Generalized frameworks: Structuring searches for new physics

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Abstract

Many areas of frontier physics are confronted with the crisis of a lack of accessible, direct evidence. As a result, direct model building has failed to lead to any new empirical discoveries. In this paper I argue that these areas of frontier physics have developed common methods for turning precision measurements of known quantities into potential evidence for anomalies hinting at new physics. This *method of framework generalization* has arisen as a sort of model-independent method for generalizing beyond known physics and organizing experimental searches. I argue that this method is well-justified given the current epistemic landscape, and that theory construction in general is much broader than simply building new dynamical models.

1 Introduction

From about the mid-1970s through the late-2000s, theory construction in particle physics proceeded by direct means of dynamical model construction.[1] With the success of the standard model, theorists could take methods and principles within known physics, and extend them to higher-energy domains in the form of concrete dynamics within a well-established framework. Grand unified theories (GUTs) took the idea of electroweak unification and extended it to the smallest simple gauge group, further unifying the couplings for each force into a single coupling at the GUT scale. This particular model—though full of unfixed free parameters—included a plethora of new particles and low-energy predictions, and led to a study of early universe phase transitions and ultimately inflation. Supersymmetry (SUSY) took the prevalence of symmetry classification in particle physics, and posited a new, spontaneously broken spacetime symmetry transforming fermions into bosons, and vice versa. Again, this theory came with a host of supersymmetric partners to the known particles, low-energy effects, and a solution to the cosmological constant problem. These and others have been heavily disfavoured by ensuing decades of searches for proposed new particles. For the former, the lack of proton decay highly constrains GUTs to be heavily disfavoured; for the latter, the scale of SUSY restoration has been pushed high enough to rule out a convincing solution to the cosmological constant problem.

This is typical of the current theoretical landscape in particle physics and gravity in many areas of frontier physics. It is not only the fact that no confirming evidence for, e.g., GUTs or SUSY was found, but what was worse for concrete model construction is that *almost no* new empirical data hinted at the limitations of the standard model. This sparseness of anomalous evidence poses a challenge to constructing models beyond known physics, especially when the prime candidates seem heavily disfavoured. In particle physics, this disappointment is exemplified by the so-called "Higgs boson blues": the disappointment in discovering a merely vanilla Higgs after 50 years of searches, and the subsequent lack of new physics in the years since. We have strong theoretical grounds to expect new physics, at least in the form of a quantum theory of gravity, but little empirical motivation. Dynamical model building is both very difficult and very easy without guidance from evidence; difficult because it is unclear where to focus attention, and easy because there are seemingly few constraints on possible models.[2]

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[1] I will define the term 'dynamical model' below, in the discussion of theory construction more broadly.

[2] As an illustration of this, think of the flood of papers published after the first suggestion that neutrinos were travelling faster than the speed of light (Brumfiel 2012). This illustrates how model construction becomes much easier when new anomalies arise, but also how quickly the deluge is culled by contact with evidence.

Luckily, straightforward model construction is not the only option for progress in physics. In fact, in particle physics, the era of theory construction leading to the standard model did not proceed with the construction of dynamical models until key aspects of the general framework were settled. What is importantly different now is the lack of new empirical data, something that drove the construction of the standard model, and arguably most other successful episodes of theory construction in modern science. Despite this important difference, the same interplay between various 'levels' of phenomenology and theoretical frameworks are relevant today to the process of theory construction. In this modern era of frontier physics, we are seeing early stages of theory construction using a method I call *framework generalization.* I will make precise what this means below, but roughly speaking, framework generalization starts with a well-established theoretical framework for known physics. One makes explicit the core principles, assumptions, and relations implicit in this framework, and generalizes a subset to create a generalized phenomenological model space. This phenomenological space serves as an arena for turning precision measurements of quantities predicted by known theory into constraints on the allowed regions of theory space, effectively allowing for a comparison of known physics with a wide range of possible competitors, without having to have explicit competitors in hand. One clear example is the use of parameterized phenomenological frameworks in gravitational research. In these parameterized formalisms, the generalized principles turn constants in the phenomenological models derived from general relativity into free functions or parameters. The example discussed in Sec 3.2 is the parameterized post-Friedmann framework, which introduces new free functions into the phenomenology of large-scale structure formation to allow for generalizations beyond the predictions of general relativity (cf. Eq. (1)).

Framework generalization is a process of theory construction in the sense of providing conceptual structure underlying otherwise structureless searches for deviations from known physics. Even if the end goal is a concrete dynamical model, early stages of theory construction are often conducted in absence of any such model. The long-term development of scientific disciplines is worthy of philosophical study, and understanding methods in what has traditionally been called the context of discovery is important for a full account of how science as a process builds knowledge over time. I argue that framework generalization currently permeates many areas of frontier physics, and that this method is in direct response to (1) the failure of direct model building strategies, and (2) the sparseness of anomalous experimental findings. For the latter, we can think of framework generalization as using known physics as a loose theoretical guide to experimental searches for new physics.

I will begin in Sec. 2 by outlining some key concepts for theory construction in physics, including a taxonomy of the interacting parts of a discipline in physics. Here we have a constant mutual interaction between high-level theoretical frameworks (consisting of core principles and mathematical formalism), low-level phenomenological models meant to model small classes of phenomena, experimental work to test models and explore new domains, and finally dynamical models (typically referred to as theories), which unify classes of phenomenological models into a single formalism, constrained by the principles of the theoretical framework. The section concludes with a more precise statement of the method of framework generalization. In Sec. 3, I provide some examples of generalized frameworks used in frontier physics. The focus of this paper will be on particle physics, but I also briefly discuss examples in gravity research and quantum foundations. Sec. 4 provides a philosophical analysis of framework generalization, using effective field theory in particle physics as an illustrative example. I discuss the reasons for the prevalence of framework generalization, its relationship to principle theories, and its inferential strength. I diagnose issues with today's epistemic environment in physics not as stemming from failure to build successful dynamical models—as one might assume from the lamentations in popular accounts of particle physics—but from the sparseness of empirical evidence. Though we can and often do make progress in science without experiment, the progress is often much more incremental. Framework generalization aims to make more empirical tests relevant to the search for new physics.

