Phase transitions and the birth of early universe particle physics

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Abstract

This paper provides a conceptual history of the development of early universe particle physics in the 1970s, focusing on the development of more sophisticated tools for constructing gauge-theories at finite-temperature. I start with a focus on early investigations into spontaneous symmetry restoration, and continue through the development of functional methods up to equilibrium finite-temperature field theory. I argue that the early universe provides an ideal setting for integrated modelling of thermal, gravitational, and particle physics effects due to its relative simplicity. I further argue that the development of finite-temperature field theory played an important secondary role in the rise of the effective field theory worldview, and investigate the status of the analogies between phase transitions in particle physics and condensed matter physics. I find that the division into "formal" versus "physical" analogies is too coarse-grained to understand the important physical developments at play.

1 Introduction

The 1970s saw the cementing of two "standard models" in frontier physics: the Standard Model of particle physics (henceforth Standard Model), and the big bang model of cosmology. While the latter has undergone tweaks and revisions in the years since, the former exists largely unchanged. It also saw the trend toward merging particle physics and cosmology in the search for beyond Standard Model physics and explanations regarding the origins of the universe. Both disciplines were enriched by their merging, as speculative beyond Standard Model physics found a testing ground in the early universe, while ideas from particle physics would end up becoming key tools to describing the earliest epochs of the universe. By the 1980s, particle physics ideas had led to the development of inflation as a mechanism for generating isotropic and homogeneous spacetime geometries with sufficiently large causal horizons to explain the uniformity of the cosmic microwave background (CMB). While this work was developing, some other, less studied developments preceded it. The emergence of early universe particle physics as a subdiscipline led to developments in finite-temperature field theory, the effective field theory view of of physics, and to a formulation of a quantum gravity effective field theory. The conceptual implications of early universe particle physics will be the subject of this paper.

I focus on the developments that led to postulating quantum field theory (QFT) phase transitions in the early universe, starting with the discovery that finite-temperature effects could restore broken symmetries for QFTs. This led physicists at the time to hypothesize a hierarchy of QFTs that describe increasingly unified interactions under a simple gauge symmetry group, and to understand the Standard Model as describing effective particle dynamics at (or near) zero temperature and low energies. I highlight three main conceptual developments leading to this discovery: the idea of spontaneous symmetry restoration (Sec. 3.1), the development of functional methods and the effective action (Sec. 3.2), and the extension of these methods to equilibrium finite-temperature field theory (Sec. 3.3). Further, more well-studied contributions are briefly discussed in Sec 3.4. The main takeaways here are that more sophisticated formal methods were needed to introduce temperature effects into non-Abelian gauge theories, and that these tools also provide an important piece for understanding the ways in which the Standard Model is an effective theory, whose form might change drastically at higher energies. These developments were inspired by a simple analogy between SSB in particle physics and in condensed matter physics, indicating that spontaneous symmetry breaking (SSB) might also imply a phase transition in the early universe.[1]

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[1] I use the term "phase transition" to refer to a temporal process in the world. "SSB" is a formal property of equations and

The conceptual development of early universe particle physics has several consequences for the development of our modern understanding of particle physics and cosmology. In Sec. 4.1 I argue that the discovery of phase transitions in the early universe amounts to various types of unification of particle physics and gravity, particularly in the form of integrated modelling and unification by extension. Phase transitions of gauge theories at high temperatures provides one step toward unification of the disjoint frameworks of quantum field theory, thermal physics, and general relativity (GR) through integrated modelling. This integration led to the birth and extension of a new field of early universe cosmology, due in part to the striking simplicity of the spacetime geometry of the early universe implied by CMB observations. In retrospect, we can see that it took a fortuitous convergence of developments in observational cosmology and in the representational capacities of gauge-theories to allow for an expanded domain of empirical relevance for the Standard Model. The relevance of the simpler, single-time formalism of finite temperature quantum field theory for the early universe is made possible by the discovery that "simple" cosmological models—using FLRW metrics to characterize the large-scale structure of the universe—seemed well-suited for explaining the uniformity of the CMB. One might expect that, generically, modelling would become more complex when incompatible frameworks are combined. The early universe provides an interesting counterexample to this expectation.

Next, in Sec. 4.2 I focus on the role of analogies between condensed matter physics and QFT for the understanding of phase transitions in the early universe. The research project started by pursuing an analogy between SSB in condensed matter physics and QFT, and its success establishes a tighter physical analogy between the two. However, I argue that this case is complex, with both formal and physical analogies playing an important role. Rather than classifying the analogy as *overall* formal or physical, I argue that we should analyze the role of specific physical, causal, and counterfactual similarities and differences in the development of an analogical argument. Discovering that a phase transition could occur in the early universe is a successful strengthening of a physical analogy, since now SSB is a temporal process in both domains.

Another key aspect of our modern understanding of QFT that emerges concurrently with early universe particle physics is the effective field theory (EFT) view of the Standard Model. I argue that the tools developed at this time provide one important line of evidence suggesting that the Standard Model (at $T = 0$) is an EFT, insulated from new fields, forces and dynamics relevant at high energies. The early universe provides a testing ground where a hierarchy of new QFTs might emerge with ever higher degrees of unification; a concrete example is grand unified theory (Sec. 3.4). In Sec. 4.3 I trace the increasing sophistication of EFT ideas in studying phase transitions by tracing the evolution of the use of the term "effective" in connection to this research. This complements the recent historical work on the development of EFT, focusing on the importance of the renormalization group (J. D. Fraser 2021; Rivat 2021). While the renormalization group methods are of central importance to EFTs, the application of particle physics to a big bang model of the early universe plays a key secondary role.

Before getting into the details of this episode of history, I briefly set the stage for the state of particle physics and cosmology in the early 1970s. We will pick up the story from there.

2 Particle physics and cosmology in 1970

The 1970s saw the start of a fruitful merging of cosmology and particle physics in the domain of the very early universe. On the side of particle physics, the main developments leading to this merger involved the establishment of the Standard Model. In particular, the increased sophistication of understanding the representational capacities of non-Abelian gauge QFTs, the idea of increasing unification at high energies, and a desire to better understand SSB led physicists to start thinking of the early universe as an observational window into high-energy particle physics. This was made possible by developments in cosmology like the discovery of the CMB leading to increased trust in simple symmetric models of the early universe, and the success of explaining features of the observed universe using nuclear and low-energy particle physics.

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the corresponding state space. SSB is often used to model phase transitions, but one can have SSB without a corresponding phase transition. One major goal in the development of finite-temperature field theory was to see if the use of SSB at the centre of the Higgs mechanism implied such a phase transition in the early universe.

2.1 Particle physics, early 1970s

By the early 1970s, the main pieces of the Standard Model of particle physics were in place. The renormalizability and representational capacities of Yang-Mills gauge theories were widely accepted, leading to a re-emergence of QFT as a suitable foundation for particle physics in the strong and weak sectors. On the theoretical side, a candidate model of electroweak unification (S. Weinberg 1967; Salam 1968) and the beginnings of quantum chromodynamics (Cao 2010) were already on the table, and renormalization group methods were being applied to understand confinement and asymptotic freedom of the latter (Gross and Wilczek 1973; Politzer 1973; K. G. Wilson 1974). While all the pieces were there, the Standard Model was not yet established, as there were some open conceptual questions with the theoretical ingredients. Experimental confirmation of some of the key predictions from QCD and electroweak theory were also lacking, in sharp contrast to the 1950s and 1960s where experiment far outpaced theory (Cushing 1990; Koberinski 2019; Ruiz de Olano et al. 2022).

First, the realization that Yang-Mills gauge theories could describe massive vector bosons was a major first step in bringing QFT back to the forefront of particle physicists' minds.[2] In particular, the proof that spontaneous symmetry breaking (SSB) as a mass generation mechanism did not spoil the renormalizability of massless Yang-Mills theory made QFT seem viable again as a basis for the strong and weak interactions ('t Hooft and Veltman 1972).[3] Weinberg, building off the work of Glashow (1961) (and concurrently with Salam 1968) had already proposed a QFT model of the weak interactions, where SSB breaks a $\mathrm{SU}(2) \times \mathrm{U}(1)$ gauge symmetry resulting in three massive gauge bosons mediating the weak interaction, and one massless gauge boson mediating the electromagnetic interaction. The mechanism for SSB was the minimal Higgs mechanism, utilizing the simplest potential that was renormalizable and able to induce local SSB. This electroweak model made several testable predictions including the existence of three new vector bosons—$Z, W^{\pm}$—and the value for a new parameter, the weak mixing angle θ_W. Measurements and direct empirical confirmation of the model would not come for almost a decade, but the model gained acceptance as it fit with existing weak phenomenology. This led to further research to fill out the Higgs sector with more realistic physics, and to further work on unifying the electroweak and strong forces into a single theory.

Developments in the strong sector were indicating that the strength of the strong coupling would decrease at higher and higher energies, leading to free-particle-like behaviour in high-energy deep inelastic scattering of hadrons. Further, the renormalization group equations indicated that a massless SU(3) Yang-Mills theory would display confinement at low energies, and would match the observed asymptotic freedom from the deep inelastic scattering. The idea that massless gauge bosons could lead to an attractive force between quarks at low energies helped explain the absence of free quarks or gauge bosons, and led to the development of quantum chromodynamics.

Much of the theoretical work at this time was focused on exploring the representational capacities of QFTs, particularly those of Yang-Mills type. New mathematical tools like the renormalization group and dimensional regularization allowed physicists to better understand the structure and properties of QFTs. Heuristics like the requirement of renormalizability helped narrow down the space of possible theories, and theory construction was focused on increased unification—inspired by the electroweak model—and filling in the details of physical schematics like the Higgs mechanism. One natural place to look for inspiration for the latter was condensed matter physics. Since the Higgs mechanism and SSB were inspired by analogies to superconductivity, it seemed natural to try to extend those analogies in various ways. One avenue was to try to make the Higgs mechanism closer in form to the BCS model of superconductivity (Sec. 4.2, also D. Fraser and Koberinski 2016, Sec. 6). A second option was to think about the general structure of SSB, expanding the formalism of QFT to include finite temperature effects. This is a challenging task, and the start of the story in Sec. 3.1. The goal of pursuing analogies with condensed matter physics was still to expand and explore the possibilities within the class of renormalizable Yang-Mills gauge theories, fitting together with the other work to be discussed.

