\rangle$, and $|\phi'_{L,i}\rangle$. The double path integral involves both forward- and backward-propagating low-energy fields ϕ_L^+ and ϕ_L^-, and the open effective action $S_{\text{open, eff}}$ involves in general a complicated set of new interaction terms.

(4) Approximate the average low-energy effect of the high-energy part by means of a (local) covariant expansion in the separation scale Λ. As for standard EFTs, integrating out forward- and backward-propagating high-energy variables ϕ_H^+ and ϕ_H^- in the double path integral typically generates non-local interaction terms in $S_{\text{open, eff}}$. These terms may be expanded into an infinite series of Λ-dependent local terms under appropriate restrictions and approximations in sufficiently simple models (e.g., Collins et al., 2013; Boyanovsky, 2015; Calzetta and Hu, 2023, chap. 5). But in contrast to standard EFTs, the covariant expansion typically includes cross-interaction terms between ϕ_L^+ and ϕ_L^- that generate dissipative effects at low energies.[10]

How are open and standard EFTs related to each other? The answer is surprisingly straightforward at the level of the abstract framework: any

[10]The simple and intuitive case of quantum Brownian motion provides a good starting point to gain some insights into the structure and physical meaning of such dissipative effects (e.g., Caldeira and Leggett, 1983; Boyanovsky, 2015).

standard EFT can be identified with the forward-propagating part of an open EFT in the special case where the parameters of its cross-interaction terms vanish (e.g., Dalvit and Mazzitelli, 1996; Zanella and Calzetta, 2006; Nagy and Polonyi, 2022). The double path integral in Eq. 3 indeed reduces in this case to a simpler double path integral with two independent branches and unconstrained boundary conditions. If the Lagrangian density on each branch does not include complex-valued interaction terms, the evolution of the low-energy system becomes unitary. Yet there is a key difference with the double path integral we start with in (1) above: each branch now involves an effective action with arbitrarily complicated interaction terms. If we further idealize S to be in its pure vacuum state at $t = \pm\infty$, we obtain the absolute square of the vacuum persistence amplitude $\langle 0, +\infty | 0, -\infty \rangle$, and we may identify the effective path integral for the forward-propagating low-energy field with a standard EFT.

To wrap up, the open EFT framework suggests that standard EFTs correspond to an idealized special class of open EFTs. This, in turn, suggests that realistic effective quantum field systems form a subset of the set of open quantum field systems. To be sure, this is far from sufficient to show that the complicated effective quantum field systems found in physics practice are more realistically theorized as open. But the open EFT framework still provides preliminary reasons to expect that the high-energy counterpart of any such system generates dissipative effects at low energies. The next section explores what it takes to defend this point.

5 Why effective systems are open

I will now provide a general argument to substantiate the claim that every realistic effective quantum field system is open. I will, in fact, provide two versions of this argument: (1) a more straightforward version starting from the reductive concept of effective system; (2) a more involved version starting from the autonomous concept of effective system. I should emphasize again that although I will frame the principles involved in (1)-(2) in general terms, I will only provide reasons to believe that they hold for quantum systems, i.e., as seems fit for the argument to go through in QFT, and leave it for further work to examine whether they face significant exceptions beyond that.

5.1 Version (1)

Suppose that E_R is an effective quantum field system in the reductive sense, i.e., a quantum field system characterized by a restricted set of degrees of freedom associated with a limited range of scales via the derivation, perhaps only partial, of an effective theory T_{eff} from a more fundamental theory T. Note that T does not need to be fundamental *simpliciter*. But we may safely take it to be a quantum theory in the present case. Suppose furthermore that the predictions of T and T_{eff} are accurate in their respective regime. E_R is thus a realistic system, in the minimal sense that it can give rise to observational effects and is amenable to empirically successful scientific theorizing.[11]

By construction, there exist additional degrees of freedom that characterize some realistic quantum system F, i.e., the degrees of freedom that T, but not T_{eff}, explicitly accounts for. In the toy example of section 2, E_R is specified by the low-energy field variable $\phi_L(x)$ and F by the high-energy field variable $\phi_H(x)$. But E_R could also be specified by a light field variable $\phi(x)$ and F by a heavy field variable $\psi(x)$, or E_R by an average variable $(\phi_1(x) + \phi_2(x))/2$ and F by a difference variable $(\phi_1(x) - \phi_2(x))/2$ for instance. Whether E_R and F are two parts of the same system or two distinct systems is irrelevant here—they may be completely disconnected in both cases for instance.

