Frameworks in physics: Abstractness, generality, and the role of metaphysics

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Abstract

In defending the fundamentality of the open systems view for quantum theory, Cuffaro and Hartmann (2024) articulate an account of frameworks in physics. They argue that the general quantum theory of open systems is a more fundamental framework than standard quantum theory. In this chapter, we articulate an account of frameworks using the examples of quantum field theory and statistical mechanics. We argue that what makes frameworks useful in physics is the combination of generality and abstractness of frameworks. In particular, their abstractness makes them poor targets for metaphysical analysis; the more concrete levels of theories or models are the appropriate target for ontological fundamentality claims.

1 Introduction

In physics, there are models and theories, but also frameworks. The explicit focus of Cuffaro and Hartmann (2024) is a set of arguments that aim to show that open systems are more fundamental than closed systems in quantum theory, but in the course of making these arguments they articulate a conception of frameworks that operate at a more general level than theories (and models). While the idea that frameworks play a role in physics is not new, we regard Cuffaro and Hartmann's account as a valuable original contribution to the recent literature on this topic. In our contribution to this volume we will critically assess Cuffaro and Hartmann's account of frameworks and analyze two other examples of frameworks in contemporary physics: (relativistic) quantum field theory (QFT) and (non-relativistic) statistical mechanics. Our main disagreement with Cuffaro and Hartmann lies in our argument that it is not appropriate to assess metaphysical claims about fundamentality at the framework level, but only at the theory or model levels. While our conclusions have implications for their position on the fundamentality of open systems, evaluating this thesis is not our main goal. In the final section we will briefly discuss the status of open and closed systems in the applications of the frameworks that we consider to quantum systems.

Over the past several decades, the models literature within philosophy of science has focused attention the important roles that models play in science. This has involved distinguishing models and their functions from theories. For example, in their own contribution to their influential volume *Models as Mediators*, Morrison and Morgan (1999) emphasize that the autonomy of models is essential for performing their function of mediating between theory and world. Theories and data are used in the construction of models, but models are partially independent of both. Roughly speaking, frameworks stand to theories as theories stand to models. A survey of discussions of frameworks in the models literature is beyond the scope of this chapter, but for our purposes it is interesting to note that Hartmann (1998) offers early reflections on the framework-theory-model distinction that are informed by an analysis of QFT. In the course of arguing that idealized models serve the cognitive function of facilitating the exploration of features of a theory, Hartmann characterizes Type A Theories as general background theories and cites the general formalism of QFT (e.g., as characterized by the Wightman axioms) as an example, which is in agreement with our own construal and examples of frameworks below. Type A Theories (or frameworks) are distinguished from Type B theories that adequately describe some relatively broad-scope but limited domain such as QED and QCD as well as from Type A Models that are toy models such as the ϕ^4 model, which are all examples of theories on our account. Type B Models are phenomenological models. From a contemporary perspective, this set of distinctions was prescient. Subsequent philosophical investigations of QFT have reinforced the moral that the framework of QFT is distant from both the particle physics theories (e.g., quantum electrodynamics (QED), quantum chromodynamics (QCD), the Standard Model) and models (e.g., of specified target systems). As we will articulate below, frameworks are more general and abstract than the theories they subsume, which in turn are more general and abstract than the models that connect theory to phenomenology. In the mainstream approach to QFT, the variety of renormalization and regularization techniques invoked to construct models with varying degrees of success in different contexts have underscored that it is a nontrivial achievement to go from a framework to a model (via theories). Similarly, within the axiomatic approach to QFT, the constructive QFT program of constructing models of some set of axioms for specified interactions has proven to be a challenging project in mathematical physics.

Cuffaro and Hartmann roughly distinguish models, theories, and frameworks as "ordered according to their generality, i.e., with regard to how 'far away' each is, conceptually, from the so-called target system in a given field of inquiry" (p. 5). Differentiation by levels of generality is a widely agreed upon starting point for philosophical analysis of frameworks, theories, and models, but it leaves many details to be specified. Cuffaro and Hartmann fill in the details by supplying a careful analysis of two examples of frameworks—standard quantum theory (ST) and general quantum theory of open systems (GT)—that highlights what they take to be the key features of frameworks. These frameworks are regarded as alternative formulations of quantum theory. We will follow Cuffaro and Hartmann in using examples to explicate the framework-theory-model distinction, but we will focus on different examples. These examples illustrate additional important features of frameworks that are not part of Cuffaro and Hartmann's explicit analysis of frameworks.