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[2] See Cao (2010) and Koberinski (2021) for a more thorough conceptual history of the developments in this period.

[3] At the time, some thought that the strong interaction would need SSB as well, since one did not observe massless gauge bosons in strong interactions (e.g., S. Weinberg 1973). The concurrent development of renormalization group methods to justify low-energy confinement and high-energy asymptotic freedom would make clear that a massless Yang-Mills was well-suited to model strong interactions.

2.2 Cosmology in the early 1970s

The late 1960s saw one of the most significant discoveries for the field of cosmology: the observation of a highly uniform electromagnetic radiation spectrum throughout the universe. The spectrum is consistent with a black body at temperature approximately 2.73K, and is uniform to a high degree of precision everywhere in spacetime (Penzias and R. W. Wilson 1965). This cosmic microwave background (CMB) was important evidence for the big bang model of cosmology, and implied that the early universe was remarkably homogeneous and isotropic. This meant that FLRW models—named after discoverers Friedmann, Lemaître, Robertson, and Walker—were well-suited to describe the early universe. FLRW spacetimes are highly symmetric, displaying homogeneity and isotropy with respect to a privileged set of cosmic co-moving coordinates. FLRW spacetimes with matter and radiation as mass-energy sources expand out from an initial singularity; the expansion rate $R(t)$ characterizes the full dynamics of the spacetime, and its evolution is governed by the Friedmann equation

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G\rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3} \tag{1}$$

and Raychaudhuri equation

$$3\frac{\ddot{R}}{R} = -4\pi G\left(\rho + 3p\right) + \Lambda, \tag{2}$$

where G is Newton's gravitational constant, Λ is the cosmological constant, $k = \{-1, 0, 1\}$ denotes negative, flat, or positive spatial curvature (and ρ and p are the density and pressure of matter and radiation sources, respectively).[4] For ordinary matter and radiation, the scale factor $R \to 0$ at a finite time in the past. At this point, $\rho \to \infty$. This indicates that the early universe is hot and dense near the initial singularity, with subsequent evolution leading to expansion, and cooling and diluting of mass-energy. Given the additional assumption of spatial flatness ($k = 0$), this spacetime setting provides a very simple background on which to calculate reaction rates for different particle phenomena, where temperature and the mean free path for particles determine equilibration rates. S. Weinberg (1977) wrote a popular book called "The First Three Minutes" detailing this reconstruction of key events in the early universe, including nucleosynthesis and the relative abundance of hydrogen and helium, as well as speculations further back into physics discussed below. By the late 1970s, Weinberg remarks that,

> it is in the early universe, especially the first hundredth of a second, that the problems of the theory of elementary particles come together with the problems of cosmology. Above all, this is a good time to write about the early universe. In just the last decade a detailed theory of the course of events in the early universe has become widely accepted as a 'standard model'. (p. 9)

Cosmology had quickly become an empirical science, amenable to methods of particle physics and yielding explanations and predictions for large-scale observations in the universe. At the same time, there was a worry about pushing simple big bang models further back into the early universe.[5] On the one hand, the initial singularity was thought to be a sign of the breakdown of FLRW models, and some suspected the singularity was an artifact of the highly degree of symmetry. Singularity theorems, like those proven by Penrose and Hawking in the 1960s, showed that singularities are generic in GR, and not an artifact of idealized models (Hawking and Ellis 1973). Given the seeming simplicity of the early universe, theorists were then concerned with ways to avoid the initial FLRW singularity. In particular, physicists like Sakharov (1966) and Gliner (1966) argued that quantum corrections to GR imply that hot, dense quantum matter might behave rather differently than a classical perfect fluid, leading to novel physics that might counteract gravitational collapse near the singularity. Further work by Zel'dovich (1967; 1968) and Gliner (1970) suggested that the right way to resolve the big bang singularity was to think of a phase transition occurring in the early universe, where geometry moved from a classical description to a quantum description, or where matter transitioned to having radically different properties. No convincing mechanism was postulated for these transitions, but phenomenological models were constructed strictly from the side of cosmology.

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[4] See Smeenk and Ellis (2017) for an introduction to the philosophy of cosmology.

[5] The short summary given here is condensed from a wonderful account of the development of inflation from the side of general relativity (Smeenk 2005). One goal of this paper is to fill in some of the details of that analysis from the side of particle physics.

Thus, in the early 1970s, cosmology was in a state where quantum physics—in particular particle physics—had direct relevance for explaining phenomena in the early universe. Quantitative predictions could be made about the history of the universe by combining the two, and there was a suggestive possibility that something like a phase transition could resolve the initial singularity of cosmological models. It is natural that physicists quickly looked to particle physics for a mechanism for phase transitions.

3 The birth of early universe cosmology

In the mid-1970s, multiple lines of research into gauge theories resulted in a consensus that particle physics methods could be extended far back into the early universe. A central focus of this work was the idea that SSB in QFT could be a temporal process in the early universe, resulting in phase transitions from highly symmetric, simple states to those of broken symmetry and separate forces we see today. These ideas would be central to the development of models of inflation, and to problems like the cosmological constant problem that would dominate particle physics in the 1980s. I outline here some of the key developments in the mid-1970s that lead to the "discovery" of QFT phase transitions in the early universe. All of these are made possible by the earlier discovery of the uniformity of the CMB, which provides a simple, symmetric global spacetime structure on which to easily set finite temperature effects for QFT.

The major developments that I will focus on are: Sec. 3.1 the discovery that models of particle physics with SSB can have the symmetry restored at high temperatures; Sec. 3.2 the increased sophistication of functional methods in QFT, and the explicit relations between fully quantum quantities and those more familiar from perturbative QFT; and Sec. 3.3 the use of equilibrium finite-temperature field theory on a cosmological scale to tie the phase transitions in gauge theory to the large-scale evolution of the universe. In Sec. 3.4 I briefly summarize some other, more well-known developments in the context of grand unified theories (GUTs) and the renormalization group. These are both of importance, but especially the history of renormalization group methods are covered extensively elsewhere (D. Fraser 2020; J. D. Fraser 2021; Koberinski and D. Fraser 2023).

3.1 Spontaneous symmetry restoration

The discovery of spontaneous symmetry breaking (SSB) as a mass-generation mechanism is one of the major developments in articulating and understanding the representational capacity of relativistic QFTs. SSB plays a central role in generating gauge boson masses in Weinberg and Salam's electroweak unification model, and ensuring its renormalizability. The philosophical import of SSB in particle physics is interesting, and has been extensively studied elsewhere (e.g., Brown and Cao 1991; Earman 2004; D. Fraser and Koberinski 2016). We pick up the story here with the details necessary to discuss the idea of restoration of spontaneously broken symmetries.

By the mid-1970s, SSB was well-established as a mass-generating mechanism for the weak gauge bosons. The development started from analogies with superconductivity; the formal analogies between particle physics and condensed matter physics led to fruitful cross-fertilization of ideas throughout the development of the Standard Model (D. Fraser and Koberinski 2016; D. Fraser 2020). By the early 1970s, the analogy led to the successful construction of a candidate electroweak unification model (S. Weinberg 1967; Salam 1968), though several key disanalogies remained between the Higgs mechanism and superconductivity. In particular, it was not clear how to think of an external temperature parameter fitting into the Higgs mechanism, such that a phase transition could actually occur in the world. Despite the loose suggestions that high-energy collisions would restore the broken symmetry, it was unclear if something like a phase transition ever occurred in our universe. Introducing temperature into the electroweak theory was not a straightforward task: temperature is not a relativistic invariant, and even fixing a reference frame, finite-temperature quantities defined in the usual way were not gauge invariant. At this point, it was an open question whether one could model the electroweak SSB as actually occurring in some region of the universe as energy or temperature decreased.

Based on extending the formal analogy between the Ginzburg-Landau model of superconductivity and the gauge boson sector of the electroweak Lagrangian, Kirzhnits and Linde (1972) simply posit that the order parameter for a toy model—the vacuum expectation value a scalar field with Higgs-like potential—has a temperature dependence of the same form as the Ginzburg-Landau model:

$$\sigma^2(T) = \sigma^2(0) - qT, \tag{3}$$

where $\sigma = \sqrt{2}\langle\varphi\rangle$ is the order parameter and φ is the toy scalar. More will be said on this in Sec. 3.3. Importantly, this toy model considers a spontaneously broken global symmetry, rather than a broken gauge symmetry. The result, however, is suggestive of a more generally applicable formalism for restoration of a spontaneously broken symmetry.[6] While this was a qualitative result, it was suggestive of the possibility of symmetry restoration at high-temperatures. Coupled to the observations of a uniform CMB from cosmology suggesting the continued applicability of FLRW-style spacetimes to the early universe, Kirzhnits and Linde suggest a possibility for cosmological relevance as well. Perhaps, in the expansion and cooling of the universe after the big bang, the universe underwent a phase transition from electroweak symmetry to a broken symmetry. If so, they estimate the critical temperature to be $T_C \sim 10^3 GeV$, about $10^{-12} s$ after the big bang.

Further, while there was consensus that the electroweak Lagrangian proposed by Weinberg and Salam was qualitatively correct, it was not taken very seriously as a detailed model for the Higgs sector. It was widely assumed that the Higgs mechanism involving a fundamental scalar was a schematic or toy model of a more realistic form of SSB, and that the true mass-generation mechanism would lead to further new physics, such as a composite Higgs or other new particles. S. Weinberg (1974b) himself was unhappy with his proposed Lagrangian, claiming that the true unifying gauge group should be simple, and attempts were made to work out possible observable differences between the SU(2)$\times$U(1) symmetry breaking and symmetry breaking with other gauge groups. As we will see below, the type of phase transition that would occur, and the resulting low-energy observables like the weak mixing angle θ_w would differ depending on the specific gauge group. So, provided one could propose a mechanism for symmetry breaking and restoration, one could in principle adjudicate between different types of electroweak SSB by looking at low-energy residual effects. At this point, the work of Kirzhnits and Linde was merely suggestive that further pursuit of analogies with superconductivity might lead to fruitful discoveries in particle physics.

