Chapter 5
Spacetime as Described by EFT

5.1 Introduction

This chapter examines the idea of treating GR as an EFT, and, drawing from the ideas presented in the previous chapters (Chaps. 2–4), explores what we might learn of emergent spacetime through the framework of EFT. Examples of both top–down and bottom–up EFT are considered; the former case is represented by analogue models of (and for) gravity, which describe spacetime (an effective curved geometry, to be more precise) as emergent from a condensed-matter system at high-energy. Although they have only recently attracted philosophical interest,[1] analogue models of gravity based on EFTs have a long history dating from the earliest days of general relativity and are successful in replicating much general relativistic phenomena and QFT in curved space.[2]

The bottom–up approach to treating gravity as an EFT, on the other hand, starts with GR as the low energy theory and aims to calculate the quantum corrections to the theory from the unknown high-energy physics. The only real obstacle to treating GR as we do other QFTs has been the non-renormalisability of gravity, however, the new conceptualisation of QFT as EFT resolves this difficulty. As should be clear from the discussion of EFT in Sect. 3.6, the non-renormalisability of the gravitational couplings is not a problem in the low-energy regime experimentally accessible to us.

The success of these approaches suggests that the strong analogy between condensed matter physics and QFT naturally carries over to GR and cosmological phenomena. The analogy between condensed matter physics and QFT has usefully been employed in the past, and described as the "cross-fertilisation" of these disciplines

[1] See Bain (2008, 2013); Crowther (2013); Dardashti et al. (Forthcoming).

[2] See Barceló et al. (2011) for a review. The earliest instance the authors identify is Gordon's 1923 use of an effective gravitational metric field to mimic a dielectric medium. A later example is Unruh's "Experimental black hole radiation" (1981), which used an analogue model based on fluid flow to explore Hawking radiation from actual GR black holes. Barceló et al. (2011), p. 42 present this example as being the start of what they call the "modern era" of analogue models.

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(Nambu 2008). A well-known example of this is the idea of spontaneous symmetry breaking, as is the RG flow. It is tempting to move from the fact that both condensed matter physics and QFT can be described using the same theoretical apparatus to the conclusion that they share some other, more profound, physical similarities. Our desire to unify GR with the rest of fundamental physics, to treat gravity on par with the way we treat other fields, naturally leads us to attempt to incorporate it into the framework of QFT also. We are thus led toward an analogy between condensed matter physics and spacetime, one that is attractive given its potential to allow us insight into the universe at large by studying the universe at small.

I argue that this analogy, however, owes its strength to the physical underpinning of EFT and the power of the RG, which, in turn, place strict limitations on how much we are entitled to draw from it. As should be clear from the previous chapters, the different senses of emergence in EFT, mean that there is very little that ties the low-energy EFT to the high-energy theory that underlies it: most of the details of the micro-theory are not relevant, apart from some particular symmetries and interactions.

Hence, drawing too strong an analogy between condensed matter systems and spacetime, by carrying over superfluous details, is liable to be dangerous or misleading—we are entitled to commitment to only some theoretical structures, and should remain agnostic about the rest (Sect. 3.8). This accords with my previous argument, that we should understand EFT as effective—as being a pragmatic, heuristic way of speaking about the world. EFT allows us to make predictions at familiar scales without making assumptions about what happens at other scales.

As stated, it is tempting to take the analogy between condensed matter physics and QFT as support for strong physical claims. The most obvious of these is the assertion, already encountered, that spacetime breaks down at some scale. This is a mistake. Although analogue models make concrete the analogy between condensed matter physics and spacetime, they fail to motivate the claim that spacetime breaks down—in fact, these models do not even support the claim that GR is an EFT, for reasons that will become clear in Sect. 5.2.3.

Also, as already argued in Sect. 3.8 (and will be re-enforced by arguments in Chap. 6), an appeal to the analogy without reliance upon the analogue models will not help either. EFT counsels us to remain agnostic about the details of the high-energy physics. Our QFTs, understood in the framework of EFT, are not expected to hold to arbitrarily high-energies: they cease to be valid at some point, when the effects of unknown, high-energy physics become important. Although the breakdown of QFT in this sense may be the result of the breakdown of spacetime, it does not, on its own, motivate the claim that spacetime breaks down.

The recovery of GR in the domain where we know GR to be applicable is one of the only generally agreed-upon criteria of acceptability for a good quantum gravity proposal. In spite of this, the recovery of GR is no indication of a theory's truth—if GR is an EFT, the low-energy degrees of freedom will probably be able to be realised by any of a number of different systems. For this reason, trying to find a good candidate theory by working top–down toward known physics is possibly misguided. As other authors have recognised, the bottom–up approach is the better one, for pragmatic reasons, i.e. it is systematic and intended simply to produce testable results within experimentally accessible energy ranges (Georgi 1993; Hartmann 2001). The bottom–up approach from GR, described in Sect. 5.3, treats GR in the same way we treat other QFTs, attempting to quantify the higher-order corrections that result from neglected high-energy physics. The aim of the bottom–up approach is not to find an elegant high-energy theory underlying GR, but rather just to reproduce the predictions such a theory would make at low energy.