As it happens, the argument indeed does not tell us anything about how E_R and F are related to each other so far. To move forward, we need to appeal to a new principle, which I will call the "principle of interactional closure" (PIC), in analogy with the causal closure principle in the debate over physicalism (e.g., Papineau, 2001, p. 9; Kim, 2007, p. 15).

Principle of Interactional Closure: For all natural divisions of the world into a set of distinct physical systems, every system interacts directly or indirectly with every other.

I will take PIC to hold only for quantum systems in the sequel and provide reasons to endorse it in this context in section 5.2 below.

A few clarifications are in order. (i) I take both the notions of natural division and direct interaction to be primitive. But I assume that we have good reasons to believe that: (a) a division is natural if each system in the resulting set is represented by some theory (or model or law) that enjoys a sufficiently significant degree of empirical success; (b) two systems interact directly with each other if there is some empirically successful theory that includes some irreducible interaction term between their respective variables.[12] (ii) I take the notion of indirect interaction to be derivative:

[11] Note that if T_{eff} is derived without eliminating any degree of freedom, it is best to treat it in the bottom-up approach and run version (2) below.

[12] Note that the notion of natural division used here builds upon philosophical discussions over natural kinds and laws of nature (e.g., Hildebrand, 2023). Strictly speaking, this notion is independent of the various notions of "naturalness" at play in the QFT setting. In particular, physical systems resulting from a natural division may be highly sensitive to each other.

two systems interact indirectly with each other if and only if they interact directly either with a third system or with distinct systems that belong to a set of intermediary systems interacting directly with one another.[13] (iii) The division may be either complete or partial. But if it is partial, the systems resulting from the division may well interact only via some unknown or unspecified system. (iv) I will make one additional assumption for the specific application of PIC to quantum systems used in the sequel: namely, that any set of quantum systems resulting from a partial natural division interact at least indirectly via some non-trivial quantum system. I will provide reasons for this in section 5.2. For now, the motivation is to exclude implausible scenarios (as of now) in which two realistic quantum systems interact only via some radically new kind of system.

Coming back to the argument, whether T_{eff} is fully or only partially derived from T, their respective empirical success provides good reasons to believe that the (partial) division of the world into E_R and F is natural. Thus, according to PIC, E_R interacts directly with F or indirectly with it via some non-trivial quantum system, i.e., E_R interacts with some system and is thus open in the reductive sense.

Suppose for simplicity that E_R interacts directly with F. If E_R interacts only indirectly with F via some non-trivial quantum system G, we may use a generic abstract Hilbert space to represent its states and run the same argument. Then, since E_R and F are non-trivial quantum systems, their states are in general best represented by a density operator. Next, since they interact directly with each other, we can introduce some generic interaction term $O_{E_R}O_F$ without knowing the details of their interaction, with O_{E_R} and O_F some operators acting on E_R's and F's Hilbert spaces. Finally, we can rely on the standard approach outlined in section 3 to show that the effective dynamics of E_R is non-unitary and thus involves dissipative terms, i.e., that E_R is open in the autonomous sense.

Our toy model gives a simple illustration. First, the division rule is straightforward in this case, i.e., $\phi(x) = \phi_L(x) + \phi_H(x)$. Then, although we may eliminate quadratic interaction terms like $\phi_L\phi_H$ with a field redefinition, the action still contains irreducible interaction terms like $\phi_L\phi_H^3$, $\phi_L^2\phi_H^2$, and $\phi_L^3\phi_H$. Finally, we can coarse-grain the system as in section 4 and obtain new kinds of dissipative interaction terms for $\phi_L(x)$.

5.2 Discussion

I will now address a couple of worries related to version (1) and provide reasons to endorse PIC for quantum systems before moving on to version

[13] A system may interact directly with itself, in which case it trivially interacts indirectly with itself. We may also safely take PIC to imply that every system interacts indirectly with itself.

(2).

First, the argument does not require making the assumption of a unique natural division, whether partial or complete. We could indeed have different sets of theories (or models or laws) that enjoy a sufficiently significant degree of predictive success and that are associated with more or less physically perspicuous and simple divisions (among other criteria). Experience teaches us how to make the best trade-off and choose relevant variables. Making the wrong choice may bring unnecessary complications. But if we have good reasons to believe that the division associated with the variables in question is natural, the desired conclusion still goes through.