2 Theory construction and framework generalization

In order to understand theory construction in physics generally, and framework generalization more particularly, it is helpful to start with some terminology, and an understanding of how different parts of disciplines in physics interact and mutually influence each other. The labels for each domain of a discipline are chosen to reduce confusion with already established terminology, though overlaps exist and will be pointed out. The taxonomy here builds off of that given in Karaca (2013), Koberinski (2019), and Koberinski (2021), in the context of constructing the standard model. In Sec. 4, we will also see some similarities between the early construction of the standard model and today, in that both are early stages of developing new theories.

Koberinski (2019) splits high-energy physics into the following parts: *theoretical framework*, *dynamical models*, *phenomenological models*, *experiment*, and *mathematical tools*. In this analysis, I leave out mathematical tools, since they are often developed and utilized at every other level in physics. Often, in the process of theory construction, the end goal is a well-defined, clear dynamical model governing a domain of phenomena. A dynamical model is often referred to as a theory, as in, e.g., quantum electrodynamics, quantum chromodynamics, and Newtonian gravity. I use the term dynamical model for two reasons. First, in physics, these are often highly abstracted models that are summarized by or lead to a set of dynamical equations governing evolution. Second, the term *theory* is ambiguous, as it can also refer to what I call theoretical frameworks. A theoretical framework is the network of principles, symmetries, and constraints, usually mathematized into a formalism that serves as the common language of a given research program. These can come at different levels of generality, but examples include quantum field theory, general relativity, Hamiltonian classical mechanics, (non-relativistic) quantum theory, nuclear physics, and optics. In the process of constructing theoretical frameworks, one must often find ways to fit abstract, fundamental principles together in a consistent and general formalism. The distinction between theoretical frameworks and dynamical models is important for my purposes, so I avoid use of the term 'theory' when necessary to avoid confusion. Dynamical models are the most general models for a given domain of phenomena, though less general in scope than a theoretical framework. They specify some form of entities and interactions within the formalism of the framework, and specify a clear domain of phenomena.

The other key pieces relevant for theory construction are phenomenological models and experiment. Phenomenological models are constructed closer to the side of experiment, and may or may not be informed by a dynamical model. These are of less general scope than the dynamical models, and therefore allow for more specific and quantitative contact with experiment. Phenomenological models are closest to models in the sense of the 'models as mediators' school of thought (Morgan and Morrison 1999), though in the context of theory construction their role as mediators is less central. The important characteristic of phenomenological models is their relative autonomy from dynamical models; though meant to fit with these more general constructs, phenomenological models need not and often cannot be derived from their subsuming dynamical model. They often schematize experimental apparatus, or at least deal with more directly observable quantities not considered in the dynamical model.

In the early stages of theory construction, phenomenological model building will generally be informed by some loose set of principles which may end up forming the basis of a theoretical framework, and experimental results. Even when a dynamical model has been worked out, phenomenological models are often still necessary to mediate between theory and experiment. Instead of dealing directly with a dynamical model, we see mutual interactions between prototype principles comprising a theoretical framework, phenomenological models organizing or predicting new phenomena, and experimental checks on the consistency of the phenomenological models and principles. As argued in Koberinski (2019), constant contact with experiment is the central underlying feature that allows theory construction to work. As we will see below, one can think of framework generalization as a method developed to facilitate theory construction in an era with sparse direct experimental access to new domains. It proceeds in part by turning precision tests of known theory into exploratory experiments for new physics.

With this taxonomy in hand, we can start to alleviate the worries summarized in the introduction above. Start by thinking about the goals of theory construction; one can think of theory construction as 'complete' for a discipline when a theoretical framework fully formalized, and some set of dynamical models is constructed based on the principles of that framework. The dynamical models link together previously unrelated domains of phenomena, and organize phenomenological models as mediators between theory and experiment. Even then, a "finished" theoretical framework and set of dynamical models is often a launching point for further theory construction. Direct model building efforts seem to start with the current framework as given, and to construct new dynamical models within that framework by proposing new dynamics consistent with it. If and when this works, we extend the domain of the framework to cover new physics, but this does not seem to require radical conceptual shifts.

Major conceptual shifts often require mounting anomalous evidence, i.e., experimental findings that do not fit with the current theoretical framework. In the face of mounting anomalies, progress sometimes comes by direct construction of a dynamical model and theoretical framework all at once—Einstein's path to general relativity is a prominent example. But more often, theory construction is a slower, messier project involving a back and forth between principles and phenomenology until a framework and set of dynamical models emerges, as with the early stages of constructing the standard model (Brown, Dresden, and Hoddeson 1989; Koberinski 2019). This even occurs with mature theories, as described for particle physics in Koberinski and Smeenk (2020), though often for mature theories the set of dynamical models plays an important mediating role. So, the fact that direct model building beyond the standard model has failed to bear fruit might be less of a crisis than one might expect. However, the real issue still remains; frontier physics is trying to understand domains far beyond what is currently directly accessible by experiments. This means that the constant checking of principles, possible theoretical frameworks, and phenomenological models against new data is not currently possible. This is where the method of framework generalization comes in:

> **Framework generalization:** framework generalization is a theory construction method that starts with a well-established theoretical framework. First, one elucidates the core principles, constraints and formalism of the framework, and determines their impact on some phenomenological domain. Next, some subset of the core principles and constraints are generalized or removed, leading to an enlarged modal space of phenomenological possibilities. This allows theory construction to proceed in the absence of direct anomalous data, by allowing experimentalists to search for deviations from the original theoretical framework within the enlarged phenomenological modal space. Statistically significant deviations from expected phenomenology indicate anomalies requiring revisions to the old framework, or eventually, new dynamical models.

Before further general analysis of framework generalization as a method, I turn in the next section to provide some examples of how this method has become commonplace in many areas of frontier physics. It will also be helpful to see the various ways that impacts from the generalized framework on a generalized phenomenological space of possibilities play out in different domains. Depending on the discipline, this will look slightly different in each case. Since the details are important for understanding the motivations and uses of framework generalization, the next section will present examples from quantum theory, gravitational physics, and particle physics in some technical detail. I try to introduce the minimum amount of formalism required to understand the examples. The examples will also be helpful for elucidating some important features of this framework generalization, and the epistemic aims for which one can use a generalized framework.