The structure of this chapter is as follows. In Sect. 5.2, I consider analogue models of spacetime as an example of the top–down approach to EFT. These models illustrate the conception of emergence in EFT outlined in the previous chapters. Interestingly, these models provide us with emergent spacetime, rather than emergent GR. I also argue that we should be wary of drawing too much from the analogy between condensed matter physics and QFT. In Sect. 5.3 I consider two different examples of the bottom–up approach to GR as an EFT. I again argue that, due to the conception of emergence suggested by EFT, we are restricted in how much we can draw from these theories. Finally, in Sect. 5.4 I outline the asymptotic safety scenario, which is an important conjecture that comes from treating GR in the same way we treat other QFTs. The suggestion, made by Weinberg (1979, 2009), is that the couplings for gravity approach a fixed point at high-energy, in a similar way to QCD.

5.2 Top–Down: Analogue Models of (and for) Gravity

Modern[3] analogue models of spacetime begin with a quantum fluid (such as a Bose–Einstein condensate) and use an EFT to describe the behaviour of the quasiparticles (phonons) that emerge as low-energy collective excitations when this system is probed with a small amount of energy. The simple conceptual picture is to imagine the quasiparticles "floating on top" of the underlying condensate (i.e. the quasiparticles possess additional degrees of freedom to the particles in the condensate). The quasiparticles are subject to an effective curved-space metric, meaning they behave as though they "exist in" curved spacetime, oblivious to the underlying (flat) surface of the condensate. As energy is increased, however, the quasiparticles eventually have short enough wavelength to "detect" the discrete particles of the condensate, and the EFT ceases to be valid.

Bain (2008) presents a simple example of relativistic spacetime emergent from a Bose–Einstein condensate (BEC) of particle density ρ and coherent phase θ. In constructing the analogue model, these variables are linearly expanded about their ground state values, $\rho = \rho_0 + \delta\rho$, $\theta = \theta_0 + \delta\theta$, where $\delta\rho$ and $\delta\theta$ represent fluctuations in density and phase above the ground state. These variables are then substituted into the Lagrangian describing the BEC, and the high-energy fluctuations are identified

[3] See Footnote 2.

and "integrated out" so that only the low-energy interactions are included in the theory. The result is, schematically, a sum of two terms:

$$\mathcal{L} = \mathcal{L}_0[\rho, \theta] + \mathcal{L}_{eff}[\delta\theta] \tag{5.1}$$

where $\mathcal{L}_0$ is the Lagrangian describing the ground state of the BEC and $\mathcal{L}_{eff}$ is the effective Lagrangian describing the low-energy fluctuations above the ground state. $\mathcal{L}_{eff}$ is formally identical to the Lagrangian that describes a massless scalar field in (3+1)-dimension spacetime, and the curved effective metric depends on the velocity, v_i of the underlying superfluid.

As Bain (2013) points out, given the substantial difference between $\mathcal{L}_0$ and $\mathcal{L}_{eff}$—the former being non-relativistic, the latter relativistic—we can treat the original Lagrangian and the effective Lagrangian as describing two different theories. The analogue models show us that emergent Lorentz invariance is incredibly easy to obtain from a variety of different systems; the high-energy theory is severely underdetermined. Barceló et al. (2001) have demonstrated that an effective curved spacetime is a generic feature of the linearisation process used in constructing the analogue models. All that is needed is a Lagrangian, $\mathcal{L}(\partial_\varphi, \varphi)$, depending on a single scalar field, $\varphi(t, \mathbf{x})$, and its first derivatives.

5.2.1 Gravity in Superfluid ^{3}He-A

Another interesting analogue model is Volovik's (2003, 2001) example in which gravity as well as the standard model of particle physics are emergent from superfluid helium 3-A.[4] Being fermions, the ^{3}He atoms must form pairs in order to condense as a BEC. These bosonic pairs are similar to the Cooper pairs of electrons described by the BCS model of superconductivity (Sects. 3.5.1 and 4.6), except that the ^{3}He Cooper pairs have additional spin and orbital angular momentum degrees of freedom, and this allows for a number of distinct superfluid phases.[5]

The non-superfluid ^{3}He liquid (and, at higher temperatures, gas) phase possesses all the symmetries possible of ordinary condensed matter systems: translational invariance, global $U(1)$ group, and two global $SO(3)$ symmetries, of spin and orbital angular momentum. Volovik (2003, p. 3) calls this $U(1) \times SO(3) \times SO(3)$ the analogue of the "Grand Unification" group (although, of course, the actual Grand Unification group in particle physics is supposed to be much larger). Decreasing the temperature, to the critical value, T_c (around 1 mK), results in the ^{3}He becoming superfluid. At this point, the analogue "Grand Unification" symmetry breaks,

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[4]Since here I am concerned with emergent spacetime, I will not Volovik's model's replication of the standard model in any detail.