The two frameworks that we will examine are (relativistic) QFT and (non-relativistic) statistical mechanics.[1] Our purpose in introducing different examples of frameworks from Cuffaro and Hartmann is to shed light on other features and functions of frameworks in contemporary physics. Unlike the ST and GT frameworks for quantum theory, the QFT and statistical mechanics frameworks are not alternative formulations of one framework. Both the QFT and statistical mechanics frameworks can be used to construct quantum models of some systems. However, we do not contend that we have uniquely identified the correct frameworks for quantum physics. We will follow Carnap's counsel of tolerance for linguistic frameworks in our approach towards frameworks that are not solely linguistic: "[l]et us be cautious in making assertions and critical in examining them, but tolerant in permitting linguistic forms" (Carnap 1983, p.257). More specifically, since the theories that fall under frameworks overlap in nontrivial ways, there are different natural choices for carving up physics into frameworks. To give another example, Wallace (2018) and Wallace (2020) takes quantum theory as a whole to be one framework, within which QFT and non-relativistic QM are sub-frameworks. The contrasting framework in that case is classical theory. But one might take Lagrangian theories to constitute a framework instead, under which both classical and quantum theories can be formulated. Of course, Carnap's recommendation of tolerance is limited: some proposed frameworks may prove not to be useful and get abandoned.[2]

Our focus will be on critically examining Cuffaro and Hartmann's account of 'views', which include metaphysical assumptions about the nature of the objects in the domain, as being integral to the formulation of frameworks (p.5). On our account, frameworks are characterized by their degree of abstractness—in the sense of the opposite of concreteness—as well as their generality of scope—in the sense of applying to a wide range of phenomena. Our thesis is that analysis of the QFT and statistical mechanical frameworks as well as the ST and GT frameworks indicates that metaphysical assumptions are not integral to the content of frameworks; instead, metaphysical commitments may enter at the theory and model levels of representation. One of the pragmatic virtues of frameworks is their abstractness; many different metaphysical commitments

[1]For the sake of brevity, in this chapter the term 'QFT' will be taken as synonymous with 'relativistic QFT' and to have its paradigmatic applications in particle physics. As we explain in the next section, the field framework is also applied to construct non-relativistic quantum representations of condensed matter systems, but we will refrain from using the term 'QFT' to describe these. For clarity, we use the term 'finite-temperature field theory' to refer to the application of the field framework to construct relativistic representations of thermal systems.

[2]Proposed frameworks and their relationships can also be subject to philosophical/foundational analysis. For example, from the perspective of algebraic QFT, it is natural to consider the general framework for quantum theory to be quantum theory with an infinite number of degrees of freedom, which admits unitarily inequivalent Hilbert space representations (see Ruetsche 2011). On this way of carving things up, Cuffaro and Hartmann's ST framework has limited applicability (e.g., to non-relativistic QM); ST applied to non-relativistic QM and relativistic QFT are related as different applications of the general quantum-theory-with-an-infinite-number-of-degrees-of-freedom framework. In contrast, Cuffaro and Hartmann present ST as a general framework for quantum theory that has both non-relativistic and relativistic applications.