3 Generalized frameworks in frontier physics

This section provides some examples of framework generalization going on in frontier physics today. The discussion in Sec. 2 was meant to provide a general motivation and definition for framework generalization; these examples are meant to provide details regarding how the method is implemented in contemporary physics. The examples in frontier physics come from reconstructions of quantum theory (Sec. 3.1), from parameterized frameworks in gravity research (Sec. 3.2), and from effective field theory in particle physics (Sec. 3.3). Table 1 provides a schematic mapping of the theoretical frameworks, the generalized frameworks, and the resulting phenomenological spaces for each case. Readers less interested in the details of each example can keep this table in mind and skip to Sec. 3.4.

3.1 Quantum foundations: reconstructions of quantum theory

Since the early 2000s, there has been a major increase in interest by the quantum foundations community in reformulating quantum theory in a more physically transparent fashion. Non-relativistic quantum theory is a formally quite clear and well-formed theoretical framework in which to construct particular dynamical or phenomenological models; physical systems are described by states, represented as density operators acting on a Hilbert space defined for the system. States evolve by action of unitary operators obeying the Schrödinger equation; probabilities for outcomes of measurements are given by the Born rule, or can more generally be represented as positive operator-valued measures (POVMs), such that each measurement

	Quantum theory	**Gravity**	**Particle physics**
Theoretical framework	Quantum theory	Metric theories of gravity, strong equivalence principle	Renormalizable quantum field theory
Generalized framework	Generalized probabilistic theories	Multimetric theories of gravity, violate equivalence principles	Effective field theory
Phenomenological possibility space	State space of generalized composite systems	Parameterized post-Friedmann space	Low-order non-renormalizable corrections to scattering amplitudes from the standard model

Table 1: Summary of how each example from Sec. 3 fits into the definition of framework generalization given in Sec. 2. Details are provided in the respective subsections.

outcome is assigned an element F_i of the POVM, and the probability that a system represented by state ρ is measured to have outcome i is given by $P(i) = \mathrm{tr}(\rho F_i)$.

This framework is formally well-understood, and provides a clear modelling procedure for physicists looking to model quantum systems mathematically. However, the framework famously gives very little physical insight into what quantum systems are, or why the world is well-described by quantum theory. Physicists like Hardy (2001) and Fuchs (2003), and philosophers like Clifton, Bub, and Halvorson (2003) sought to reformulate quantum theory in a way that makes its core physical principles more transparent. These reconstructions are often inspired by the physical principles underlying Einstein's theory of special relativity,[3] where clear generalizations from empirical/phenomenological laws lead to core principles. For Einstein, these were the constancy of the speed of light and the invariance of physics across different inertial frames. For reconstructions of quantum theory, there is no consensus yet, but the hope is that a good reconstruction will mix information-theoretic constraints on information transfer with other principles constraining the type of dynamics allowed.

In this section, I will focus on reconstructions utilizing the generalized probabilistic theory (GPT) framework, which is an operational generalization of the above recipe for quantum theory (cf. Masanes and Müller 2011; Koberinski and Müller 2018). The generalized framework is inspired by the rather operational character of the ordinary quantum framework: the primary concepts are *states*, which represent systems of interest, and encode all possible information about probabilities of measurement outcomes, *transformations* to change states, either through experimental interventions or dynamical evolution, and *measurements* that allow agents to extract information from the state. Importantly, the GPT framework is generalized beyond the setting of Hilbert spaces, or even their underlying algebras. The GPT framework is a generalized theory space, within which one can recover (finite dimensional) quantum theory, classical probability theory, and other, more general theories, at least in the form of state spaces for representative systems—bipartite 'bit' states—for each theory. The space of no signalling theories is especially interesting, as it allows physicists to explore the foundational significance of certain core quantum principles. For example, there are many possible theories that violate Bell-type inequalities, some more than quantum theory and some less. The GPT framework provides a direct link to phenomenology by casting theories in terms of preparations of states, transformations, and measurements.

Reconstructions of quantum theory will start with a generalized framework like the GPT framework, and impose "physically transparent" principles as constraints on the framework. The goal is to find the minimal number of maximally physical constraints that single out quantum theory uniquely. In Masanes and Müller (2011), for example, the principles imposed on the framework are:

1. Continuous reversibility of dynamics

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[3] I will discuss the parallels between principle theories and framework generalization in Sec. 4 below.

2. Tomographic locality: states of a composite system are uniquely determined by the statistics of local measurements
3. Existence of a minimal information unit (generalized bit)
4. No simultaneous encoding: a generalized bit can only encode up to one classical bit of information.

From these, one can show that the generalized bit is a qubit, and that composites of qubits combine the way they do in quantum theory. The reconstruction provides operational principles that allow one to understand why our world is described by quantum theory, and not something else.

Though the first goal of quantum reconstructions is to enlarge theory space and then narrow it back down to quantum theory, a longer-term goal of such projects is to generalize beyond quantum theory to new physics (cf. Mazurek et al. 2021; Adlam 2022). As Fuchs (2003) argues, a good principle theory reconstruction of quantum theory will tell us what constraints are more general and information-theoretic (3,4 and part of 2 above), and what pertain specifically to the physical content of quantum theory (1 and part of 2 above). These will then lay a clear groundwork for generalization with the purpose of finding new physics beyond quantum theory; perhaps even a theory of quantum gravity. In the reconstruction above, generalizations of continuous reversibility and tomographic locality could pave the way to new physics, and the GPT framework provides the phenomenological generalization necessary to derive concrete predictions beyond quantum theory. Deviations from quantum theory in next-generation precision measurements could point the way to new physics using this method. Part of the reason that such indirect methods are needed is that quantum theory as a framework has been able to accommodate all known tests thus far; rather than an unguided search for new anomalous phenomena, generalized frameworks help physicists pinpoint classes of phenomena where deviations might be most expected.

3.2 Parameterized frameworks in gravity research

Large-scale gravity research is in the midst of a boom of precision measurements, allowing physicists to test many of the previously inaccessible predictions and feature of general relativity. With these new tests now available, there is an incentive to try to understand or explain away dark matter, dark energy, inflation, and to test modified gravity theories to find deviations from the predictions of general relativity. Many of the generalized frameworks used in gravity research are *parameterized* frameworks: they begin with some functional relationships for a particular phenomenological domain covered by general relativity and other metric theories, and turn constants into free parameters, whose values are constrained by precision measurements.[4] Some examples of parameterized frameworks in gravitational physics are: parameterized post-Newtonian (Will 1971), parameterized post-Einstein (Cornish et al. 2011), parameterized post-Friedmann (PPF) (Fang, Hu, and Lewis 2008; T. Baker, Ferreira, and Skordis 2013), and inflation effective field theory (EFT) (Cheung et al. 2008).[5] For brevity, I will focus here on the PPF formalism, to illustrate how it is a generalized framework in the sense outlined in Sec. 2.