3.2 Development of functional methods and the effective potential

Another important source of analogies with condensed matter physics, related to the presence of SSB, was the use of the effective action formalism, that developed further into more general background field methods. Standard uses of relativistic field theory in the early 1960s treated quantized perturbations about the overall lowest energy state—the vacuum. The vacuum was assumed to be the state left invariant by all spacetime and dynamical symmetries in the model. In practice, this meant that the vacuum was assumed to be the unique, Poincaré invariant state in which all observables had expectation value zero. Perturbative QFT was dominant as well, where the field theory was treated as approximately free, with a small interaction coupling treated as a perturbation to the free solution. Drawing on inspiration from condensed matter physics, but cast in the language of relativistic quantum field theory, people like Jona-Lasinio (1964) brought more general methods over to particle physics, able to treat a wider variety of situations. In condensed matter physics, methods from quantum field theory were routinely used, with the caveat that the ground state around which one was quantizing was not necessarily a lowest energy, symmetry invariant state. These generalizations were important for SSB and the introduction of temperature into QFT.

Early uses of functional methods in QFT involved borrowing the concept of a partition function Z from condensed matter physics. Standard approximation techniques included the saddle point approximation, where an integral of the form

$$Z = \int \mathcal{D}\phi \exp\left(-iS[\phi] + J\phi\right) \tag{4}$$

is approximated to leading order by its value where the action $S[\phi]$ attains its minimum and the resulting Gaussian integral that results from expanding

$$S[\phi] \sim S[\phi_{min}] + \frac{1}{2}\frac{\partial^2 S}{\partial\phi^2}(\phi - \phi_{min})^2. \tag{5}$$

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[6] The simplification here makes a big difference. It was known that there were qualitative differences between local and global SSB; the Higgs mechanism depends on the breakdown of a local gauge symmetry to avoid the presence of Goldstone bosons. So this result, while suggestive, needed to be worked out in detail. The details follow in Sec. 3.3.

In principle, this allows for a situation in which the background field ϕ_{min} differs from the vacuum, and is not a symmetry invariant state. However, this is still limited to small deviations from the classical solution, such that quantities are treated perurbatively. With the advent of Goldstone's theorem and the Higgs mechanism, more sophisticated general methods for understanding SSB in the QFT context were being developed. Jona-Lasinio (1964)—building on the early functional methods of Schwinger (1951)—found an analogue of the free energy to be the generator of connected time-ordered Green's functions $W(J) = -i \log Z(J)$. In modern notation, one performs a Legendre transformation

$$\Gamma[\phi] = W(J(\phi)) - \int dx J(\phi)\phi(x), \tag{6}$$

giving the effective action $\Gamma(\phi)$ now as a functional of the fields.[7] Variation of Γ with respect to the source term J gives the vacuum expectation value $\langle \phi_{min} \rangle$ of the minimum value of the field. One can then expand the effective action about this semiclassical vacuum state, giving an exact form of Γ in terms of the 1-particle irreducible Green's functions $\Gamma^{(n)}(x_1, \ldots, x_n)$:

$$\Gamma[\phi_{min}] = \sum_n \frac{1}{n!} \int d^4x_1 \cdots d^4x_n \Gamma^{(n)}(x_1, \ldots, x_n)\phi_{min}(x_1) \cdots \phi_{min}(x_n). \tag{7}$$

This formalism is very powerful for understanding a fully quantum treatment of SSB, as one can manifestly see the symmetries of the effective action, even if the ground state expectation value does not fully respect those symmetries. The effective action encodes a fully quantum treatment of the field theory, since the perturbative expansion is in terms of the 1-particle irreducible Green's functions. Compare this to what is usually called perturbative QFT, which only allows one to explore the neighbourhood of theory space close to classical free field theories. There, perturbative expansions are in powers of the coupling constant and $\hbar$; additional terms in the expansion may qualitatively alter the structure of the theory.[8] From the perspective of perturbative QFT, which was still the dominant paradigm in the early 1970s, the effective action was unfamiliar and difficult to use for calculation. Work on finite-temperature field theory tended to reformulate the effective action into a perturbative expression for an effective potential. The functional formulation of the effective action in Eq. (7) is a complicated expression giving an exact form of the fully quantum action. Similar to the LSZ reduction formula, it is a powerful conceptual tool for understanding key physical features of QFTs. The effective action is particularly useful for highlighting qualitative features of the full quantum treatment, in particular for determining the symmetry structure, but in the form of Eq. (7) has little direct connection to quantities familiar from perturbative QFT. Thus it takes almost a decade for functional methods to take over, as the shift beyond pertuabative QFT permeates within the field.

Even without the direct use of the effective action formalism, it was becoming clear in the early 1970s that features of a perturbative QFT apparent at the classical tree-level could be drastically changed, both quantitatively and qualitatively, when considering quantum corrections. The term "effective" was used to modify classical quantities like mass, potential, and eventually action to include these quantum corrections. One important step in merging this new understanding with the functional formalism was the Coleman and E. Weinberg (1973) model, which was a toy model of massless scalar electrodynamics. In this model, there is no SSB at the classical tree-level, but SSB is induced by radiative corrections, leading to a model with a massive vector boson and massive scalar boson. Unlike the Higgs mechanism, for which SSB is present at the classical level, it is only through analysis of the higher-order quantum corrections that the massless bosons are found to acquire mass. The importance of this model is that it reinforces the need for a fully quantum treatment of symmetries and symmetry breaking in QFT. Starting with the semiclassical approximation for SSB, the symmetry properties of the full QFT are not immediately apparent. Instead, one needs functional methods for which one can see both the semiclassical vacua and the quantum corrections. Luckily, a slight tweaking of the functional methods developed by Jona-Lasinio makes this explicit.

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[7] For notational convenience, I suppress the spacetime arguments for the fields ϕ. Once we get to the alternative expansion for Γ in Eq. (8), the spacetime argument disappears because we have assumed ϕ_{min} is constant.

[8] In this paper, I reserve the term "perturbative" to refer to quantities calculated within perturbative QFT. While this may be potentially confusing, since for example, Eq. (7) may be thought of as a perturbative expansion as well, I will call such quantities power series instead. A perturbative expansion is a perturbation to a free, classical theory, and is often calculated as a similar power series (or asymptotic expansion) in powers of the coupling. I thank an anonymous reviewer for suggestions to clarify this usage.

Taking the effective action, and expanding in powers of the momentum rather than in powers of ϕ_{min},[9] one gets an (exact) expression of an expansion of the form:

$$\Gamma = \int d^4x \left[-V(\phi_{min}) + \frac{1}{2}(\partial_\mu \phi_{min})^2 F(\phi_{min}) + \cdots \right], \tag{8}$$

with $V(\phi_{min})$ an ordinary function, called the effective potential, F a function determined by the form of the theory, and other higher-order terms in higher powers of the momentum. When the effective potential can be defined, it provides an important conceptual tool for understanding how quantum corrections alter the qualitative structure of the theory. This non-perturbative characterization in terms of an effective potential allows one to more directly compare perturbative QFT calculations as corrections to the classically interpretable, tree-level action. One can think of the effective potential as the classical potential, plus *all* quantum corrections; this can be approximated to a given loop order in perturbation theory.

For the Coleman-Weinberg model, they find that, at tree order, the effective potential—which is just the classical potential—has a minimum at the classical fields $\phi_{min} = 0$, so that the theory has no SSB at this level of approximation. When all one-loop diagrams are included as a first approximation to the true $V(\phi_{min})$, however, the symmetry is broken, leading to a theory of a massive boson (instead of the photon) interacting with a massive scalar meson.

This work by Coleman and Weinberg was an important step to understanding symmetry restoration, and an important paper for the widespread uptake of the effective action functional formalism. The transformed expansion of the effective action into terms that characterize the effective potential is a key step in the uptake and usefulness of the functional formalism, as it allows one to directly compare fully quantum relations that hold exactly with quantities that are calculated using perturbative QFT, and that have a clear classical interpretation. With it, one can see each successive loop order as additional quantum corrections to the classical quantity. The original formulation due to Jona-Lasinio and Schwinger lacks this direct connection.

A major insight of this work, picked up in subsequent work and combined with finite-temperature methods, is the idea that "corrections" to the classical form of physically significant quantities can be significant enough to qualitatively change the physics. In the Coleman-Weinberg model quantum corrections at loop order spontaneously break the gauge symmetry, which is seen by examining the shape of the effective potential. With the increased sophistication of finite-temperature field theory, we also see qualitative changes to the effective potential with increasing temperature. Seeds are planted here for the idea that QFTs can change drastically under different conditions, a key insight for the development of EFT.

3.3 Equilibrium finite-temperature field theory

By the 1970s, it had long been known that one could perform a formal trick to turn a relativistic QFT into an equilibrium thermal field theory at a single time. The partition function for a quantum system fluctuating about thermal equilibrium and the partition function for a relativistic quantum field system are formally analogous, if one makes the following substitutions: 1) replace i times the time variable in the relativistic case with temperature, $-it \to \beta$; 2) replace the single vacuum expectation value with a sum over a basis of thermal states at temperature $T = 1/k_B\beta$. This leads to a shift from Hamiltonian evolution to a Boltzmann weighted sum of thermal basis states, which can be interpreted as a thermal partition function, $Z = \mathrm{Tr}[exp(-\beta\hat{H})]$, up to normalization constant. The key insight is that the same change is made on the path-integral used to calculate expectation values, turning the path-integral into a Euclidean integral, with periodic boundary conditions on the $-it$ variable, integrated over the inverse temperature:

$$\begin{aligned} Z &= \mathrm{Tr} e^{-\beta\hat{H}} \qquad (9)\\ &= \sum_a \langle\phi_a| e^{-\beta\hat{H}} |\phi_a\rangle, \qquad (10)\\ &= \int \mathcal{D}\pi \int_{periodic} \mathcal{D}\phi \exp\left[\int_0^\beta d\tau \int d^3x \left(i\pi\frac{\partial\phi}{\partial\tau} - H(\pi,\phi)\right)\right]. \qquad (11) \end{aligned}$$

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[9] To do this, one must assume that the classical minimum ϕ_{min} is translationally invariant: $\phi_{min}(x) = \phi_{min}$. This is a plausible assumption for SSB, where the new minimum defines a metastable vacuum state.