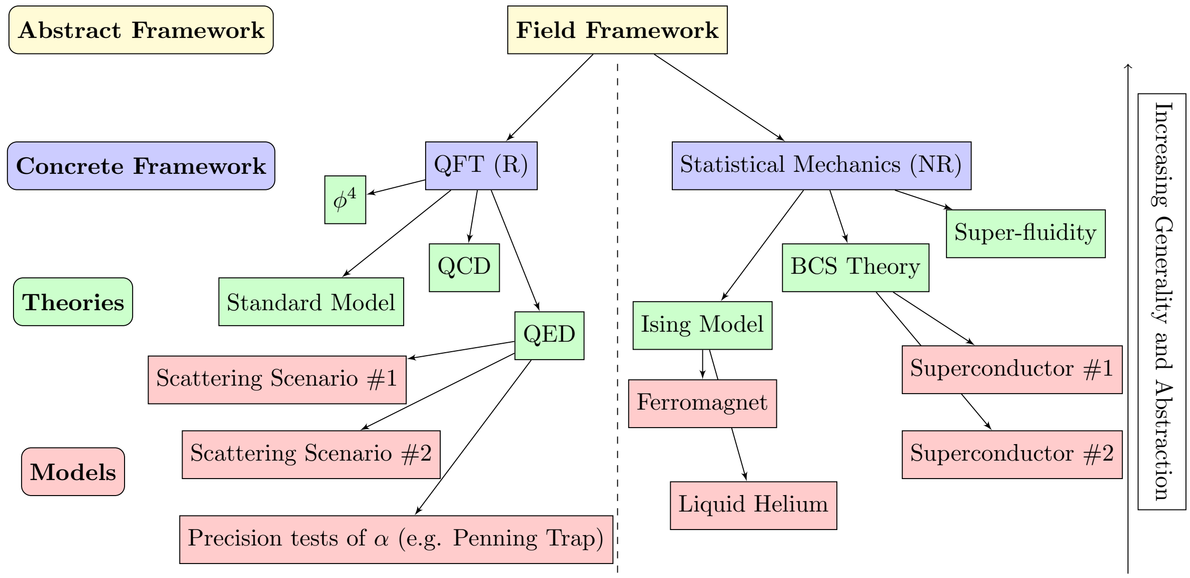

Figure 1: Some examples of concrete frameworks, theories, and models falling under the abstract field framework. Of particular focus here is the division between (relativistic) QFT and (non-relativistic) statistical mechanics as frameworks incorporating different physical interpretations (e.g., relativstic vs. non-relativistic spacetime structure). The frameworks sit at higher levels of generality and abstraction than theories, which in turn are more general and (typically) abstract than models.

may be added in the step of moving from thin physical interpretation to a more concrete theory or model. In Sec. 2 we describe the statistical mechanics and QFT frameworks. In Sec. 3 we compare and contrast our account of the statistical mechanics and QFT frameworks to Cuffaro and Hartmann's account of the ST and GT frameworks. In Sec. 4 we briefly consider how the QFT and statistical mechanics frameworks are used to represent open and closed quantum systems.

2 Examples of frameworks: Non-relativistic statistical mechanics and relativistic QFT

One broad motivation for carving up frameworks in contemporary physics along non-relativistic vs. relativistic lines is that the division corresponds to one of the major revolutions in twentieth century physics. As noted, an alternative carving slices along the lines of quantum vs. classical physics, the other major revolution. A more specific historical motivation for examining non-relativistic statistical mechanics and relativistic QFT as parallel frameworks is that analogies between models constructed using these frameworks have led to important discoveries. Our account in this section is informed by the case studies in Fraser and Koberinski (2016) and Fraser (2020), and the account of QFT in Koberinski (2019). We will begin by explicating these examples in order to set up our general philosophical characterization of frameworks at the end of this section.

Both the QFT framework and the statistical mechanics framework fall under the more abstract *field framework* (see Fig. 1). While it is not strictly necessary to identify the field framework level, it is helpful to recognize that the QFT and statistical mechanical frameworks have some common elements. For example, they share the representational strategy of representing a large number of degrees of freedom using mathematical fields $\phi_i(x)$ over some stratum x. $\phi_i(x)$ is not necessarily scalar-valued; it may be vector-valued or operator-valued. x may be either continuous or discrete. Field values fluctuate; physically significant quantities take the form of products of fields evaluated in privileged states (e.g., vacuum expectation values or correlation functions). Another ingredient of the field framework is the use of a Lagrangian or Hamiltonian to represent the dynamics. Renormalization group methods are an example of a representational and calculational component (Koberinski and Fraser 2023).

The framework of QFT is a field framework that is mainly used for high-energy particle physics. Some of its core conceptual features may include[3] fields defined on Minkowski spacetime, a privileged vacuum state, vacuum expectation values, local interactions, cluster decomposition, functional integrals, and perturbative renormalization techniques. These are a mix of physically motivated principles that underlie theories formulated within the framework, methodological strategies for formulating theories and constructing models, and mathematical tools for derivation and calculation.

The statistical mechanics framework is a field framework that is typically applied to represent condensed matter systems. A significant difference from the QFT framework is that the mathematical and methodological strategies are applied to describe non-relativistic causal structure. The space(time) structure is usually taken to be either Galilean or Euclidean. There is a global time variable, simultaneity is absolute, and there is no upper limit on the speed of signal propagation. This crucial difference has several downstream implications for the implementations of each framework, both conceptual and calculational. For example, there is an absolute standard of simultaneity that makes the use of spatial representations, such as an array of spins on a spatial lattice of atoms to model a ferromagnet, straightforward. Importantly, statistical mechanics can be used to construct either quantum or classical theories of field systems. When the field variables are defined over a continuum they are often regarded as an idealization, since many systems treated statistically in this way are taken to be composed of many discrete degrees of freedom (e.g., a lattice of atoms in a ferromagnet). Philosophical discussion of the statistical mechanics framework has focused on coarse-graining, which involves systematically transforming from a theory that includes all fine-grained details relevant at one scale to different theories which exclude fine-grained details that are negligible at larger distance scales. Coarse-graining is a physical interpretation of the application of renormalization group methods which is specific to the statistical mechanics framework; this aspect of the concrete physical interpretation of the statistical mechanics framework is not shared with the QFT framework (see Koberinski and Fraser (2023) for elaboration and analysis.)