Second, we might be worried about being restricted in practice to partial natural divisions. We indeed seem to be far from having enough evidence to believe that current theories represent every existing degree of freedom and thus far from having a reliable all-embracing vantage point from which to assess whether any two systems interact at least via some other system. And this may seem all the more worrisome as current physics presents us with apparent counter-examples, i.e., partial natural divisions for which the subsystems do not seem to interact indirectly with each other. To illustrate this, consider for instance pure quantum electrodynamics (QED). We can divide the photon field variable into a low-energy and a high-energy variable. Since the standard photon field dynamics is quadratic and does not include higher-order self-interaction terms compared, say, to the standard pure gluon field dynamics, we may eliminate any quadratic interaction term between these variables by redefining them. This suggests, in turn, that the photon field may be divided into two parts across energy scales that do not interact with each other.

There are two things to say in response here. On the one hand, we can always appeal to the best theories available at any given time to assess whether existing partial natural divisions satisfy PIC. In the current situation, insofar as any known form of matter is irreducibly coupled to gravity, PIC-violating natural divisions do not seem to be a genuine threat. In particular, we can couple the photon field variable to the metric field in the effective quantum version of general relativity with matter fields (e.g., Donoghue, 2023). On the other hand, when confronted with apparent counter-examples, we have to keep in mind that the subsystems at stake may be only approximately isolated from each other. For instance, the absence of higher-order self-interaction terms in pure QED stems from the fact that we have ignored interactions between the photon and electron fields (among others). If we were to integrate out the electron field in the first place, we would automatically obtain such terms (as in the Euler-Heisenberg effective Lagrangian).

Third, regarding the issue of whether PIC holds for quantum systems, the first thing to say is that our best current QFTs underwrite it: they provide us with good reasons to believe all the quantum field systems they represent interact directly or indirectly with each other. The same goes for natural divisions obtained by dividing existing quantum field systems across scales: the existence of at least indirect interactions between any of them implies that any effective system obtained by integrating high-energy degrees of freedom interacts with its counterpart across scales (as illustrated by the case of pure QED above).

The set of systems described by our best current QFTs is still presumably smaller than the set of realistic quantum field systems, let alone the set of realistic quantum systems, and one might wonder whether there is any good reason to believe that they all interact at least via some non-trivial quantum system. The strongest reason to endorse PIC in this case is ultimately empirical in my sense. If there was a perfectly isolated quantum system at all times and under any circumstances, it would be causally inert and make no difference whatsoever in the world. We would probably be able to safely eliminate its description from any empirically successful quantum theory too (e.g., we can always factorize out an isolated quantum subsystem in the path integral formalism). But more importantly, there would be no way for such a system to affect other systems and thus no way for us to tie it to any observable effect. In the absence of evidence to the contrary, we would probably have good reasons to believe that no such system exists, or, at the very least, to exclude it from the set of systems we have any good reasons to commit to.

We might still wonder about the restriction to intermediary non-trivial quantum systems above. After all, it is perfectly conceivable that some quantum systems interact, say, only via a classical system. The most plausible candidate in the current situation would be the metric field in classical general relativity, which we may indeed not need to quantize (see, e.g., Huggett and Callender, 2001; Wüthrich, 2005, for a philosophical discussion). I should say, however, that this option is usually deemed unattractive for a variety of reasons (e.g., a seemingly disunified theoretical framework) and that most existing attempts to go beyond the QFT framework not only take seriously the idea of quantizing gravity but also postulate the existence of new quantum degrees of freedom (see, e.g., Rickles, 2008; Oriti, 2009, for philosophical surveys). This certainly provides a strong rationale to endorse the restriction above. But even if we take the metric field to be a classical system, as of now, there are still good reasons to believe that realistic quantum field systems interact at least indirectly via some quantum field system. For instance, the $W^{\pm}$ and gluon fields do not interact directly with each other according to the SM. But they both interact directly with quark fields. So the restriction to intermediary non-trivial quantum systems is also supported by existing physics independently of quantum gravity.

Finally, we might wonder whether PIC holds for composite and elementary systems insofar as a composite system and the set of its elementary components do not seem to be two distinct physical systems, strictly speaking. I am inclined to bite the bullet here. If we are ontologically permissive, i.e., ready to include sufficiently stable non-fundamental entities and structures in our inventory of the world, and have no metaphysical qualms about self-interacting systems, there does not seem to be any good reason left to deny that a composite system may interact with its component parts.