In the second line, $\{\phi_a\}$ are a complete set of basis states, and in the the path integral, π is the conjugate field to ϕ, $\tau = -it$, and periodic boundary conditions are imposed to ensure that one is performing a trace.[10] What is gained is the ability to calculate thermal expectation values about equilibrium states in QFT. What is lost is a way to calculate time evolution in this formalism. While the thermal n-point functions themselves may still involve time, this imaginary time formalism lacks the resources for calculating temporal evolution explicitly, since the time parameter in the path integral has been repurposed.

In some sense this technique leads to a generalization of vacuum QFT, but in another sense it is also a restricted technique since dynamical evolution can no longer be explicitly calculated.[11] Further, temperature is not a relativistically invariant quantity, so a reference frame is fixed. When time is not an important parameter to track, one can use this formal change to calculate expectation values for quantum field theories in thermal equilibrium.[12] These simplifications are well-suited to describing the early universe as described by the big bang model, where there is a privileged global notion of cosmic time and one can approximate the universe as being in thermal equilibrium as it adiabatically expands.

As first used heuristically by Kirzhnits and Linde (1972) and described in Sec. 3.1, one can use this clever transformation to motivate a further analogy between the Ginzburg-Landau model of superconductivity and the form of the Higgs potential, and roughly estimate the temperature at which an electroweak phase transition might occur, restoring the $\mathrm{SU}(2) \times \mathrm{U}(1)$ symmetry. This order of magnitude prediction was based largely on extending the analogy between SSB in particle physics and condensed matter physics by simply inputting T by hand into a toy SSB model with global phase symmetry. Nevertheless, it was suggestive that the electroweak $\mathrm{SU}(2) \times \mathrm{U}(1)$ symmetry corresponded to a "true symmetry" in nature, and that a phase transition might occur in the early universe. The calculation was carried out perturbatively at tree-level, and the work of Coleman and E. Weinberg (1973) showed that quantum corrections to the effective action could alter the effective potential as well. A more-developed, gauge-invariant finite-temperature field theory treatment was needed to understand the structure of electroweak symmetry breaking.

This work was taken up in a series of papers prepared together, shortly after the Coleman and Weinberg result. The final papers were all published in 1974 together in Physical Review D (Bernard 1974; Dolan and Jackiw 1974; S. Weinberg 1974a). The authors were sharing progress during regular meetings, and all cite each others' work in the finished drafts. The motivation given by all is to extend the suggestive analysis of Kirzhnits and Linde to find a more realistic, quantitative analysis of spontaneous symmetry restoration for gauge theories, using functional methods and the effective action formalism.

First, Bernard (1974) provides a method for writing Feynman rules for gauge theories at finite temperature. The ordinary form of the finite-temperature partition function, $\mathrm{Tr}[exp(-\beta\hat{H})]$ is a gauge-variant quantity, and therefore thought to be unphysical. The argument is relatively straightforward: in some gauges, unphysical degrees of freedom appear in the Hamiltonian. Taking the trace, i.e., summing over all states, therefore involves summing over unphysical degrees of freedom in that gauge. Other gauges avoid this, and so the trace is gauge-dependent. The original heuristic arguments of Kirzhnits and Linde used models without gauge degrees of freedom, where the original partition function is therefore trivially gauge-invariant.

Bernard provides a general ansatz for the form of the finite-temperature partition function, motivated by determining the partition function the usual way in some fixed gauge with only the correct number of physical degrees of freedom. He argues that this general form will be a gauge-invariant quantity, and that it tracks the true finite-temperature partition function Z, even for a gauge choice for which $Z \neq \mathrm{Tr}[exp(-\beta\hat{H})]$. Thus, one now has a reliable functional form for the partition function at finite-temperature, from which

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[10] In a formal sense at least, vacuum quantum field theory is the $T = 0$ limit of single-time finite-temperature field theory, as taking $T \to 0$ corresponds to $\beta \to \infty$, thereby integrating over the full range of the (imaginary) time variable. If we take the basis states to be eigenstates of the Hamiltonian, then only the $a = 0$ state survives in this limit, corresponding the the vacuum state.

[11] As I will discuss further below in Sec. 4.1, this is an instance of what M. Wilson (2017) calls physics avoidance, switching from an evolutionary modelling strategy to an equilibrium, steady state strategy. While it is possible (though often challenging in practice) to analytically continue the quantities from imaginary time to real time, what results are real-time expressions for quantities calculated in or near equilibrium. From there, dynamical evolution within the real-time formalism can proceed, using the features calculated on the basis of equilibrium (for example, the spectral function may be generalized beyond equilibrium to calculate dynamical transport properties). I thank an anonymous reviewer for clarifying this point.

[12] Later developments in finite-temperature field theory generalize this formalism to non-equilibrium cases, using two-time generating functionals to allow for explicit representation of time in the formalism. This formalism is much more complicated, and is used only in limited situations in particle physics, though it is more widespread in condensed matter (e.g., Fradkin 2013 provides a sample textbook account). These modern treatments are outside the scope of this paper.

to derive Feynman rules. This is a further elaboration of the functional methods that lead to the effective action and effective potential, with a shifted focus on finite-temperature effects.

Dolan and Jackiw (1974) provide the next paper in the series, and provide a more detailed calculation of the critical temperature for a gauge theory, refining the results of Kirzhnits and Linde. They systematically set out the functional form of the effective action and effective potential at finite temperatures, and argue that symmetry restoration does not occur in dynamical symmetry breaking—i.e., when the symmetry is broken in the full quantum theory, but not at tree level.[13] This paper provides a key step forward, and shows that the earlier estimates of a critical temperature based on a global symmetry restoration were qualitatively correct. Importantly, the discussion of dynamical symmetry breaking would have implications for models of electroweak symmetry breaking; if a complete version of the Higgs mechanism had a dynamical mechanism for symmetry breaking, then there would be no electroweak phase transition in the early universe. Thus understanding the form of the phase transition (if any) would have implications for how to complete the Higgs sector of the Standard Model.

S. Weinberg's (1974) paper is largely complementary to Dolan and Jackiw's, using an operator formalism instead of functional methods and Feynman graphs. He tracks symmetry breaking for both gauge and global symmetries, finding that the order parameter for both is the effective bare mass of the scalar bosons in each model. An important conceptual step here is Weinberg's analysis of the temperature and energy dependence of effective terms in a Lagrangian; these parameters are not fundamental, but instead indexed to some particular set of external parameters like temperature. This has implications for EFT, as I will discuss below. Weinberg also finds that temperature effects can break a symmetry that is present at $T = 0$, and discusses the possibility of observing a phase transition or assessing a finite temperature broken symmetry in a gauge theory. Since the order parameter is gauge-variant, one needs a proxy observable to mark whether the symmetry is present or broken. Additionally, S-matrix elements do not exist at finite temperature, so the ordinary methods of vacuum particle physics do not lead to finding particle masses as poles in the Green's functions for the theory. Weinberg suggests that observables could be built from the partition function on a case-by-case basis, where the overall requirement is that the observables be built from Green's functions carrying zero energies and moderate momenta.

Like Kirzhnits and Linde before him, Weinberg mentions potential cosmological implications of this work, now more justified due to the more complete formulation of equilibrium finite-temperature field theory. Given the increased plausibility of FLRW big bang models from observations of the CMB, the early universe provides a globally privileged reference frame in which to define an approximate but spatially global temperature, and an extrapolation backwards to hotter, denser conditions, an ideal setting for finite-temperature field theory. Given the strong suggestion that a spontaneously broken gauge theory would have the symmetry restored above some critical temperature, one would expect to extrapolate backwards to a time in the early universe where the electroweak symmetry was restored. This would have profound effects on early universe dynamics, and potential observable consequences today. One interesting point, in analogy with first-order phase transitions in condensed matter physics, is the possibility of distinct domains in the universe, where symmetry breaking in distinct regions results in settling into different "vacuum" states. Think of an iron bar, whose magnetization after cooling is set in different directions in different spatial regions of the bar. Depending on the details of how an electroweak phase transition might occur (i.e., whether it is a first or second order phase transition) it is possible that symmetry breaking could also result in domains of different broken symmetry vacuua within the same universe. S. Weinberg (1974b) picks up on the relationship between models of electroweak symmetry breaking and possible implications for the early universe in a review article published the same year.

One interesting thread underlying this collection of papers is the view that our current best quantum field theories and our treatment of them are incomplete, effective descriptions in some way. First, we start with the fact that a fully quantum treatment of a given QFT can reveal qualitatively new features not present at tree level. This does not lead to the conclusion that our theories themselves are incomplete, but instead that standard perturbative treatments using the operator formalism might miss important qualitative features of the full theory. The use of the effective action formalism allowed for a more complete computation of the effective potential including all quantum corrections, as well as other effective quantities like mass, understood as order parameters for symmetry breaking. At this level, the qualitative changes are counterfactual, since

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[13] So the Coleman-Weinberg model discussed above, in which quantum corrections without temperature break the symmetry, would not undergo symmetry restoration at higher temperatures.

the full theory contains all orders of quantum "corrections" to the tree-level description. Nevertheless, there is a sense is which the details are not manifest at tree-level, and caution should therefore reign in interpreting QFTs given solely their classical Lagrangian form.

The subsequent move to finite-temperature, using the same functional methods, leads to a form of effective mass, potential, and action that is strictly an extension of the original vacuum QFT. This further leads to a reinterpretation of the effective quantities, since they are now functions of temperature. The qualitative changes in the shape of the potential or the effective mass are now *actual* changes, rather than counterfactual changes. The fact that a field theory can undergo qualitative changes at different temperatures—and therefore different energies—is a key piece of the shift to an effective field theory view that happens by the end of the 1970s. Another key ingredient, discussed below, is the idea of a new, more unified theory becoming a better description of physics at those high energies.

Given the possibility that an electroweak phase transition might or might not have happened in the early universe, physicists were inspired to try to work out the details of a more realistic Higgs mechanism for the electroweak theory. The development of realistic finite-temperature methods was a first step to establishing the plausibility of such a phase transition, but more details were desired. As used in Weinberg's original electroweak unification model, the Higgs mechanism is the simplest possible mechanism that leads to SSB. There is motivation to "fill out" the Higgs sector of the Standard Model with a more complete theory, either providing some form of dynamical mechanism for SSB (D. Fraser and Koberinski 2016, Sec.6), or by further unifying the forces in grand unified theories. The possibility of observing residual effects from electroweak symmetry breaking in the early universe would place constraints on the types of models allowed, and the range of parameter values (like the Higgs mass, weak mixing angle, etc.).