Each framework can be used to formulate a variety of theories that each describe large classes of phenomena. In the QFT framework, examples of theories include QED, QCD, the electroweak theory, and ϕ^4 theory. In statistical mechanics, examples of theories include the Ising model for ferromagnetism, theories of superconductivity (like the BCS theory), and superfluidity. These are closest to what philosophers have traditionally called theories. Models for each theory are typically not strictly derived from the theory, but have some phenomenological input to connect the more abstract theory to a specific set of phenomena.

In common with Cuffaro and Hartmann's characterization of the tripartite framework-theory-model distinction, these frameworks are more general than theories, which are in turn more general than models, in the sense of scope of applicability. A framework is more general than a theory in that a larger class of physical phenomena can fit under the framework than the theory. Similarly, theories are more general than models in this sense. Furthermore, the levels in Fig. 1 represent increasing levels of *abstractness* from models to frameworks. A decrease in the level of abstractness means that concrete physical interpretation is added. For example, the statistical mechanics framework introduces a concrete physical interpretation of the fields as representing degrees of freedom arranged in non-relativistic space(time). Moving down one more level involves further interpreting the degrees of freedom as being atoms, electrons, photons, or phonons, for example. On the other side of Fig. 1, moving from the abstract field framework level to the concrete QFT framework involves specifying that the fields used to represent degrees of freedom are operator-valued, that vacuum states are privileged, and that both figure in vacuum expectation values. Moving down another level, in QED expressions involving vacuum expectation values can be given an empirical interpretation in terms of scattering amplitudes. In QCD, quark confinement adds to the empirical and physical interpretation in a different way.

Generality and abstractness are related, but conceptually distinct. Generality is a measure of the scope of applicability of a framework, theory, or model: the more general it is, the more phenomena fall under it. Abstractness, on the other hand, is a measure of the degree to which physical interpretation is specified. In physics, it is often the case that a greater degree of generality is achieved by making something more abstract, but the two are at least conceptually distinct. Increasing abstraction as one gets to the framework level results

[3]We set aside debates about how to characterize QFT both physically and mathematically that are not relevant to our discussion here. Examples of other elements of the framework are the use of Fock space to represent particles and the template for spontaneous symmetry breaking.

in greater generality, but also less physically contentful descriptions. For the frameworks discussed here, there are high level physical principles, spacetime structure, and the mathematical machinery of fields that allow one to treat large numbers of degrees of freedom. These are all physically motivated, but at the level of the framework are so abstract as to admit a range of possible concrete physical interpretations. Even the field framework common to both contains abstract physical content (e.g., the concept of a degree of freedom); it is still applied mathematics, not pure mathematics. However, the physical descriptions afforded by frameworks are usually so thin that most questions about the ontology (of a represented domain) are only answerable at the more concrete levels of theories or models, when a representational modelling strategy is specified. Note that abstractness as opposed to concreteness aligns with traditional definitions of the term, but differs from other definitions offered in the context of the recent philosophical debate regarding explanation in paradigm applications of the statistical mechanics framework such as critical phenomena (e.g., Morrison (2015, p. 20), Reutlinger and Andersen (2016), Jansson and Saatsi (2019), and Batterman (2019)). This debate has centered on the role of coarse-graining in applications of the statistical mechanics framework, which as noted above is an aspect of the concrete physical interpretation of the statistical mechanics framework. The QFT framework is not given a concrete physical interpretation in terms of coarse-graining, and the field framework is more abstract (in our sense) because it refrains from adding a physical interpretation of the coarse-graining type or any other type (see Koberinski and Fraser (2023) for details).