The PPF framework is a generalized framework for comparing cosmological models of general relativity to candidate models that modify gravity at large distance scales. Some physicists have pursued modified gravity models as an alternative explanation to cosmic expansion via a non-zero cosmological constant term.[6] This parameterized framework, like many others in gravity research, takes an empirical domain characterized by some set of solutions to the Einstein field equations, derives phenomenological equations relating certain

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[4] There has been a corresponding increase in attention to precision tests of gravity in the philosophical literature; some have dealt directly with the idea of generalized frameworks (Smeenk 2019; De Baerdemaeker 2021), while others are concerned with the boundary between simulation and experiment in gravitational physics (Vanderburgh 2003; Gueguen 2020; Abelson 2022). Here as elsewhere, the target phenomena are far removed from direct manipulability or observation, so there is much theory-mediation between data and phenomena.

[5] The EFT framework will be the subject of increased focus below, in the context of particle physics. Inflation and dark matter are two domains where gravity and particle physics often come together, so there is overlap here with the goal of discovering new physics unifying the two domains.

[6] Often one hears—for both dark matter and dark energy—of competing models that either add new exotic matter or forces, and those that modify the theory of gravity. Martens and Lehmkuhl (2020) argue convincingly that the distinction is at best a blurry one; it would be very difficult to find decisive evidence favouring one over the other. For the case of dark energy, there is a very clear contrast between the current ΛCDM model, in which dark energy is a cosmological constant term, and models for which dark energy is something other than a true cosmological constant.

observable quantities, and generalizes them by turning constants into free parameters or functions to be constrained by observation. Though the frameworks are often inspired by certain classes of models for new physics, the parameterization creates a much broader theory space where each neighbourhood implies different physics, even if there are likely no concrete models that pick out that neighbourhood specifically.

For the PPF framework, one starts with the class of FLRW spacetime metrics, with small matter perturbations away from complete homogeneity and isotropy. One then derives a relationship between the standard gravitational potential $\Psi(\mathbf{k},t)$ as a function of wavenumber and time, and the parameter representing matter overdensity, δ:

$$-k^2\Psi(\mathbf{k},t) = \frac{3}{2}\Omega_m(a)(aH)^2\,\delta, \tag{1}$$

where H is the Hubble parameter, a the scale factor, and Ω_m the fraction of energy density in the universe due to matter (Joyce, Lombriser, and Schmidt 2016). This equation is generalized in two ways: first, one introduces a second effective potential $\Phi(\mathbf{k},t)$, which can differ from the usual gravitational potential by a general function $\gamma(\mathbf{k},t)$; second, one allows for a further functional parameterization of Eq. (1) by including another free function $\mu(\mathbf{k},t)$ in the relationship:[7]

$$\Psi(\mathbf{k},t) = \gamma(\mathbf{k},t)\Phi(\mathbf{k},t) \tag{2}$$

$$-k^2\Psi(\mathbf{k},t) = \mu(\mathbf{k},t)\,\frac{3}{2}\Omega_m(a)(aH)^2\,\delta. \tag{3}$$

General relativity is recovered in the special case where $\gamma = \mu = 1$, but all other types of functions correspond to new points in theory space, reduced to this phenomenological domain of cosmic evolution of density perturbations.

This class of parameterized frameworks in general relativity is perhaps the best understood instance of framework generalization. The well-established theoretical framework is general relativity generalized for different sets of dynamical equations. This takes the form of a generalized space of metric theories of gravity; general relativity fits in this space by imposing a form of the strong equivalence principle. The principles and foundational relations of this framework are quite explicit. Their impact on a particular domain of phenomena—in the PPF case, the domain is cosmological scale structure formation—is worked out as in Eq. (1), and the generalization comes in the form of introducing new parameters to these phenomenological relations. The functions γ and μ create a much larger modal space of possibilities for evolution of density perturbations, corresponding to phenomenological signatures of new physics. Precision measurements of the phenomena can then be repurposed; statistically significant deviations from, e.g., Eq (1) would indicate that some principles of general relativity are violated, and the PPF framework provides a means of organizing, searching for, and interpreting such deviations.

3.3 Particle physics: effective field theory

By the mid-1970s, when the standard model of particle physics was taking shape, particle physics rested firmly on the framework of (relativistic) quantum field theory (Koberinski 2021). Broadly speaking, quantum field theory (QFT) as a framework is the best attempt at merging quantum theory with special relativity, and is centred on scattering cross sections as the fundamental phenomenological quantities, extracted from Lagrangian densities describing sets of basic fields and their interactions. Particles (again, roughly speaking) are elementary excitations of the various fields in the Lagrangian.[8] Importantly, to move from the Lagrangian to a finite scattering (S-)matrix encoding transition probabilities requires a complicated formal process called renormalization; without renormalizing a given model, the S-matrix yields infinite quantities and fails to be predictive. For this reason, perturbative renormalizability was a central constraint for the framework of quantum field theory.[9]

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[7] The PPF framework allows for other further parameterizations beyond this particular relationship, but this is an important one for comparing modified gravity and general relativity on cosmic evolution of perturbations.

[8] There is a significant amount of philosophical controversy; the interpretation of particles (Falkenburg 2007; Fraser 2008) and fields (D. J. Baker 2009) in QFT is a contentious matter. The framework of QFT is notoriously "messy", and there has been debate over whether one should interpret the framework as given (Wallace 2006), or use a more rigorous axiomatic framework as a proxy (Fraser 2009). These issues are orthogonal to the discussion here.

[9] See Koberinski and Fraser (2022) for philosophical discussion about the meaning and significance of renormalization and renormalizability in quantum field theory.

However, since the mid-1980s, a new framework has emerged, and has grown in significance through the 2010s in the particle physics community: the effective field theory (EFT) framework. A generalization from renormalizable quantum field theory, EFT uses the renormalization group methods to justify dropping the requirement of renormalizability. Along with this comes a new perspective on models in EFT: they are effective theories describing interactions and particles/fields at a given energy scale, and come with intrinsic limitations on their domain of applicability (cf. Williams (2018), Manohar (2020), Rivat (2020), Koberinski and Fraser (2022), and Koberinski and Smeenk (2020) for more technical philosophical discussion of EFT). The EFT framework grew out of phenomenological modelling of particle interactions, and is now used as a phenomenological sorting tool in searches for new physics. One major reason for this shift is the lack of success in confirming predictions from dynamical model construction, as mentioned above. Another is a shift in worldview, to the idea that EFTs make for better dynamical models, since they explicitly note their own domain of validity.