Kirzhnits and Linde (1976) pick up on this thread, and provide a relatively systematic overview of the relationship between parameter values and types of symmetry breaking in gauge theories. They find that the types of symmetry breaking allowed by Higgs-like mechanisms are split, depending on the relationships between parameter values in the model. Of key importance is the value of the Higgs mass, which at best could only be estimated at the time. The parameter values in the electroweak model had not yet been tightly constrained by collider experiments, and therefore open questions remained about the nature of the phase transition. One could work backwards, and place constraints on parameter values from observing remnants of a phase transition in the early universe. For example, a first-order phase transition could lead to domain walls where different vacuua meet. Thus, cosmological observations could come to bear on filling out the Standard Model, leading to a growth in interest in early universe particle physics. As S. Weinberg (1974b) writes, upon symmetry restoration at high-temperatures,

> W and Z intermediate bosons become massless, like the photon[...] The leading effect for weak coupling and high temperature is a change in the effective bare scalar mass; the phase transition occurs when this mass vanishes. This may provide some sort of answer to the question discussed in Sec. III; whether a spontaneously broken gauge symmetry should be regarded as a true symmetry. (p. 274)

What does he mean by a "true symmetry"? In the referenced Sec. III, Weinberg considers possible arguments against the claim that SSB for a local gauge theory is simply a formal trick to write down a unitary, renormalizable Lagrangian for massive vector bosons, and finds them inconclusive. If SSB is simply a formal mechanism for mass generation, but the symmetry is never displayed in nature, then for Weinberg it is not a true symmetry. At zero-temperature, there is no way to restore the broken symmetry, and therefore no way to tell whether the symmetry actually exists in nature, indicating that it is not a true symmetry. But with the developments leading to a more sophisticated equilibrium finite-temperature field theory, there are at least in principle observations that could detect remnants or effects from the breaking of electroweak symmetry in the early universe as it expands and cools. Establishing that an electroweak phase transition actually occurred in the evolution of the universe would, for Weinberg, establish the electroweak symmetry as a true symmetry.

3.4 Grand unified theories, early universe particle physics, and the renormalization group

The final ingredients for early universe particle physics focus on the idea of the Standard Model as an effective field theory, and the prospect of using the early universe as a laboratory for beyond standard model physics. A key aspect to the development of effective field theory is the work by Kenneth Wilson and others on the renormalization group for particle physics (K. G. Wilson 1971; K. G. Wilson and Kogut 1974). This side of the development is already well-studied, and is therefore not the focus of this paper. I will elaborate only as much as is needed to fill in the details here; see J. D. Fraser (2021), D. Fraser (2020), and Koberinski and D. Fraser (2023) for historical and philosophical accounts of the renormalization group methods in QFT. The renormalization group provides a systematic, internal mechanism for understanding how a given QFT changes at different energy scales. In particular, terms in a theory's Lagrangian will change magnitude at different energy scales: terms that get larger at lower (higher) energy scales are IR (UV) *relevant*, terms that get smaller at lower (higher) energy scales are IR (UV) *irrelevant*, and terms whose magnitude remains approximately constant are *marginal*. For understanding early universe particle physics, the renormalization group provides another mechanism for exploring the high-energy—and therefore high-temperature—properties of a theory while treating it as a closed system. Finite-temperature field theory, by contrast, treats the theory as an open system coupled to a heat bath; qualitative agreement between the two provides convergent evidence from different modelling assumptions that one is getting at the real structure of the theory. The renormalization group formalism also underwrites the effective field theory worldview: a given (renormalizable) Lagrangian provides a sort of universal low energy description of physics compatible with many different possible high-energy successor theories. One should also treat a given set of fields and symmetries as an appropriate description of physics indexed to an energy scale; far beyond that scale the description will break down, requiring an increasing number of nonrenormalizable terms.

Beyond the renormalization group scaling properties, other theoretical developments contributed to thinking of the Standard Model as an effective field theory, to be replaced by something more fundamental at higher energies or earlier epochs in the universe. One key aspect is the development of grand unified theories (GUTs), which were supposed to further unify the strong and electroweak forces. While the details of how this works from the point of view of renormalization group scaling differ from that of GUTs, they both point toward the idea that the Standard Model will have to be replaced in the high-energy regime. Georgi and Glashow (1974) hypothesized that a unified field theory would describe physics at a grand unified energy scale; an energy scale at which the electroweak couplings—which increase with increasing energy—would match the strength of the strong coupling—which decreases with increasing energy. The original GUT was an SU(5) gauge theory, with a single gauge coupling α, whose energy scale sat around 10^{15} GeV. This scale was estimated from extrapolating the β functions for the strong and electroweak couplings and finding the energy at which they all approximately intersect.

Developments in GUT compliment the advances in finite-temperature field theory, pointing to the idea of further symmetry restoration at the GUT energy scale, such that the early universe goes through successive phase transitions of increasingly broken symmetry. At high energies (equivalently high temperatures), one expects the GUT symmetry to be restored in a similar fashion to the electroweak symmetry, and the three forces to be unified into one. The SU(5) gauge group was thought to be an elegant choice as it was the smallest simple group that contained SU(3), SU(2), and U(1) as subgroups. Similarly to the way that electroweak symmetry restoration would result in qualitative changes to, e.g., W and Z boson behaviour, restoration of the grand unified symmetry would lead to qualitative changes to all three forces. From a theoretical standpoint, GUT provided an elegant unification of the forces, an explanation for electric charge quantization, and made predictions for the value of the weak mixing angle and the instability of the proton. S. Weinberg (1974b) notes that the GUT proposal makes concrete the idea that all forces are unified into a single simple gauge group, and notes that GUTs of a realistic form predict a very low rate of baryon number nonconservation. One should therefore expect to see proton decay, and to calculate the decay rate, which is related to the energy scale at which the GUT symmetry breaks. This began an experimental search for proton decay, which has yet to be found. So far, the lower bound for the proton half-life is on the order of 10^{34} years (Bajc et al. 2016). We know now that GUTs are largely empirically disfavoured, due to null results like the failure to detect proton decay placing too high an upper bound on the scale of symmetry breaking. At the time, however, they seemed a promising step towards further unification of the forces, and methodologically in line with the developments in the Standard Model.

Importantly for the development of early universe particle physics and effective field theory, the original GUT proposal also provided a concrete model of a high-energy successor to the Standard Model, whose predictions were approximated by the Standard Model as an effective theory. One can think of GUT as providing a top-down motivation for viewing the Standard Model as an effective field theory, while finite-temperature field theory provided a complimentary bottom-up motivation. With the developments of finite-temperature field theory, the relevance for this effective field theory relationship in the early universe is that, at some point above the electroweak unification scale but below the GUT scale, the Standard Model will cease to be a good description of the phenomena. Either the full GUT would need to take over, or more nonrenormalizable terms would need to be added to the Standard Model effective field theory in order to capture the phenomena. This continues the pattern of early universe epochs dominated by higher-energy physics as one gets closer to the big bang, suggesting a hierarchy of increasingly unified theories. The GUT proposal inspired continued work on understanding phase transitions in the early universe, as working out the cosmological implications of particle physics seemed to be one of the best ways of testing the high-energy regimes of QFTs. The GUT framework also provided motivation for Kirzhnits and Linde's (1976) systematic exploration of symmetry breaking in gauge theories, leading to a classification of the types of symmetry breaking possible in QFT. Motivated by the idea that there is a hierarchy of QFTs at higher energies, characterized by greater internal symmetries, they provide a general classification of SSB in particle physics. After detailing the ways in which parameter values, external fields, and fermion number affect the qualitative and quantitative features of phase transitions in relativistic QFT, they end with some direct cosmological implications for understanding phase transitions in the early universe. Of particular interest for later developments in early universe particle physics is the idea of a shift in global vacuum energy during a phase transition. They argue that the separation of the energy-momentum of a QFT with scalar field into a "vacuum" term[14]—a scalar condensate—and a term describing the effective excitations to the vacuum-plus-condensate changes with SSB.

> In the theories without spontaneous symmetry breaking such a division is fixed once and forever. In our case the characteristics of the vacuum state are temperature-dependent[...] We should emphasize that we are not dealing with small corrections to the substance energy: The density of energy released due to the condensate formation is comparable with the substance energy density at the point of the phase transition[...] From the point of view of general relativity the division [...] corresponds to the representation of the total energy-momentum tensor as a sum of the energy-momentum tensor of substance and of the cosmological term. (Kirzhnits and Linde 1976 pp. 225-7)

Thus, phase transitions in the early universe might alter the qualitative evolution by introducing a temperature-dependent shift in the cosmological constant term in the Einstein field equations. By this stage, foundational work on early universe particle physics is overlapping with foundational work on singularity resolution in cosmology (Smeenk 2005). As briefly discussed in Sec. 2.2, physicists had been looking for some sort of mechanism to provide a phase transition as one got closer to the big bang, in an attempt to resolve the initial singularity of FLRW solutions. The work on early universe particle physics seems to provide a tempting convergence, with the hope that some quantum phase transition will lead to a new phase in the very early universe where the classical GR evolution can no longer be extrapolated back. The convergence of ideas and overlap starts a new community of researchers, working on GUTs, phase transitions, and their cosmological implications for new physics in the early universe. Linde (1979) provides a comprehensive overview of the theoretical work done in this new field by the end of the 1970s, which is quickly proceeded by inflation as a mechanism to generate flat, homogeneous spacetimes from supposedly generic initial conditions (Guth 1981; Starobinsky 1980). Indeed, Linde is widely recognized as one of the originators of the inflationary paradigm, for his work in this formative era of early universe particle physics.

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[14] Kirzhnits and Linde repeatedly refer to the temperature-dependent ground state of the theory as the vacuum state of the theory. Note that this terminology is non-standard in contemporary finite-temperature field theory. That the lowest energy state at finite temperature is a thermal equilibrium state—and not a vacuum state—is important for the phenomenology of finite-temperature field theory. In particular, ordinary S-matrix elements are not well-defined in thermal states, since the idealization of treating scattering particles as asymptotically free breaks down.