One of the benefits of a good framework is an optimal tradeoff between specificity and flexibility it allows for modelling diverse types of physical systems. The specificity is needed to provide direction for choosing an appropriate formalism and a template for modelling, while the flexibility is needed to allow a larger class of systems to fall under the framework. The payoff of a good framework is that it facilitates the transfer of successful modelling strategies from one domain to another. For example, RG methods are a family of techniques used to derive physically and empirically significant quantities in models that apply the field framework. One indication that RG methods might be a suitable problem-solving strategy is that field values fluctuate over a wide range of scales. Scale is an abstract physical concept that can be given different interpretations (e.g., space, energy, time) in different models. While in each specific case the scale takes a specific form, the abstractness helps one to identify contexts in which some form of the RG can be used. The framework serves as a toolkit for modelling situations in which field values fluctuate and are weakly coupled across that scale. This is a pragmatic virtue that would disappear if the framework is too specific. There is a tradeoff between specifying the physical content of the representation so that potential applications for the problem-solving strategy can be recognized and preserving the abstractness that allows a wide range of physical problems to solved using the same strategy.

3 Abstractness, metaphysics, and fundamentality

Now that we have explicated our own examples of frameworks, we turn to comparing our account of frameworks with Cuffaro and Hartmann's account. Cuffaro and Hartmann (2024) distinguish *framework*, *theory*, and *model* as "ordered according to their generality, i.e., with regard to how 'far away' each is, conceptually, from the so-called target system in a given field of inquiry" (p. 5). This suggests a combination of abstractness and generality as we have defined them. However, the abstractness of frameworks plays a more important constitutive role in our account of frameworks. What is important in Cuffaro and Hartmann's account is that frameworks are formulated with reference to a *view*, which is associated with "(i) a set of methodological presuppositions in accordance with which we characterize the objects of a given domain, that is (ii) motivated by a particular metaphysical position concerning the nature of those objects" (p. 5). We agree that frameworks incorporate methodological presuppositions, but disagree with the central role attributed to metaphysical assumptions. In particular, Cuffaro and Hartmann argue that the closed systems view is the metaphysical position that motivates ST, while the open systems view motivates GT in the sense that "the subject matter of a given scientific domain is thought of (a priori) to consist of systems that are in general" closed or open, respectively (p. 6). While a metaphysical position may motivate the formulation of a framework, we will argue that this metaphysical position need not be retained in the output when the framework is used to construct a model. This is apparent for QFT and statistical mechanics as well as the ST and GT frameworks. We take a consequence to be that frameworks are not the appropriate level at which to assess fundamentality claims.

In the same way that the open and closed system views are taken to motivate the GT and ST frameworks, respectively, the metaphysical position that the objects of study are fields is the obvious candidate for the view that motivates the field frameworks of QFT and statistical mechanics. Is there an implied commitment to a field ontology in the use of these frameworks to represent systems? The applicability of the framework entails that a system can be *approximated* using systems of mathematical fields, but is there necessarily a further commitment to a field ontology? The answer is no for both the QFT and statistical mechanics frameworks. Consider statistical mechanics. In prototypical examples such as the representation of continuous phase transitions in fluids or ferromagnets, models represent a target system with a large number of discrete degrees of freedom. Mathematical fields $\phi(x)$ are used to represent these degrees of freedom, but physical fields with continuously many degrees of freedom are typically only introduced as an idealization. The use of mathematical fields as a modelling tool does not entail an ontological commitment to the system consisting of physical fields. While a commitment to fields as modelling tools may be constitutive of the framework, it is not an ontological commitment, and certainly not a commitment to the fundamentality of fields. Idealizations are a widely used modelling strategy for representing a target system. Idealization allows frameworks to be flexibly applied to a broader range of theories and target systems. In the continuous phase transition case, a payoff of employing the idealizations that allow the field framework to be applied is arguably explanatory power (Batterman 2002).

What about QFT? Here the answer is not so straightforward, but it remains the case that the framework does not determine the answer. The appropriate ontology for QFTs is still up for debate, but there is general consensus that particles are not part of the fundamental ontology (see Fraser (2022) for a review). This leaves many options open, including embracing particles as emergent ontology (e.g., Wallace (2001)). One might think that some form of field is the best candidate for the fundamental ontology, but there are also arguments against some varieties of field ontologies (e.g., Baker (2009)). What is important for present purposes is that these debates are not settled by noting that fields play a primary role in the *formalism* of QFT. We cannot read off the ontology of QFT from examining the formalism at the framework level. Further arguments, physical and philosophical, are needed to draw conclusions about ontology. We take this to be a general point of caution in metaphysical analysis of physics: ontological commitments cannot simply be read off of mathematical formalism, especially when that formalism is presented at an abstract level in the context of frameworks. Further specification is needed to determine *what* is being represented, and *how* it is being represented. This is made concrete through physical interpretation in models which represent systems of the same type.