The EFT framework retains from QFT the principles of Poincaré covariant local field interactions encoded in Lagrangians and the S-matrix as a central pillar. The requirement of renormalizability is dropped, which expands the number of possible interaction terms in a given Lagrangian to infinity. Individually, the terms are rendered finite through a procedure known as regularization: in the simplest case, one imposes some energy-momentum cutoff Λ, above which the particular EFT breaks down. The nonrenormalizable terms in the Lagrangian are then suppressed by powers of that cutoff term, meaning that for energies far below the cutoff, these terms are negligible. The cutoff procedure leads to a power counting formula, organizing terms in order of increasing mass dimension. Operators with mass dimension greater than or equal to 5 are nonrenormalizable, but suppressed by powers of the cutoff. The so-called Wilson coefficients for a term of dimension n, providing the coupling strength between fields in a given operator, are given by $\alpha_{i,n}\Lambda^{4-n}$, where the $\alpha_{i,n}$ are dimensionless coupling coefficients typically expected to be of order 1. Since Λ is large, later terms in the expansion (in general) have smaller and smaller contributions to any observable of interest.

The EFT framework provides a clear generalization of QFT, expanding the number of allowed operators in a Lagrangian from those of mass dimension less than or equal to 4 to all possible operators. One chooses a set of fields and symmetries to constrain the phenomenological modelling of a given target system, and then allows for all possible polynomial combinations of those fields constrained to obey the given symmetries in the full EFT. If a given model—with specified fields and couplings at a given energy scale—represents a possible set of dynamics for a system, then the EFT framework provides a greatly enlarged theory space, in which the principle of renormalizability is removed. The impact of this generalization is to permit many more possible Lagrangians encoding possible dynamics for a given domain of phenomena. The framework allows for a larger class of phenomenological models, mediated through the current dynamical models applicable at a particular energy scale. The additional EFT terms parameterize the effects of physics at higher energy scales, therefore turning the particular EFT into a skeleton for many possible phenomenological domains at higher energies than those described by the renormalizable terms.

Bechtle et al. (2022) illustrate how an EFT generalizing the standard model—the SMEFT—provides a framework for conceptualizing deviations from known physics. One can derive predictions from the (renormalizable) standard model, and look for deviations in precision experiments. These deviations hint at new physics, to be phenomenologically captured by fixing a subset of couplings for lowest-order terms in the SMEFT. However, for the standard model as a whole, even just taking the terms of mass dimension 6—the next level up from the renormalizable standard model terms—there are 2499 new operators to consider.[10] Due to the conceptual distance between a given operator in a Lagrangian and a small increase or decrease in magnitude of a more directly accessible phenomenon, there are many ways one could fix new couplings to accommodate a single new prediction. By itself, then, the SMEFT is far too permissive of a generalized framework; there are far too many free parameters to tune in the face of new physics. However, physicists use judgments about standard model sectors most likely to yield new physics and constraints from within the standard model to drastically reduce the number of salient couplings to consider for any given test.

Koberinski and Smeenk (2020) and Koberinski (2022) have illustrated one important way that the EFT framework can structure searches for new physics: by turning precision tests of quantities well-understood

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[10] The Bechtle et al. (2022) paper is concerned with determining whether the SMEFT is a model or not; they conclude that it lacks certain characteristic features of models. Using my distinctions here, I think that EFT in general provides a generalized framework, and the SMEFT provides a generalized theory space for comparing different dynamical models in the same language. As mentioned above, the model-theory dichotomy is too crude to capture the methods and goals of physicists here.

within the standard model into searches for small deviations that fit within the SMEFT. The case studies examined there involve precision measurements of the electron and muon anomalous magnetic moments, both of which are very precisely understood within the standard model. Statistically significant deviations—like those that currently exist in the case of the muon—could be accommodated within the SMEFT by fixing constants on particular nonrenormalizable interaction terms. These new terms would in turn imply deviations from the standard model in other phenomena, allowing a systematic cataloguing of new physics. If multiple lines of evidence are found to validate the new term(s), one can say that new physics has been discovered. This is the early stage of theory construction, which could be followed by a stage of building new dynamical models constrained to predict the same phenomenological deviations detected by the SMEFT.

One major benefit of the SMEFT is its flexibility; almost any observable deviation from the standard model at energies near current tests could be accounted for within the framework.[11] Things like the current W-boson mass anomaly (CDF Collaboration et al. 2022) or new decay modes due to new particles could also be captured by new terms from the SMEFT. As a generalized framework, EFT provides a conceptual framework going beyond known physics, allowing theory construction to proceed in a framework-mediated, focused fashion.

3.4 How framework generalization is instantiated

Now that we have seen some detailed examples of framework generalization in practice, I pause here to reiterate that, despite major differences in each field, each of these is an example of *framework generalization*. In each case, one starts with some principles central to the original theoretical framework, retains some and generalizes others. The goal of this generalization is to create an enlarged possibility space at the level of the phenomena, including predictions from the current framework plus dynamical models as a subset of this space. Different phenomenological predictions are thought to correspond to different possible theories fitting within the generalized framework, while observations help constrain possible deviations from currently accepted theories or indicate quantitative tension between our current theories and the phenomena.

What can differ—and indeed *does* differ—in different instances of framework generalization is the scope of the original framework, the degree to which that framework is generalized, and how explicit the connection is between deviations from current theory and the specific principles that must be violated. Regarding scope, we can see a contrast between each of the examples above, with quantum theory having the broadest scope, while the gravitational framework of metric theories obeying the strong equivalence principle being of much smaller scope, comparable to that of renormalizable quantum field theory. We also see a contrast in the above examples of the degree to which each framework is generalized. Given the already highly general nature of standard quantum theory, the generalization to the GPT framework is also substantially general. All that is retained from the textbook formulations of quantum theory is the notion of states, transformations, and measurement, as well as the condition of no-signalling. The generalizations for gravity are at an intermediate stage, allowing for the possibility of multiple metrics, as well as violations of the strong and/or weak equivalence principles. In one sense, the generalization to the EFT framework is quite limited: nearly all of the framework of quantum field theory is retained, while only the requirement of renormalizability is dropped. However limited this generalization, it still serves the purpose of framework generalization by creating a greatly enlarged theory space, in which the phenomena of renormalizable quantum field theory form a small subset.