4 Analysis

Before the Standard Model was even settled, the mid-1970s saw the birth of a new field of particle physics extending well beyond energies plausibly accessible by particle colliders. Early universe particle physics owes its existence to the development of theoretical extensions—equilibrium finite-temperature field theory—and tools—effective action, effective potential, and background field methods—to examine phase transitions in QFTs at high energy. There are a few key conceptual aspects of this development that I will highlight here. First, in Sec. 4.1, the understanding from cosmology that the early universe was highly symmetric plays a key role in creating a simplified system for modelling phase transitions. Despite the supposed incompatibility of QFT and general relativity, the early universe provides an ideal system for integrated modelling involving considerations from thermodynamics, QFT and, cosmology. Next, an important step for developing finite-temperature field theory was the further elaboration of suggestive analogies between SSB in particle physics and in condensed matter physics. I discuss the role of analogies and disanalogies between these two domains, and how further analogies are used to motivate and justify equilibrium finite-temperature field theory in Sec. 4.2. Finally, in Sec. 4.3 I bring attention to the role that early universe particle physics played in the rise of the effective field theory worldview. Though less impactful than the well-studied role of the renormalization group formalism, I note here some complementary developments that encouraged viewing our most well-established QFTs as indexed to some energy scale and ultimately replaced by a more fundamental QFT at higher energies.

4.1 Integrated modelling in the early universe

Early universe particle physics is a first step towards a form of unification between three major pillars at the frontiers of physics: QFT, general relativity, and thermal physics. However, this is not the sort of unification that often gets discussed in philosophy of physics, or even philosophy of science more broadly. Two important features are at play in the development of early universe particle physics, neither of which are the standard unification through a more fundamental theory of wider scope. Classic examples of standard unification include Newton's unifying terrestrial and celestial mechanics into a single theory, Maxwell's unification of electricity and magnetism, and Einstein's unification of special relativity and gravity. In early universe particle physics, we instead get an integrated model that requires input and justification from distinct theories, and a combination of restriction and extension of QFT to include thermal effects. Both share important features with unification that do not focus strictly on constructing more fundamental theories.

In the development of new, unifying theories, a first step is identifying domains where one expects the initially distinct theories to all be relevant to an adequate model of the phenomena in that domain. One can think of this as finding a system that lies in the overlapping boundaries of the theories. It is well-known that modelling phenomena requires far more than derivation from theory; simplifications, idealizations, approximations, empirical input, and input from other disciplines is often required (Morgan and Morrison 1999) Despite the claims one often hears that general relativity and QFT are inconsistent with one another, a sort of unification by integration can occur in the domains where both overlap. In the case of modelling phase transitions in the early universe, we see an early success in integrated modelling. Inverting expectations that input from multiple, incompatible theories would complicate the modelling process, the early universe ends up being a highly simple domain. Complex techniques of finite temperature condensed matter physics are greatly simplified due to: the simplicity of the spacetime structure of the early universe; the ability to use the scale factor as a proxy for time, justifying the use of the simpler imaginary time equilibrium formalism for QFT; and the large separation of relevant timescales (for expansion, equilibration, and particle dynamics) that further justify treating the early universe as an adiabatically evolving equilibrium system. The simplifying assumptions are inputs from GR and QFT that allow the "inconsistencies" between each framework to wash out, and to allow for a simple thermal treatment in this domain, allowing physicists to construct models of phenomena. This is a clear case, in the quantum realm, of what M. Wilson (2017) has dubbed "physics avoidance" for classical modelling of systems. In particular, this is a clear example of moving from an evolutionary modelling strategy to an equilibrium modelling strategy (Ch. 2), justifying the move with background knowledge of the spacetime structure of the early universe. The physics avoidance here involves switching from methods for calculating dynamical evolution equations to those for calculating fluctuations about an equilibrium state.[15] Whether or not the end goal of theoretical unification plays out, this sort of integrated modelling is an important enterprise in science in its own right.

After the discovery of the CMB, and its uniformity, physicists were emboldened to apply simple FLRW cosmological models back into the early universe. Extrapolating backwards, the universe gets denser and hotter back toward an initial singularity. Modelling the large-scale degrees of freedom for the early universe therefore requires at least some input from particle physics and general relativity, with consideration paid to thermal effects. As matter density increases, one might generically expect both quantum effects of matter and spacetime curvature to become increasingly relevant. At the level of general theory, unifying these three disciplines might appear to be an insurmountable task. Luckily, the early universe is simply a system to be modelled; one need not have a coherent theory unifying the three domains to model a given system. Instead, we can focus on integration.

Philosophical accounts of modelling complex systems have focused on the ways that models mediate between abstract theory and the world. Though often informed by theories, models can obtain a degree of autonomy and function independently of a given theory. In many cases, a complex system is modelled with input from different, even incompatible theories. Batterman (2001; 2021) has explored this extensively in the context of mesoscale modelling in physics, where lower-level discrete theories of condensed matter systems must meet in the middle with phenomenological models of the same systems as continua. Similar issues arise in climate models and astrophysical models, where for the latter general relativity, chemistry, particle physics, and hydrodynamics must all be integrated to model complex particle dynamics in things like galaxy formation and supernovae (Abelson 2022). The idea that *complex* systems often require input from distinct, sometimes incompatible theories is not new, though perhaps unfamiliar in instances of purportedly fundamental physics. Interestingly, the emergence of early universe particle physics can be cast in terms of model integration, *despite* the fact that the early universe was thought to be an incredibly simple system! In fact, I will argue that it is *because of* the simplicity of the early universe that such modelling integration could take place.

There are distinct difficulties in developing a fully relativistic finite-temperature field theory, and in constructing a realistic QFT on arbitrarily curved spacetimes, but these difficulties wash out in the context of the early universe. In the general case, one can neglect spacetime curvature effects, or backreaction effects of relativistic quantum matter on the spacetime geometry when one is concerned only with the effects of local physics. But problems can occur here when one extrapolates from local physics to larger (cosmological) scales (Bianchi and Rovelli 2010; Koberinski and Smeenk 2023), since these effects may no longer be negligible for larger distance and timescales. This is especially pressing for SSB, where in principle different, incompatible vacua may emerge in different local regions. The CMB convinced physicists that the hot big bang model—based on highly symmetric FLRW solutions to the Einstein field equations—was a good extrapolation back into the early universe, so many of these difficulties of QFT on curved spacetimes are simply irrelevant to understanding particle physics in this regime. At a given time, spatial hypersurfaces have constant curvature, allowing for the straightforward definition of states and fields that implicitly relies on global spacetime structure. Further, comoving coordinates that grow (slowly) with the scale factor define a natural notion of cosmic time, allowing for an approximate notion of equilibrium and temperature on each time slice. In the simplest case (and one that has since been vindicated as most applicable to our universe) the spatial geometry at each time is flat, allowing for a standard Euclidean space on which to define the QFT. While the theory must still be relativistically invariant, the highly symmetric global spacetime structure allows one to define an equilibrium QFT for one frame, and uncontroversially apply it to the early universe as a whole. Different, but similarly helpful simplifications occur when doing QFT on black hole spacetimes, where the high degree of symmetry greatly simplifies the calculations. From these two examples, one might argue that the best windows into unifying QFT and GR actually allow for easy integration through simplification of the spacetime dynamics.

By admitting a global privileged reference frame in which to define a QFT, the early universe also simplifies the introduction of thermal physics into the formalism. There are two major barriers to a fully relativistic finite-temperature field theory. First, temperature is a reference frame relative concept, so field theory at

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[15] Time-ordered vacuum expectation values calculated via the perturbative QFT formalism involving path integrals are connected to dynamical evolution via the LSZ reduction formula, which relates them to direct transition amplitudes for asymptotically free input and output states. As previously mentioned, at finite-temperature one cannot define an S-matrix, and so this connection is severed here.

finite temperature is a local generalization of QFT usable for specific instances, rather that a complete generalization of the framework.[16] This is not a problem for local uses where we have an unambiguous reference frame in which to define temperature, but it does become an issue when trying to extrapolate from local to global in generic solutions to the Einstein field equations. Second, the simple transition from vacuum QFT to finite-temperature—replacing $-it \to \beta$—only allows for calculation in the special case of equilibrium for finite-temperature field theory. Transition amplitudes are limited to fluctuations around equilibrium, and one cannot treat temporal evolution within this framework. Developments in the real-time or two-time formalism for finite-temperature field theory came after this period, but did not yet exist in a developed form. Both of these issues are dissolved in the context of the early universe, where again there is a unique privileged reference frame that applies globally, and a natural external clock variable that is inversely correlated to the temperature. The expansion rate serves as an external, near adiabatic process of monotonic decrease in temperature. Again, we see that the discovery of the highly uniform CMB was essential in justifying the extension of equilibrium finite-temperature field theory formalism to large-scale descriptions of the early universe. Thus the applicability of FLRW spacetimes in the early universe provides justification for the simplifications needed to integrate gravitational, particle, and thermal physics. Here, the system removes many of the complicating features of both formalisms that make them notoriously difficult to unify at the level of "pure" theory.