Cuffaro and Hartmann's own analysis in this volume reaches the similar conclusion that the metaphysical commitment associated with a view is not necessarily retained in the application of a framework. They conclude that "from the closed systems point of view, the ontology of ST actually includes open systems either exclusively (for orthodox interpreters) or in addition to closed systems (for Everettians)" (Cuffaro and Hartmann n.d., p.??). The metaphysical input to a framework is dissociated from its metaphysical output when it gets applied. Moreover, determining the ontology requires going beyond the framework itself by specifying an interpretation of some sort. This is the feature of abstractness that we have made explicit and emphasized in our account frameworks; here it enters implicitly in Cuffaro and Hartmann's account of the use of the ST and GT frameworks.

The abstractness of frameworks carries further consequences for Cuffaro and Hartmann's arguments for the fundamentality of the open systems view. Cuffaro and Hartmann argue that GT *as a framework* is more more fundamental than ST. We contend that the framework level is not the appropriate level at which to assess claims of fundamentality. If relative fundamentality claims are taken to be metaphysical claims, then frameworks are not the appropriate targets for these claims. On one standard understanding of fundamentality, the metaphysical relation of fundamentality is primarily applied to things in the world, though it finds a natural extension to theories and models when we take these latter to represent things in the world. But, on our account, frameworks are too abstract to to support the evaluation of relative fundamentality claims. For example, consider the statistical mechanics framework. The Galilean or Euclidean space(time) structure of statistical mechanics, for example, is a metaphysical assumption that is an input to the framework. But there is no case to be made from looking at the framework alone that this space(time) structure is fundamental, or that all systems modelled within this framework are fundamentally Galilean. Again, the use of idealizations or approximations in the construction of a model factors into judgments about the relative fundamentality of the representation. The frameworks provide a formalism and set of concepts within which to construct models, and we learn about the ontology of the world through studying the relationship between models and the world, not the framework and the world.

Cuffaro and Hartmann (2024) implicitly recognize the abstractness of frameworks in their definitions of fundamentality. As a starting point for defining the ontic fundamentality of a framework, they introduce the concept of a 'capital-O' Object of a framework that is common to every theory and model constructed using the framework (p. 15). In contrast, a 'little-o' object is a (constituent of) a given system, which is the referent of a model (p. 15). Cuffaro and Hartmann draw attention to the abstractness of capital-O Objects, at one point describing the capital-O objects in the ST and GT frameworks as the abstract concepts of a state vector $|\psi\rangle$ and a density operator ρ, respectively. The proposed definition of ontic fundmentality of frameworks in terms of capital-O Objects is rejected by Cuffaro and Hartmann on the grounds that it is "too abstract": "we have not considered the little-o objects—the ontologies—that the capital-O objects of ST and GT actually represent" (p. 17). Again, as Cuffaro and Hartmann's analysis of ST illustrates, the problem is that it is not possible to determine the relevant ontological properties of the 'capital-O' Objects because different interpretations and assumptions that enter in at the model level affect the ontological properties of the 'little-o' objects (e.g., orthodox vs. Everett interpretations). The views associated with a framework do not settle questions about relative ontic fundamentality. Cuffaro and Hartmann offer a revised definition of ontic fundamentality (Ont-Fund-2) that still applies at the framework level (p. 21). This definition breaks the connection between the view associated with a framework and the determination of relative fundamentality and introduces the representation of little-o objects as a determining factor. From our perspective, continuing to apply ontic fundamentality to frameworks is not the right way to proceed. Instead, abstractness needs to be recognized as a central feature of frameworks. As a result, questions about ontic fundamentality are not appropriately posed at the framework level because they cannot be settled at this level.[4]

In some instances it may make sense to talk of the relative fundamentality of different frameworks as a convenient shorthand. This is the case when all of the theories and models constructed using one framework are relatively more fundamental than the theories and models constructed using the second framework. In these cases the conceptual foundations of the less fundamental framework can often be found as limits or approximations to the conceptual foundations of the more fundamental. So, for example, we can say that the framework of quantum theory is more fundamental than classical theory, or that the relativistic framework is more fundamental than the non-relativistic framework. But these are special cases. We can't similarly say that Lagrangian mechanics is more or less fundamental than QFT, nor that the relativistic framework is more fundamental than quantum theory. For QFT and statistical mechanics, only loose relative fundamentality claims can be made, owing to the relativistic structure of QFT not present in statistical mechanics.[5] But the same does not hold for the case of ST and GT, since they are purportedly rival frameworks covering the same domain of quantum theory.