One might still find it overly contrived to introduce interaction terms between composite and elementary variables since, in typical situations, either we cannot use the former (e.g., pion fields at high energies) or we can safely ignore the latter (e.g., quark and gluon fields at low energies). In response, it is worth emphasizing that the QFT framework is sufficiently flexible to accommodate interactions across scales. For instance, we may even couple low-energy pion field variables to high-energy or heavy quark field variables if we wish. The real issue is whether the resulting set of variables does a good representational, explanatory, computational, and predictive job. But in principle, there is no limitation. We may even define a Hilbert space for a composite field and a Hilbert space for elementary fields and apply the standard approach to open quantum systems.

5.3 Version (2)

Suppose that E_A is an effective quantum field system in the autonomous sense, i.e., a quantum field system specified by a theory T_{eff} that irreducibly takes the form of a local covariant expansion in some scale, say, some high-energy scale Λ. Suppose furthermore that the predictions of T_{eff} are accurate in some limited low-energy regime much below Λ, which, again, implies that E_A is a realistic system in the minimal sense used so far. Compared to version (1), the reason we take E_A to be an effective system comes from the structure of its dynamics. The autonomous concept of effective system does not presuppose that E_A is a coarse-grained part of a more fundamental system, which is represented by a more fundamental and empirically successful theory.

Now, by virtue of its structure, the predictions of T_{eff} must become inconsistent at sufficiently high energies beyond Λ. To be sure, if the expansion is completely unconstrained, we may fine-tune its dimensionless coefficients to make it work at arbitrarily high energies (at least at the formal level, since the theory may for instance fail to account for interaction processes involving new high-energy inputs or outputs). But for the purpose of the argument, what matters is that for *any* such set of non-zero coefficients and if we put practical concerns aside, the predictions derived from the complete expansion do break down at *some* finite scale. To give a concrete example, the effective theory of pion fields works well for interaction processes at sufficiently low energies. But its predictions break down for energy scales much higher than the pion decay constant $F_\pi = O(10^2)$ MeV.

We are confronted with two main options to account for T_{eff}'s predictive breakdown at this point: (2a) T_{eff} inaccurately represents or fails to represent some high-energy degrees of freedom; (2b) there are no such misrepresented or missing high-energy degrees of freedom, and T_{eff}'s predictive breakdown stems from the existence of a physical limit at high energies, say, some discrete worldly structure.[14] Option (2a) builds on the realist intuition that the predictive success of a theory relative to a given domain stems from its ability to represent it accurately. Taking the contrapositive, if a theory does not make accurate predictions about a given phenomenon, it must misrepresent or fail to represent the system that gives rise to it. Option (2b) builds on our ability to reformulate T_{eff} as a lattice QFT. T_{eff}'s predictive breakdown indeed disappears once we restrict the possible range of momenta via a lattice cut-off π/a, with a the lattice spacing.[15] This suggests, in turn, that T_{eff}'s predictive breakdown in the standard continuum formulation of EFTs stems from our attempt to take into account physically impossible high-energy configurations beyond π/a. And we may of course fine-tune the parameters of the most fundamental EFT known at any given time so that the scale of its predictive breakdown as parametrized by a matches that of a fundamental physical limit (if any).

There are strong internal reasons to prefer (2a) over (2b) in my sense. To begin with, our best current EFTs provide little support for the existence of a particular physical limit. On the one hand, their formulation on a particular lattice is largely arbitrary: we can both rescale the lattice spacing and change the lattice structure of the theory without affecting its predictions by adjusting its dynamical structure and parameters. On the other hand, their standard (perturbative) continuum formulation does not contain any internal physical principle or constraint implying that the range beyond any particular finite cut-off is physically forbidden. The best option would probably be to appeal to the existence of a non-perturbative Landau pole singularity. As of now, this is a genuine possibility for the quartic self-interaction term of the Higgs fields in the SM and for the electromagnetic charge in QED (e.g., Gockeler et al., 1998a; 1998b; Gies and Jaeckel, 2004). Yet the existence of a Landau pole is in general highly unstable under the introduction of higher-order interaction terms. In particular, formulating the SM as an effective theory appears to affect the high-energy behavior of its

[14] I speak of representational accuracy to keep the discussion at a general level. But we may equally speak of approximate truth for descriptive statements and similarity for models. I am also assuming that T_{eff}'s predictive breakdown does not reduce to the breakdown of some approximation method (e.g., perturbation theory).