The form of unification is an extension of QFT to thermal domains, under the restriction of an equilibrium modelling strategy. This is a more familiar type of unification, at the level of formalism rather than in the context of modelling a system. But it is not a unification by subsuming distinct theories into a single, more fundamental formalism. Instead, it is a first step toward opening (relativistic) QFT to broader applications, by both restricting and expanding the formalism. Standard formulations of QFT that were successfully used in the late 1960s and early 1970s revolved around the formalism developed by Feynman, using the path integral to calculate transitions from one set of free particle states to another. This evolutionary formalism utilizes the interaction picture and the vacuum state as central concepts, and is best suited to understanding particle scattering. While this was the ideal formalism to predict outcomes of collider experiments, it is ill-suited to settings like the hot, dense early universe. As we know now, Hilbert space representations in QFT can be constructed by picking a privileged state, and defining the action of operators on the state. For different choices of state, one will in general be led to unitarily inequivalent representations. If we think of the QFT as strictly greater than a single Hilbert space representation, then the formalism of scattering amplitudes built out of the vacuum state is only a small part of the representational capacity of a QFT (Ruetsche 2011). The development and elaboration of equilibrium finite-temperature field theory discussed above is a step into this new space of possible representations. It marks both an expansion of the framework of QFT, and a restriction of applicability when a particular model and thermal state are chosen. Rather than defining the theory as manifestly Lorentz invariant and building states from the vacuum state, we instead choose a reference frame and consider a thermal equilibrium state as the foundational state. The development of functional methods, gauge-invariant analogues of the partition function, and analyses of temperature effects on the qualitative features of a given QFT were steps to elaborate and fill out this sector of QFT, in order to apply it to new phenomena. The main system of interest at this time was the early universe, including the large-scale qualitative effects that come with decreasing temperature after the big bang. But this formalism goes beyond modelling this one system, as other phenomena (e.g., heavy ion collisions and particle interactions in stars) were later modelled using finite-temperature field theory. In a sense, thermal physics was unified into QFT, leading to an expanded domain for QFT and a broader range of representational capacities.

These nonstandard, partial unifications—integrated modelling of the early universe and the new framework of finite-temperature field theory—led to predictions of a new phenomenon of a phase transition in the early universe. Different signatures of a phase transition—domain walls, a changing cosmological constant, particle asymmetries—would indicate different types of phase transitions to fill out the details of the electroweak domain of the Standard Model, and possibly extend the latter through GUTs. In some completions—i.e., dynamical symmetry breaking—the phase transition would not occur at all. So even a failure to observe remnants of a transition would help fill in details of the Higgs sector, and potentially fill out the analogy with phase transitions in condensed matter physics. The unification started with a key insight

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[16] Chua (2022) provides a good argument for why a relativistic generalization of temperature cannot unambiguously extend the concept.

from Kirzhnits and Linde (1972) of extending the analogy between SSB in particle physics with that in condensed matter physics, with subsequent work undertaken to fill out the analogy in different ways. From today's vantage point, how tight is that analogy, and should it be used to help interpret finite-temperature field theory?

4.2 Finite-temperature field theory and analogies with condensed matter physics

Kirzhnits and Linde (1972; 1976) were explicit in their motivation for exploring the possibility of phase transitions in particle physics. Given the success of analogies between condensed matter physics and particle physics in developing SSB and the Higgs mechanism, they wanted to further extend the analogy by seeing if SSB (and symmetry restoration) in particle physics was a process that could happen in time, and in particular as temperatures cross a critical value.[17] To what extent were they successful in tightening the analogy, and what should we make of it? As a heuristic in the process of discovering new features of the formalism, the work of extending the analogy was clearly fruitful, as it was the first step in the development of early universe particle physics as a subdiscipline. In this respect, there is ample evidence that pursuing analogies between condensed matter physics and particle physics has been a great strategy for developing both disciplines. But what does this analogy tell us about the physics of each discipline? Does the success of analogical reasoning have implications for interpreting our theories? Or should we engage in ontological analysis of a theory independently of the means by which it was constructed?

Analogical reasoning in science has recently re-emerged as a focus in philosophy (Dardashti, Thébault, and Winsberg 2017; Crowther, Linnemann, and Wüthrich 2021; D. Fraser 2022). Intuitively, analogical reasoning involves finding a source domain that shares some set of features in common with the target domain under study. Given that some features are shared between source and target, analogical reasoning is supposed to provide some level of support that the target shares some further feature(s) of interest with the source. Much of the literature has followed Hesse (1966) in categorizing analogical mappings as *horizontal relations*—analogical relations between objects in the source and target domains—or *vertical relations*—analogical relations between the (causal, mathematical, formal) relations in each of the source and target domains. Many of the general accounts of analogy turn on assessing when an analogy is justified, and how much support an analogical argument should lend to its conclusion. A plausible account of success is that a successful analogical argument must be grounded in there being a real physical similarity between the target and source, instead of only formal similarities in the theories used to model them (Bartha 2010). Spelling out exactly what this means leads to many of the different views found in the literature, but there is some sense in which physical similarity between source and target domain is often thought to be necessary to justify an analogical argument in science.

However, Fraser has argued extensively that purely formal analogies can—and have—played an important role in the development of modern physics, especially in the mutual development of condensed matter physics and QFT (D. Fraser 2020; D. Fraser 2022). In D. Fraser and Koberinski (2016), in particular, they argue that the analogies between SSB in superconductivity and the Higgs mechanism are purely formal, and that this is nevertheless a successful analogical argument due to the wide applicability of the field theory formalism. But the story outlined above goes beyond the analysis of that paper; in particular, the consensus in early universe particle physics is that an electroweak phase transition *actually* occurred in our universe, which seems to extend the physical analogy between superconductivity and the Higgs mechanism. Does this mean that the analogy turns out to be physical? I claim that this sort of framing breaks down in this case. There are both physical *and* formal aspects to the analogies relevant here. What is important to take away from this episode is that the development of finite-temperature field theory establishes that SSB can model phase transitions in both QFT and condensed matter physics, but that this higher degree of physical analogy does not license a wholesale carryover of interpretation from condensed matter physics to QFT. Important physical disanalogies in general remain.

Following D. Fraser (2022), let an analogy be physical if at least one of the horizontal relations is a physical similarity *or* if the vertical relations are of the same physical type (e.g., causal). Let an analogy be formal if at least one of the horizontal relations is a formal similarity *or* if the vertical relations are

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[17] Here, I follow the common usage in the philosophical literature, and restrict the term "QFT" to high-energy, relativistic particle physics. For my purposes here, this helps to disambiguate the theories and disciplines of high-energy and condensed matter physics.

of the same formal type (e.g., mathematical). By this definition, the distinction between physical and formal analogy is not mutually exclusive; an analogy can be both physical *and* formal. This should not be surprising in physics, given the high degree of abstraction and mathematization that is found. Often, physical relationships are suggested by or inferred from mathematical relationships. Rather than trying to classify the overall relationship between SSB in QFT and condensed matter physics as formal or physical, we should then look at individual analogical relationships.

As argued in D. Fraser and Koberinski (2016), there are strong formal analogies between SSB in superconductivity and in the Higgs mechanism. The analogy is strongest with the phenomenological Ginzburg-Landau model and the simple Abelian Higgs model, but the analogies generalize well when the latter is taken to the non-Abelian case. But when the Higgs mechanism is treated in the evolutionary modelling strategy as part of a vacuum sector QFT with manifest Lorentz covariance, the analogy is purely formal. Indeed, as Fraser and Koberinski argue, the analogy between the Ginzburg-Landau model and the Higgs mechanism involves two phenomenological models, so the potential for physical analogy there is already rather slim. What changes in the initial work of Kirzhnits and Linde (1972) is a self-conscious attempt to extend the analogy between the Ginzburg-Landau model and a simplified version of the Higgs mechanism, by inserting temperature in the latter. Initially, there is no temperature analogue in the Higgs mechanism, so the inclusion of temperature in this toy model tightens the analogy. Temperature plays the same role on both sides of the analogy, making this a physical analogy; the horizontal relation is between the same physical quantity. The important step in furthering this analogy is putting the Higgs mechanism (or a simplified analogue) into the same equilibrium representation as the Ginzburg-Landau model. The developments using functional methods by Bernard (1974), Dolan and Jackiw (1974), and S. Weinberg (1974a) help to fill out the physical analogy, such that non-Abelian gauge theories also can also include temperature. Therefore, the development of (equilibrium) finite-temperature field theory extends the physical analogy between (a sector of) QFT and condensed matter physics. The analogy is now *both* physical *and* formal, as defined above.

When we start thinking about the possibility of a large-scale phase transition in the early universe, either from the electroweak sector or the GUT sector, then one of the major physical disanalogies mentioned by Fraser and Koberinski becomes a physical analogy. In particular, for at least some systems described by QFT (e.g., the early universe) SSB is a temporal process. However, up to the stage of development of finite-temperature field theory discussed here, this analogy can only by made convincing in the context of modelling the early universe. The analogy was not present at the level of theory, between a given interaction in QFT and condensed matter physics, but the case of the early universe provides convincing evidence to justify the physical analogy and to identify a novel phenomenon for particle physics. This further motivates the continued development of finite-temperature field theory to establish the analogy at the theory level.

As already mentioned, one step in the development of finite-temperature field theory was the shift to modelling systems in QFT as timeless, equilibrium systems, born out of necessity, since the imaginary time formalism repurposes the time variable in the path integral. Earman (2003) notes that "as long as the system of interest is closed, there is no temporal evolution involved in spontaneous symmetry breaking in QFT since every physically relevant state is asymmetric with respect to the symmetry of the Lagrangian" (p. 337). It is therefore a necessary step to shift to an open perspective on QFT to allow for the possibility of SSB as a temporal process. This is done for equilibrium finite-temperature field theory by shifting to a particular reference frame, allowing for an introduction of temperature, and removing dependence on the time variable. Instead, we deal with systems at thermal equilibrium and have a notion of external control; we can act on the system by changing the temperature. Instead of temporal evolution, we have adiabatic evolution with respect to temperature. How, then, can one establish that a phase transition is possible as a temporal process, or that the qualitative features relative to a given reference frame will hold globally?

This is where it is essential that the physics being modelled simplifies when applied to the early universe. For flat big bang models in particular, the applicability of equilibrium finite-temperature field theory is straightforward. In these models, space at an instant is Euclidean, so no curvature effects need to be taken into account. Further, time and temperature are inversely correlated quantities, so monotonically increasing time "after" the big bang corresponds to monotonically decreasing temperature. The expansion parameter acts as the external control in an open system perspective, since expansion occurs in time, driving a decrease in temperature. This corresponds to temporal evolution for the early universe, thus establishing that phase transitions in time can occur in both domains.