To summarize, on our account of frameworks their defining features are generality and abstractness. The degree of abstractness of frameworks precludes them from fixing the ontology of the systems which are represented with models constructed using them. For example, the field frameworks of QFT and statistical mechanics do not entail a commitment to field ontology; similarly, the ST and GT frameworks do not automatically imply the fundamentality of closed and open systems, respectively. On our account, this is not an accidental feature of the ST and GT frameworks for quantum theory, but an essential feature of frameworks in general. Frameworks are powerful due to their abstractness and generality, and both of these features depend on assigning minimal physical interpretation at the framework level. Cuffaro and Hartmann argue that the open systems view is more fundamental by arguing that the framework associated with this view, GT, is more fundamental. On our account, it is not appropriate to assert relative fundamentality claims about frameworks. The utility of frameworks lies in their ability to accommodate many different types of systems by getting "filled-in" with different physical and metaphysical content in theories and models. As

[4]Ontic fundamentality is the most well-developed notion of fundamentality in Cuffaro and Hartmann (2024). Insofar as the arguments for epistemic and explanatory fundamentality rely on ontic fundamentality, our criticisms also apply to these conceptions.

[5]One can further argue that QFT is in some sense more fundamental that statistical mechanics, but this is only by appeal to the systems that each framework is used to represent (fundamental particles versus atomic scale matter) or the main theories fitting into each framework (the Standard Model of particle physics versus various condensed matter theories). This serves to illustrate the point that the notion of fundamentality is better suited to less abstract representational content, at the level of theories, models, or the entities themselves.

a result, theories or models are the appropriate objects of claims about the relative fundamentality of the represented systems (or their constituents). We note that a similar conclusion is drawn by Wallace (2020) in the context of interpreting quantum theory; he takes quantum theory to be a framework, and argues that ontology must be specified relative to particular theories or models constructed within this framework.[6]

These criticisms of the argumentative strategy in Cuffaro and Hartmann (2024) do not bear on the truth of their conclusion that open systems are more fundamental than closed ones. We will consider how the models constructed using the QFT and statistical mechanics frameworks bear on this question in the next section.

4 Open systems in the QFT and statistical mechanics frameworks

Instead of arguing that GT is a more fundamental framework than ST, Cuffaro and Hartmann could instead skip the arguments regarding the frameworks and argue directly that the open systems view is better suited to the actual modelling practices of *both* GT and ST, or to quantum theory in general. In fact, they do provide such arguments in this volume (Cuffaro and Hartmann n.d.); we take these as being an appropriate way to argue for the fundamentality of the open systems view in quantum theory. Even in frameworks where the paradigmatic modelling assumptions treat a system as closed, it can still be the case that open systems are themselves more fundamental. The positive point we take from Cuffaro and Hartmann is a methodological point about modelling practices: that proper consideration of frontier physics practice should motivate a methodological switch to treating systems as open by default, with closed systems being a special case. They focus on frameworks of quantum theory, but can the field frameworks discussed here accommodate such a switch? In both cases the answer is a clear yes, with some qualification.

First, we need to clarify what it means for a system to be open. There seem to be three related, though distinct, conceptions at play. First is the idea that a system modelled as open is treated in a context where the environment with which it interacts is also modelled. Second, and somewhat stronger, an open system representation might be one that includes exogenous control variables, implicitly modelling the system as interacting with some part of the environment. Third, and strongest, is a representation that treats interactions with the environment on a par with dynamics internal to the system. We take a permissive understanding here, taking all of these to count as open systems. Due to the flexibility of modelling strategies within and across frameworks, different conceptions may be needed in different contexts.

Start with QFT. Paradigmatic uses of the QFT framework involve the scattering matrix: modelling transition amplitudes between states of free particles at asymptotically early and late times. This typically involves adopting a closed-systems perspective in which one can model the in and out states as effectively free particles. But this is only one (admittedly paradigmatic) use of the QFT framework; there are others. In particular, the effective field theory framework involves an explicit split of system and environment in the form of low- and high-energy degrees of freedom, respectively. While the standard uses of effective field theory make strong assumptions about the high-energy degrees of freedom (the environment) to ensure a minimal impact on the system, the split is essential to the definition of an effective field theory. An effective field theory is inherently an open system, with impacts from the environment modelled systematically as higher-dimensional interaction terms of the low-energy fields. While the QFT framework as a whole does not require an effective field theory perspective, this is one major application in which the QFT framework admits of the widespread use of open systems, albeit in the weakest sense of "open". The QFT framework is flexible in accommodating different modelling practices within it.