Finally, the degree of connection between the regions of phenomenological possibility space and the specific principles generalized can vary heavily. It is not always apparent what principles would be violated if observation favoured some region of that space significantly different from that predicted by current theory. In the case of the PPF framework for gravity, there is some clarity of connection, at least for some regions of the parameter space. Joyce, Lombriser, and Schmidt (2016) provide a survey of different models to explain the accelerated expansion of the universe, and argue that there are two clear ends of a spectrum of possibilities, corresponding to modifications to gravitational dynamics and the addition of new energy sources, respectively. Modified gravity models are classified by violating the strong equivalence principle, while adding dark energy sources is classified as the addition of a dynamical field obeying the principle. Many regions of parameter space will be a mix of these two options, but certain classes of functions $\tilde{\gamma}$ and

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[11] That doesn't mean that the EFT framework doesn't make substantive assumptions that could turn out to be wrong; the next section provides some words of caution for recognizing the inherent limitations of a generalized framework.

$\tilde{\mu}$ will correspond to modified gravity, while other classes Γ and M will correspond to dark energy. For the GPT space, one can actually visualize the state spaces for bipartite systems obeying certain sets of principles as polytopes, and one can see the degree of deviation from quantum theory given by some subset of the principles used for reconstruction (cf. Masanes and Müller 2011; Koberinski and Müller 2018). The connection between principles and deviations for EFT is much more opaque, however. Within the particle physics community, one expects, due to Weinberg's (1995) folk theorem, that any theory in a sufficiently low energy regime, that obeys Poincaré covariance and cluster decomposition will look like a quantum field theory (but not in general a renormalizable one). Other than giving up on renormalizability, the connection there is a bit less clear. However, variation of this degree is fine within the method of framework generalization.

As given in the definition of framework generalization in Sec. 2, Table 1 helps to show how each example fits into the scheme. However, what is missing from the table is a story filling out the end of the definition. All of these instances of framework create phenomenological possibility spaces in order to make evidence relevant that would normally be considered irrelevant for searches for new physics. In all cases, precision tests of current frameworks can be converted into constraints on the phenomenological space. The GPT framework repurposes precision tests of Bell inequality violations into constraints on the degree of super-quantum correlations; the PPF framework repurposes precision observations of structure formation into constraints on the degree of violation of the equivalence principles; and the EFT framework repurposes precision tests of scattering sectors of the standard model into constraints on the magnitude of nonrenormalizable interactions within that sector. With the examples sufficiently motivated, I now turn to back to a more general discussion of the implications of framework generalization.

4 Implications of framework generalization for methodology of physics

Above, I have argued that theory construction is a long process, and large parts of the development of a discipline in physics can proceed without any clear dynamical model building. Instead, one can deal directly with the core principles of a theoretical framework and determine their impact on phenomenological models, and vice versa. Framework generalization is one method that has arisen in quantum foundations, gravitational physics, and particle physics that avoids direct model building. Though some generalizations are inspired by previous model building, the method is explicitly neutral as to what—if any—underlying dynamical model(s) would give rise to a given point in the phenomenological theory space. I have claimed that framework generalization has emerged as a methodology across frontier physics to deal with the lack of means for direct detection experiments, or lack of glaring anomalies between current theories and experiment. In this environment, constructing dynamical models within the current framework has failed to bear fruit. In this section, I will elaborate on the general philosophical interest in framework generalization. First, I note the similarity in the distinction between the methods of framework generalization and model building, on the one hand, and Einstein's principle versus constructive theory distinction, on the other. The similarities here may be part of a greater trend toward abstraction in frontier physics. Next, I will assess the inferential strength that generalized frameworks provide for understanding new physics. Framework generalization casts a wider but shallower net in phenomenological theory space than many other methods for theory construction, especially direct model building. However, there is no clear way to compare which methods are generically better than any other. Given the evidential constraints facing frontier physics today, framework generalization seems a more promising first step. Even if the end goal is a dynamical model describing physics beyond the standard model and general relativity, framework generalization provides a first step in organizing searches for anomalous phenomena.

4.1 Comparison with principle theories

As is well-known in philosophy of science circles, and even among many physicists working in the foundations of quantum theory or general relativity—Einstein thought that there were two classes of theories in physics: principle and constructive. In a *Times* article explaining his theories of relativity, Einstein (1919) wrote,

> There are several kinds of theory in physics. Most of them are constructive. These attempt to build a picture of complex phenomena out of some relatively simple proposition. . . When we say

> that we understand a group of natural phenomena, we mean that we have found a constructive theory which embraces them.
>
> But in addition to this most weighty group of theories, there is another group consisting of what I call theories of principle. These employ the analytic, not the synthetic method. Their starting point and foundation are not hypothetical constituents, but empirically observed general properties of phenomena, principles from which mathematical formula are deduced of such a kind that they apply to every case which presents itself.

Though Einstein, and many others since, thought of constructive theories—similar to what I would call dynamical models—as the gold standard of theories, principle theories like his special theory of relativity have certain advantages as providing clear connection to the physical principles that jointly necessitate a given theoretical framework. Philosophers have often preferred constructive theories as they often provide a clearer ontology and dynamical underpinning for the target phenomena, compared to the constraints imposed by principle theories.[12] For my purposes, it is important to draw an analogy between Einstein's distinction between types of theories, and the methodological distinction between framework generalization and dynamical model building as strategies for theory construction.

Principle theories start from well-established empirical principles, and construct a mathematical formalism based on those as core axioms. The empirical principles determine constraints on what sorts of processes are allowed or forbidden, and we reason from secure empirical generalizations to a theory or framework. Thermodynamics is the classic example of a principle theory: the principles are the phenomenological laws dictating that energy is conserved and entropy never decreases. Constructive theories start from some foundational entities or ontological base, and derive measured empirical phenomena from the postulated entities and their dynamics. A successful constructive theory tells us what the world is like such that it gives rise to observed phenomena. Statistical mechanics is the classic example of a constructive theory: from the dynamics of classical point particles, we arrive at a probabilistic understanding of the laws of thermodynamics. The method of framework generalization similarly starts from a well-established theoretical framework, and constructs a generalized mathematical formalism based on generalizations of those core principles. One then uses precision experiments to determine constraints on what sorts of generalizations are allowed or forbidden, and we reason from generalized principles to find deviations from known physics. Model construction starts from some postulated foundational entities or set of dynamical equations, and one then derives new predictions from the postulated entities and/or dynamics. Successful model construction tells us what the world is like such that it gives rise to the new phenomena unexplainable within the old set of models or frameworks.