However, establishing that an early universe phase transition can happen in time does not thereby establish a full physical analogy with the underlying BCS model of superconductivity. The closest analogy is still between the Higgs mechanism and the Ginzburg-Landau model. As discussed in Sec. 4 of D. Fraser and Koberinski (2016), there are significant physical disanalogies between BCS and Higgs, even when the latter is generalized to finite temperatures. For the BCS model, SSB is marked by the presence of Cooper pairs, which are bound states of electrons that interact via phonon exchange. Formally, there is no analogue for the Cooper pairs in the Higgs mechanism, as the proper analogue of the Higgs boson is a much later discovered Anderson-Bogoliubov collective mode (Anderson 2015), which fits the analogy by being related to the order parameter in BCS. Historically, attempts were made to make the Higgs mechanism a dynamical mechanism by similarly describing the Higgs boson as a bound pair of other fermions—either as a quark composite or via introduction of a new technicolor interaction (D. Fraser and Koberinski 2016, Sec. 6). These models failed, indicating that—at least at our present state of knowledge—there is no relevant analogy between the Higgs boson and Cooper pairs within the respective setups of SSB, either formal or physical. The idea that the phase transition is a dynamical process is also subtle, and worth pausing on. In one important and obvious sense, establishing that a particle physics system could evolve from a state of electroweak symmetry to one where that symmetry is broken shows that the process is dynamical. In this sense, SSB in the early universe is a dynamical process. However, there is a more technical contrast class that is often referred to in the physics literature, between SSB and dynamical symmetry breaking. Dynamical symmetry breaking is a particular form of SSB, where the broken symmetry arises at an emergent level of description. The order parameter is still a scalar field, but this field is an emergent composite of more fundamental fields. For non-dynamical SSB, the scalar field is taken to be fundamental. Given the failure of attempts to construct a composite Higgs model, our best evidence then suggests that the Higgs mechanism is SSB, while superconductivity arises from dynamical symmetry breaking. Here again is another disanalogy between the domains. Further, as argued by Dolan and Jackiw (1974), dynamical symmetry breaking of this type for particle physics would imply the *lack* of a phase transition in the early universe.[18] So even if a convincing model of dynamical symmetry breaking underlying the Higgs mechanism were constructed, it would serve to break the analogy that phase transitions occur in both. We should think of the analogy between the two domains as having relevant disanalogies as well, this being one of them.

While finite-temperature field theory extends the analogy of SSB between particle physics and condensed matter physics, it does so in subtle ways. Historically, the ability to simplify the theoretical description in the early universe was essential to extending the analogy. While significant physical disanalogies still exist at a more abstract level of formalism, the development of finite-temperature field theory established phase transitions as a further physical process shared between the Higgs mechanism and superconductivity. Thinking about modelling particular systems also allows one to adopt an open systems, equilibrium perspective on the early universe, removing the requirement of explicit time dependence in the finite-temperature description. The analogy with superconductivity is still best suited to the formal Ginzburg-Landau model. So this is a messy case, where both physical *and* formal analogies play an important role. I submit that attempts to classify the overall analogy as formal or physical are missing the more interesting points of complex intertheoretic relationships that actually matter to the progress of physics.

4.3 The rise of effective field theory

Much of the recent literature in the philosophy of particle physics has been focused on the novel features of effective field theories (EFTs) and how they challenge traditional ideas of theory structure, and whether they should be counted as theories, models, or something in between (Rosaler and Harlander 2019; Williams 2019; Franklin 2020; Wallace 2022; Bechtle et al. 2022; Koberinski and D. Fraser 2023). The history of effective field theories has also been the focus of recent work, with more of a focus on the development of renormalization group methods as the key conceptual development (J. D. Fraser 2021; Rivat 2021). While this is clearly correct, it is not the whole story. I want to highlight the underappreciated role that early universe particle physics also played in shifting perspective to thinking of the Standard Model as an effective field theory. First, I will discuss the important conceptual role played by the effective action and effective potential as an illustration of evolving understanding of the structure of QFTs. I will then argue that this

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[18] At least for the class of dynamical symmetry breaking models "based on renormalizable field theory" (p. 3340). Dolan and Jackiw state that their argument does not apply to cutoff theories, and so this might not extend in general to EFTs as understood today.

evolving understanding fits well with the EFT perspective that the Standard Model is an effective theory suited to low energy scales relative to the GUT scale or other scales relevant in the very early universe.

As first elaborated by Jona-Lasinio (1964) for the context of SSB in particle physics, the effective action Γ was simply a more complicated transformation of the generating functional Z defined using the classical action. The advantage of the effective action was that it provided a nonperturbative expression that ensures the principle of least action holds, and is the generator of one-particle irreducible Green's functions. Thus it gives an exact expression for the fully quantum form of a given interaction, when starting with the classical Lagrangian density. Rather than calculating perturbative quantum corrections to the classical expression order-by-order in the theory's coupling constant, one had an expression that captured the full quantum treatment. The power of such an approach is that even approximations to the full effective action respect the full set of quantum symmetries, which was important for understanding symmetry breaking and restoration at finite temperatures. When first introduced, however, the term "effective" action simply meant that it was the QFT analogue of the formalism for determining dynamics through the least action principle (Schwinger 1951). The quantity is the fully quantum analog of the classical action; it plays the same functional role. The term "effective" does not yet have any relationship to the eventual EFT program.

This changes slightly with the Coleman and E. Weinberg (1973) paper. They make explicit that, using the effective action, one can show that theories without SSB at the classical level may have an induced SSB due to the quantum corrections, and vice versa. The effective action is rewritten to express an effective potential term, and later generalizations include things like the effective mass, where "effective" is again signifying the functional role played by these quantities. These new quantities are introduced to build a bridge back to familiar concepts from the classical action and its perturbative corrections. The "effective" labels here start to take on a meaning that these quantities are the exact form of generalizations of the classical quantities that would otherwise be taken to be defined only up to a given order in perturbation theory. The effective potential is the potential that a particle "sees", and in general depends on energy scale. The terms are labelled "effective" since they are what would count as the true quantities under appropriate field redefinitions, and are related to the classical quantities via perturbative QFT (Coleman and E. Weinberg 1973, Sec. 2).[19]

The generalization of the effective action (and related effective quantities) to include temperature-dependence leads to an important shift in perspective, which is accompanied by the shift to an equilibrium, open-system perspective. By making the effective potential, effective mass, etc. functions of temperature (equivalent to functions of energy scale) the quantities instantly become provisional and indexed explicitly to a background energy scale, set by external considerations. Unlike the renormalization group treatment there are no additional terms in the Lagrangian for the theory, as one is still working with a strictly renormalizable interaction. However, the effective action now has an additional independent parameter, allowing one to explore how models can undergo qualitative changes as temperature (or energy) is increased.

This idea of theories changing qualitatively at higher energies—particularly the prospect of symmetry restoration—found a concrete realization in the GUT proposal for a unification of all three forces in the Standard Model. This was a concurrent, complimentary step in understanding the Standard Model as an effective field theory. Not only do higher energies lead to qualitative changes in the physics described by the Standard Model, but the proposal was that, beyond some threshold, an entirely new theory would describe the unified interactions. Thus the Standard Model was effective in that it would *break down* as a description of particle physics. This is one step closer to the understanding of EFTs we have today. Having a candidate successor theory makes it easier to see the Standard Model as an EFT constructed from the top-down (Koberinski and D. Fraser 2023). While the actual relationships between an EFT and its successor require renormalization group techniques to spell out, one can plausibly arrive at some of the key qualitative features of the EFT perspective just by focusing on phase transitions in the early universe.

An important historical lesson here is that the EFT perspective on the Standard Model was taking shape before the Standard Model was even complete. This has been argued for by Rivat (2021) in the context of understanding Wilson's work on the renormalization group, and I think the case of early universe particle

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[19] This use of "effective" is slightly different from the sense of effective renormalized parameters in perturbative QFT. The perturbative expansions used in perturbative QFT are differnt from the fully quantum power series definitons of functional quantities. The insight of Coleman and Weinberg was to compare the two, and relate effective functional quantities to effective renormalized quantities. I thank an anonymous reviewer for pressing me on this point.

physics strengthens the claim.[20] The reasons given for taking the Standard Model as provisional differ from those given today, but both share the idea that a new theory of particle interactions will be necessary at higher energies. Of the work considered in this paper S. Weinberg (1974b) and Kirzhnits and Linde (1976) are the most explicit in stating this proto-EFT view, the latter especially drawn to the idea of a GUT as providing a top-down justification for the EFT perspective.

5 Conclusions

The development of early universe particle physics resulted from combined progress in functional methods for QFT, generalizations to finite-temperature, and through the pursuit of analogies with phase transitions in condensed matter physics. Concurrent developments involving further unification in the form of GUTs and the use of renormalization group methods helped create the effective field theory view of the Standard Model. By having a concrete candidate for a successor theory, it was easier to see the Standard Model as a merely effective description of physics, valid within a certain energy regime. The setting of the early universe provided a specific modelling situation in which energies would be high enough for successor theories to dominate. The resulting view of the early universe was one of cooling and phase transitions down to lower energy effective field theories. By the early 1980s, the mechanism of inflation was added to the picture, leading to a near consensus view of the evolution of the universe that survives to this day. While the specific proposal of GUT as the successor to the Standard Model did not pan out, the overall evolution remains largely unmodified.

This period is interesting philosophically in that it provides much of the standard foundational understanding of particle physics, cosmology, and the relationship between the two. We see the early universe emerge as a key system for integrating particle physics, gravity, and thermal physics into a single modelling framework. It also illustrates the fruitfulness of analogical reasoning in developing new formal tools, or in extending a theoretical framework to new domains. The context of concurrent creation of the Standard Model and of early universe particle physics is important for understanding the way that certain problems—the horizon and flatness problems (Guth 1981) and the cosmological constant problem (S. Weinberg 1989), among others—played a central role in theory construction and extension into the modern day. In particular, a common misconception about the nature of bare parameters in effective field theories may stem from thinking of something like a GUT as the true ultimate theory, whose bare parameters are hinted at by renormalization group flow from the Standard Model.

From this analysis, the natural next question is to understand further developments in finite-temperature field theory, generalizing beyond single-time, equilibrium formulations. It is worth investigating what (if any) new conceptual hurdles are introduced in two-time formalisms. It is also worth exploring the relationship between finite-temperature field theory and the open quantum system formalism. I leave this analysis for future work.

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[20] I disagree with some of the characterization of Wilson's work in Rivat's (2021) account, though I endorse this bigger picture conclusion. See D. Fraser (2020) and Koberinski (2021) for different accounts of Wilson's interpretation of his own work on the renormalization group.

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