More obviously, finite-temperature field theory (aka thermal field theory) offers a relativistic treatment of open, thermally interacting systems. The general strategy involves combining elements of the QFT and statistical mechanics frameworks. Instead of dealing with isolated excitations to a vacuum state, finite-temperature field theory takes the background state to be a thermal state. For example, the thermal state can be a KMS state defined by its satisfaction of the KMS condition in (non-relativistic) quantum statistical mechanics, which is an infinite dimensional generalization of the Gibbs state for a system at inverse temperature β (Haag, Hugenholtz, and Winnink 1967).[7] One can deal with quantum fluctuations

[6]For an opposing view, see Guo (2023).

[7]While the original formulation of the KMS condition was in the context of (non-relativistic) quantum statistical mechanics, there has more recently been a generalization to real-time, relativistic contexts (Birke and Fröhlich 2002). The construction

about an equilibrium state, or more generally with larger departures from equilibrium. Temperature is now an exogenous control variable in finite-temperature field theory, and the degrees of freedom that are the focus of the modelling context are coupled to the background thermal state. Thus finite-temperature field theory uses a hybrid of the QFT and statistical mechanics frameworks to treat systems that are in some sense irreducibly open.

Finally, there is recent work on treating open systems within the effective field theory approach to QFT. In this case, one derives an effective density matrix for the effective field theory, and shows that its evolution satisfies a modified Lindblad equation (Braaten, Hammer, and Lepage 2016). Effective open QFT combines the openness of standard effective field theory with the dynamical evolution of GT, thereby providing the strongest example of open systems in QFT. While their use remains limited due to the technical complexity of the general calculations, it is clear that the QFT framework admits of many different formalisms relating to open systems.

For statistical mechanics, the systems under study are typically systems for which thermodynamic treatments prove informative of their properties. Statistical mechanical and thermodynamic treatments of systems often deal with open systems, where the system under study is allowed to exchange certain macroscopic quantities (e.g, heat, particles, energy) with an environment modelled as something like a heat bath. While closed systems are also part of statistical mechanics, they are in general a special case. The open systems view is therefore a good fit for the disciplines that use the statistical mechanics framework. Most systems modelled in this framework are taken to be open by default, in line with the methodological conclusion from Cuffaro and Hartmann.

5 Conclusion

We have argued that the distinction between frameworks, theories, and models in physics is characterized by both *abstractness* and *generality*. Frameworks are more abstract and general than theories, which are in turn more abstract and general than models. Generality is a measure of scope: a representation is more general when it applies to a larger domain of phenomena. Abstractness, by contrast, is a measure of concrete physical interpretation: a representation is more abstract when its physical interpretation is less elaborated. Both of these qualities are important for the flexibility and usefulness of frameworks: abstractness is often needed to increase generality.

While we agree with some aspects of the characterization of frameworks laid out in Cuffaro and Hartmann (2024), we argue that the abstract nature of frameworks makes them poor hosts for metaphysical views. Part of the value of a framework lies in its flexibility for modelling many different types of systems; a framework wedded to a particular metaphysical view about the fundamentality of a given representation would be unnecessarily restricted in its application. Therefore, we argued that the framework level is not the appropriate level at which to argue for the fundamentality of an open systems view.

In our analysis of the field frameworks of QFT and statistical mechanics, we highlighted their generality and abstractness, and their resultant flexibility. We argued that Cuffaro and Hartmann's analysis of the ST and GT frameworks also recognizes their generality and abstractness, at least implicitly. As a result, metaphysical and interpretative commitments are applied downstream of the framework, at the level of theories or models. Illustrations of this point are that different kinds of systems—not only fields—can be modeled in the QFT and statistical mechanics frameworks, and that open systems models can be constructed using both frameworks.

Our conclusions are compatible with Cuffaro and Hartmann's thesis that open systems are more fundamental than closed systems in the methodological sense that proper consideration of frontier physics practice should motivate a methodological switch to treating systems as open by default, with closed systems being a special case. The appropriate level at which to argue for relative fundamentality, however, is at a more concrete level than the framework level, where the physical interpretation is sufficiently specified to support ontological claims.

involves analytically continuing "imaginary time" Green's functions that satisfy the Euclidean KMS condition into "real time" Green's functions. The analogous condition satisfied by these real time Green's functions is a relativistic version of the KMS condition.

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