[15] Compared to perturbative continuum EFTs, all momentum-dependent contributions become trigonometric and thus bounded functions in perturbative lattice QFT (see, e.g., Capitani, 2003, for more detail).

perturbatively renormalizable couplings and remove its known perturbative Landau poles (see, e.g., Djukanovic et al., 2018, for a discussion).

By contrast, we do have strong inductive grounds from existing low-energy physics to believe that the predictions of EFTs ultimately break down because they misrepresent or fail to represent some high-energy degrees of freedom. For instance, the effective formulation of QED with matter fields breaks down around 80 GeV, i.e., where physical effects associated with the $W^{\pm}$ fields start to become too significant to be approximated with higher-order interaction terms in QED. To be sure, the scale at which new physics kicks in may not be exactly equal to the scale at which the predictions of an effective theory break down. This depends partly on the strength of interactions between the low-energy and high-energy systems. But there is little doubt from existing EFTs that their predictive breakdown is ultimately tied to their inability to represent some high-energy system. Moreover, even if an effective theory only misrepresents some high-energy degrees of freedom, it is always possible to restrict its scope by some appropriate cut-off scale and assume that its predictive breakdown arises from its failure to represent them.

Although this is much more speculative, current research in quantum gravity also provides external reasons to prefer (2a) over (2b). First, it remains a highly controversial and uncertain matter whether existing attempts to go beyond the QFT framework support the existence of a fundamental physical limit. Some programs in quantum gravity like causal set theory are rather unambiguous about their commitment to the existence of fundamental discrete quantum structures. But the matter is far from being settled from the standpoint of many other contenders, including the string theory and asymptotic safety programs (see, e.g., Oriti, 2009; Hossenfelder, 2013, for a discussion). Second, even if the structure of the world is ultimately discrete, most programs in quantum gravity, including programs in which this scenario is explicitly vindicated, do postulate the existence of new kinds of quantum degrees of freedom. This suggests, in turn, that the most fundamental EFTs known at any given time will break down at least partly because of their inability to represent such degrees of freedom.

The discussion so far supports the claim that T_{eff}'s predictive breakdown at high energies stems from its inability to represent degrees of freedom that characterize some non-trivial quantum system F. We may safely assume that F gives rise to some phenomena that T_{eff} does not account for (and run the argument with the relevant quantum system otherwise). But this does not tell us anything about our ability to represent F by means of an empirically successful theory. Compared to version (1), we thus do not have any reason to believe that E_A and F form a natural division at this point. Accordingly, we cannot appeal directly to PIC. And we do not seem to have any other independent grounds to believe that E_A and F interact with each other. To move forward, we need to appeal again to a new principle, which I will call the "principle of physical accountability" (PPA).

Principle of Physical Accountability: For any physical system that can give rise to observational effects, there is at least one theory that accurately represents it and makes accurate predictions about it.

I will take PPA to hold for quantum systems and quantum theories in the sequel (and provide reasons to endorse it in section 5.4 below).

Several clarifications are in order. (i) PPA states that any system that can give rise to observational effects is amenable to empirically successful scientific theorizing and thus constitutes a realistic system in the minimal sense used so far. (ii) PPA is trivially satisfied by philosophers' toy theories of the form 'there is a system that gives rise to observational effects P' and should thus be restricted to genuine physical theories that specify at least the degrees of freedom of the system of interest and some non-trivial constraints holding between them. (iii) In accordance with the traditional commitments of scientific realism, the theory of interest does not need to provide a perfectly and exactly accurate representation of the system. We only need a sufficiently successful theory to reach the conclusion that E_A and F form a natural division and appeal again to PIC.

Then, if we use PPA in the discussion so far, it implies that there is a quantum theory T that accurately represents F and makes accurate predictions about some phenomena beyond Λ. Quantum chromodynamics provides a good example for the effective theory of pion fields. But we could even restrict ourselves to a more comprehensive effective meson theory derived in chiral perturbation theory.