The parallels should be quite striking. Both principle theories and framework generalization have a phenomena-first flavour: quantifying observation or experiment are prioritized, and the formalism or principles start from generalizations over the known phenomena. Further, many philosophers have a strong preference for model building over other theory construction methods, in the same way that they similarly have preference for constructive over principle theories. Einstein himself favoured constructive theories as the end goal of inquiry. Similarly, one might take the end goal of theory construction to be a (set of) dynamical models. But this does not mean that indirect avenues to that goal, including framework generalization, should be dismissed.

Rising trends in quantum theory have led physicists to think of principle theories as perhaps a better or more productive way forward, despite the philosophical objections. Similarly, framework generalization has arisen as a favoured method throughout frontier physics, despite philosophical objections regarding its strength as a method for theory construction. This may turn out to just be physicists making the best of a bad situation; if we can only build principle theories or only use generalized frameworks given our epistemic circumstances, then perhaps we follow up by looking for reasons that those theories or methods are better. I explore this question in the next section.

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[12] Preference for constructive theories may also stem from Einstein's original examples of principle and constructive theories: thermodynamics and the kinetic theory of gases respectively. For these examples, the constructive theory is thought to be a more fundamental theory that encapsulates all or most of the principle theory.

4.2 The role of generalized frameworks in theory construction

Some of the strongest inferences one can make in physics come in the form of consilience arguments: given a certain theoretical framework or dynamical model, one can unify otherwise independent phenomena as stemming from a single underlying entity of phenomenon within the framework or model. The classic example of such a consilience argument is Perrin's (1909) argument in favour of the atomic theory, using various independent measures of Avogadro's number. Without the underlying atomic hypothesis, these phenomena would have little connection; the fact that they all predict a single number would be a staggering coincidence. This is taken to be very strong evidence in favour of the atomic theory of matter. Philosophers of science have treated consilience-style arguments as a gold standard of scientific inference, and other types of inference are treated as better or worse the closer or further they are in strength to consilience, respectively.

Another prototypical form of model-based inference is when a new candidate model predicts some phenomena qualitatively distinct from the current accepted model or framework. Confirming observation of a qualitatively new phenomenon provides strong evidence in favour of the new model. Both of these are theory-first forms of inference: with a specific framework or dynamical model in hand, experiment serves theory by confirming parts of the new model, leading to the inference that the rest of the model must also be true or accurate. For this reason, one might understand why there is some concern over the inferential strength of the various forms of framework generalization as described above. Without a concrete model at hand, deviating evidence will not lead to strong inferences supporting specific new physical models, even when conceptualized within a generalized framework.

For particle physics, Bechtle et al. (2022) argue that (bottom up) EFTs on their own are not models, and that they therefore lack some important inferential qualities we usually assume to hold between models and the world. In particular, they argue that the SMEFT is not fully autonomous from theory, does not represent new entities or fields, and therefore is neither a model nor a full theory. They argue that one only begins concrete model building *after* using the SMEFT to find deviations from known physics. Until deviations are found, the SMEFT is something different, and lacking in inferential power. I agree that we should not think of the SMEFT as a model, and that it cannot support inferential links between the world and the terms in the EFT expansion. However, I would diagnose this case rather differently. First, we should think of the SMEFT as a generalized dynamical model, constructed using the new principles of the generalized framework. The SMEFT is what one obtains when dropping the renormalizability requirement at the level of a particular dynamical model of QFT. Its purpose for structuring searches for new physics fits within the broad context of theory construction, and does so by building an inferential structure that is more easily amenable to experimental check. Rather than a theory-first (or model-first) comparison of diverging predictions from two or more concrete candidate models, framework generalization provides the theoretical tools for an experiment-first approach. The generalized background provides an enlarged phenomenological theory space, in which deviations from known physics are easily quantifiable. For the SMEFT, one searches for new physics in sectors of the standard model that are least precisely constrained, or in those where increased precision is most experimentally feasible.[13] Predictions can be made very precisely, and deviations come in the form of statistically significant deviations from those predictions. The generalized framework of EFTs provides the necessary conceptual space in which to turn deviations into constraints on new nonrenormalizable terms in the SMEFT. It provides the minimal "theory" in the form of guiding principles needed to turn currently accessible experiments into effective searches for new physics. Rather than thinking of the SMEFT as a (phenomenological) model only after deviations are found, and restricting the term 'theory construction' to model building, we should think of the SMEFT as a generalization that facilitates theory construction by converting precision measurements into constraints on the phenomenology of future physics (Koberinski 2022). Since Bechtle et al. fit their assessment into established accounts of models and theory construction, I provide here an alternative account, extending the discussion from Sec. 2.

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[13] These are often quite distinct realms. This is because, within the EFT framework, the goal is to increase experimental sensitivity to nonrenormalizable effects to the point that $\delta \approx \mathcal{O}(\mathcal{E}/\Lambda)$, where δ is the experimental sensitivity, $\mathcal{E}$ is the energy scale of the experiment, and Λ is the (unknown) scale for new, beyond standard model physics. There are two ways to do this. The first is to raise the energy scales at which we probe, i.e., increasing $\mathcal{E}$. This is done by using particle accelerators at very high energies, and has been the primary mode for testing the standard model. Unfortunately, however, experiments are generally less precise at higher energies, and an increase in $\mathcal{E}$ also results in an increase in δ. The second way is to perform precision tests of the standard model, thereby lowering δ. Precision tests like those mentioned in Sec. 3.3 try to minimize δ, at the cost of also lowering $\mathcal{E}$.