Finally, since E_A and F are both accounted for by empirically successful theories, we can directly use the last steps of version (1) to reach the desired conclusion. Using PIC in the specific case of quantum systems, E_A interacts directly with F or indirectly with it via some non-trivial quantum system, i.e., E_A interacts with some system and is thus open in the reductive sense. And since they are both non-trivial quantum systems, the reduced dynamics of E_A must involve dissipative terms, i.e., E_A is open in the autonomous sense.

5.4 Discussion

I will now briefly address a few remaining worries related to version (2) and provide reasons to endorse PPA for quantum systems before concluding.

First, the argument relies on the idea that realistic effective quantum field systems in the autonomous sense are ultimately incomplete. And insofar as the predictions derived from their theoretical description ultimately break down at some scale, this implies that they are also effective in the reductive sense. Again, I am inclined to embrace this conclusion for realistic systems. But this does not mean that we should conflate the two concepts of effective system at play in the argument.

Second, the application of PPA in the argument reflects an optimistic epistemic attitude toward the progress of physics that may seem to be at odds with the usual epistemic vigilance of EFT practitioners. Agreed: PPA implies that we should be able to account at some point for any kind of new physics that our best current EFTs fail to account for. But it is worth emphasizing that PPA does not require the next theory to be fundamental or even much more comprehensive than existing theories. The notion of progress at work here is rather modest and gradual, and perfectly compatible with an epistemically vigilant attitude toward, say, putatively fundamental theories.

Finally, despite its apparent weakness, there does not seem to be any convincing way to endorse PPA on *a priori* grounds. For all we know, we may well have reached a point where we will not be able to account for new physics. But we do seem to have strong inductive grounds to endorse PPA at the frontiers of physics right now, i.e., for new quantum systems that are likely to lie just beyond the reach of our best current physics. For one thing: we have very much been able as of now to account for new physics by extending or replacing former theories with even more successful and comprehensive ones. We have, in other words, a very good track record of finding better and more comprehensive theories in the (perhaps indefinite) space of possible theories. For another: we have been very competent as of now at constructing sophisticated theories and deriving predictions out of them even when their putative target system had nothing to do with what the world is like. That is, we also have a very good track record of covering increasingly larger parts of this space. And in light of these two points, it would be somewhat of a miracle if unknown target systems that can give rise to observational effects just beyond existing quantum systems were to resist any of our genuine theoretical attempts.

6 Conclusion

Philosophers have started to pay increasing attention to physicists' treatment of physical systems as effective and open. Yet little has been said about how the concepts of effective and open systems relate to each other. Using quantum field theory as a case study to make a first stab at the matter, I have distinguished between two concepts of effective and open systems—a reductive and an autonomous concept, depending on whether it makes any reference to some other system—and I have argued that on both counts, every realistic effective system in this context is also open.

The more involved version of the argument, which starts with the autonomous concept of effective system, may be summarized as follows. Suppose that a given effective quantum field system is described by an empirically successful effective theory regardless of whether there exists a more fundamental system or theory. By virtue of its structure, the predictions of the effective theory must break down at some scale. The best explanation for this in the case of QFT is that the theory fails to describe some other quantum system beyond this scale. According to the principle of physical accountability, there must be another successful quantum theory that accurately represents this new system and makes accurate predictions about it. From there, we may closely follow the last part of the more straightforward version of the argument, which starts with the reductive concept of effective system. According to the principle of interactional closure, since the effective quantum field system and the new quantum system are accounted for by successful theories and thus form a natural, perhaps only partial, division of the world, they must interact, either directly or indirectly via some other quantum system. And since the effective quantum field system interacts directly in both cases with some quantum system, its reduced effective dynamics must be non-unitary and display dissipative effects.

Besides making explicit two key principles behind the idea that effective systems are open, the argument also provides new insights into the concept of open system across scales. So far, philosophers have indeed mainly focused on the concept of open system across space-time and interpreted the concept of environment in terms of the local surroundings of a system (e.g., Cuffaro and Hartmann, 2024; Williams et al., 2024; Ladyman and Thébault, forthcoming). But as we have seen, if there is any way to provide a natural division of a quantum system across scales, be it energy scales, distance scales, or velocity scales, each subsystem will be open in the sense that its complement across scales interacts with it and generates dissipative effects via its reduced dynamics. This will be the case for localized coarse-grained systems, in the sense that they interact and exchange something with more fine-grained items (including their own components if we are ontologically permissive). But this will also be the case for a spatio-temporally closed universe if its degrees of freedom are effective (e.g., the metric in the quantum version of general relativity).

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