From the work of Smith (2014) and Stein (1995), one can see any scientific discipline as fundamentally temporal, with progress being the core characteristic of good science. Adopting this account of scientific progress, we can think of any moves within a framework that allow for greater exposure to ongoing tests at greater levels of precision as productive lines of inquiry. Often, one must assume the validity of the underlying framework in order to reveal stable causal relationships or other lawlike dependencies in nature. Despite the theory-ladenness of inquiry, knowledge generated in this way is stable and precise, often surviving theory change (cf. Koberinski and Smeenk 2020). Theory construction is thus an ongoing process of productive lines of inquiry, both utilizing current frameworks and dynamical models, as well as refining them in light of new evidence. Because theories do not wear their consequences on their sleeve, things like precision tests provide details to fill out our understanding of a domain, weaving together frameworks, theories, and phenomenological models into a robust coherent picture of the world. Within this picture, we can see framework generalization as a response to the failures of direct model building in frontier physics, especially in particle physics. Framework generalization is a new strategy to use principles from current frameworks to provide a new framework on which to predicate searches for new physics. In this way, one can alleviate the issue of a lack of direct experimental access to new physical domains by making a large class of accessible evidence indirectly relevant. Its inferential power differs markedly from that of consilience or decisive testing between candidate models, but that is exactly the intention. Theoretical constraints are made as permissive as possible while still retaining sufficient structure in which to organize new empirical findings, while sophisticated experimental techniques lead the way in theory construction by exploring regions of the generalized theory space.

Generalized frameworks guide searches for new physics in a way that inverts the inferential strength, compared to inferences made from direct model building. With a concrete model in hand, positive evidence of new physics predicted by that model supports the model as a whole. Inferences to other effects predicted by the model are also thereby supported, and theory guides the search for these other effects. For example, if the model is representational, positive evidence supports the inference to the existence of the entities or relations within the model; one then conducts a search to confirm the unestablished features of those entities or relations. Searches to determine the properties of the Higgs boson fit this inferential pattern. Consilience arguments are especially strong versions of this positive inference: one looks for new evidence that would otherwise be inexplicable if the new model were false. With framework generalization, positive evidence—in the form of constraints ruling out current theory—provides less of an inferential base, since the framework does not point to a worked out model. At best, the inference is to new physical effects that go beyond the principles of the old framework, and the specific deviation might indicate which principle(s) should be replaced. Despite this lack of depth accompanying a positive result, the inferential base is much wider with framework generalization; instead of one specific deviation, the generalized framework will often support a wide search for deviations from known theory in larger regions of parameter space. Thus one can compare current theory with a host of as yet unconceived alternative models, at least within the confines of possibility defined by the generalized framework.

Because the phenomenological theory space generated by framework generalization admits potentially a continuous infinity of different physical possibilities, negative evidence—i.e., results supporting the hypothesis of no deviation from known physics—is also much more informative in this context. In the context of testing specific models, failed predictions emphatically do not rule out anything besides the specific model tested; new physics could arise in many other regions of parameter space, and one must build an entirely new candidate model for direct testing. Within the context of a generalized framework, finding a lack of significant deviation from known physics allows for a much stronger inference in the form of constraints on theory space. One can rule out alternatives to current physics whose deviations exceed the bounds placed by null results using standard falsification.

Thus, even if no significant deviation is discovered, a generalized framework allows one to constrain future physical models in a much stricter way. Framework generalization has a wider but shallower inferential base for positive results compared to direct testing of models, and a stronger base for negative results. Rather than arguing that one is better than the other, we should look at different methods of theory construction as tools, with some more suitable for a given social-epistemic environment than others. Given the lack of direct evidence for new physics, framework generalization seems well-suited to many domains of frontier physics today.

5 Conclusions

Framework generalization is a new method for theory construction in frontier physics. It starts with a well-established theoretical framework and its connection to some phenomenological domain. By generalizing some subset of the core principles of the framework, one generates a phenomenological theory space within which many possible deviations from current theory are possible. Framework generalization is most easily explicable in the terms for theory construction given in Sec. 2, and inspired by Karaca (2013), Koberinski (2019), and Koberinski (2021). As argued in Koberinski (2019), theory construction without model building is not new to frontier physics, and it is only recently that model building has taken prominence for particle physics. Its failures are not as disastrous for progress in physics as one might think; instead, it is the lack of new empirical anomalies that is most pressing for progressive theory construction. Framework generalization alleviates the lack of direct empirical access by expanding the domain of indirect tests able to find evidence of new physics. When we think of theory construction as the overall process by which a discipline formalizes a theoretical framework and settles on dynamical models built within that framework, we can see framework generalization as a first step in theory construction. By relaxing principles within the current framework, one is exploring the ways in which it may be inadequate to account for precision data.

Framework generalization has risen to prominence in contemporary quantum foundations, gravitational physics, and particle physics, in part due to the failure of concrete model building as a strategy for finding new physics, and in part as a response to the lack of feasible direct tests for new physics. For the latter, framework generalization works by turning precision tests of known quantities within the current framework into tests that place constraints on a larger, generalized theory space. For the former, framework generalization bypasses construction of dynamical models going beyond current physics. Even if one takes the goal of theory construction to be a worked-out (set of) dynamical model(s), it is often the end product of a longer process. Framework generalization allows one to deal directly with the interplay between theoretical frameworks, their principles, and phenomenological models. Framework generalization is thus an experiment-first, rather than model-first, approach to theory construction. When significant anomalies are found, model building can start to gain traction.

Framework generalization as a method bears some resemblance to principle theories, though the end result of framework generalization may not end up being a principle theory. Additionally, the inferential power of framework generalization is nearly opposite to that of comparison between models: while positive evidence allows for only weak inference to new physics, negative or null evidence is much stronger in the context of a generalized framework. This is due to the much larger space of possibilities considered by a generalized framework. However, I end on a note of caution. Physicists—especially those on the experimental side—will often refer to searches for new physics in a generalized framework as "model independent searches". It should be clear from my analysis here that this is an apt term in many ways. But one should not infer that these searches are completely assumption free; some background principles and assumptions are necessary for any inquiry, and there is a tradeoff between structure to a search and the search's generality. The best uses of framework generalization make the assumptions used to set up the framework as explicit as possible. For particle physics, for example, EFTs assume a local Lagrangian framework, in which the concept of energy is well-defined beyond a local region. Ruetsche (2018) and Koberinski and Smeenk (2022) provide some reasons to question the validity of those assumptions in some applications of EFTs, like in cosmology and when spacetime concepts are expected to break down. Though generalized frameworks are more model-independent than many other approaches to theory construction, they still build off of the known framework in ways that could turn out to be inapplicable to future physics.

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