[5]In particular, the A-phase of ^{3}He is characterised by pairs of ^{3}He atoms spinning about anti-parallel axes that are perpendicular to the plane of their orbit. See Volovik (2003) or the short review in Bain (2008).

and the only symmetry the system possesses is translational invariance (being a liquid). Decreasing the temperature even further, however (approaching 0 K), the ^{3}He acquires new symmetries, including an analogue of Lorentz invariance, local gauge invariance, and elements of general covariance.

Volovik (2003) explains that the appearance of these symmetries at low-energy owes to the *universality class* of the Fermi liquid, ^{3}He. At low-energy, *any* condensed matter system in this universality class will describe chiral (left- and right-handed) fermions as quasiparticles and gauge bosons as collective modes. The universality class is determined by the topology of the quasiparticle energy spectrum in momentum space, where the quasiparticle energy spectrum is obtained by diagonalising the Hamiltonian that describes the ^{3}He Cooper pairs. This Hamiltonian takes the schematic form,

$$H_{3_{\text{He-A}}} = \chi^\dagger \mathcal{H} \chi, \mathcal{H} = \sigma^b g_b(\mathbf{p}), b = 1, 2, 3 \tag{5.2}$$

where χ and $\chi^\dagger$ are non-relativistic 2-spinors that encode creation and annihilation operators for ^{3}He atoms, σ^b are Pauli matrices, and g_b are three-functions of momentum that encode the kinetic energy and interaction potential for $^3\text{He} - \text{A}$ Cooper pairs. Equation (5.2) is essentially the standard BCS Hamiltonian, but modified to account for the extra degrees of freedom of the ^{3}He Cooper pairs.[6]

The energy spectrum in momentum space vanishes at two points, known as *Fermi points*, which may be represented as, $p_i^{(a)}, i = 1, 2, 3, a = 1, 2$. The Fermi points arise via a symmetry-breaking process, and are stable features of the system in the sense that small perturbations will not remove them. Because the Fermi points define topologically-stable singularities in the one-particle Feynman propagator, $\mathcal{G} = (ip_0 - \mathcal{H})^{-1}$, their existence is protected by the topology. The quasiparticle energy spectrum is given by the poles in the propagator,

$$g^{\mu\nu} \left(p_\mu - p_\mu^{(a)}\right) \left(p_\nu - p_\nu^{(a)}\right) = 0 \tag{5.3}$$

where $g^{\mu\nu} = \eta^{bc} e_b^\mu e_c^\nu$ and $\eta^{bc} = \text{diag}(-1, 1, 1, 1)$.

While the existence of the Fermi points is insensitive to small perturbations of the system, however, their positions in the energy spectrum can change as a result of such perturbations. The positions of the Fermi points are given by the values of $p_\mu^{(a)}$. For a bosonic quasiparticle (a collective mode of the "fermionic vacuum" represented by the underlying ^{3}He system), the motion that shifts the position of the Fermi point corresponds to the gauge field $\mathbf{A}$. The small perturbation can also change the slope of the curve of the energy spectrum in momentum space, and this forms the metric tensor field, $g^{\mu\nu}$ (Volovik 2003, p. 100). The Lagrangian density corresponding to the energy spectrum (5.3) can be written as,

$$\mathcal{L}'_{3_{\text{He-A}}} = \bar{\Psi} \gamma^\mu (\partial_\mu - q^{(a)} A_\mu) \Psi \tag{5.4}$$

[6]For details see Volovik (2003, pp. 82, 96). This summary follows Bain (2008, pp. 309–311).

where $\gamma^\mu = g^{\mu\nu}(\sigma_\nu \otimes \sigma_3)$ are Dirac γ-matrices, the Ψ's are relativistic Dirac 4-spinors (constructed from the pairs of 2-spinors in (5.2)) and $q^{(a)}A_\mu = p_\mu^{(a)}$. This Lagrangian describes massless Dirac fermions interacting with a 4-vector potential A_μ in a curved Lorentzian spacetime with metric $g_{\mu\nu}$.

The topology of the energy spectrum (5.3) in momentum space determines a *universality class* that essentially characterises the type of EFT that describes the system at low-energy. As Volovik (pp. 99–100) explains, systems with elementary Fermi points (those with topological charge $N_3 = +1$ or $N_3 = -1$) have the remarkable property that Lorentz invariance always emerges at low-energy, even if the system itself is non-relativistic. Thus, in the vicinity of the Fermi point, the massless quasiparticles are always subject to $g_{\mu\nu}$. While the micro-details of the underlying system—for instance, the superfluid velocity and density—play a role in specifying the energy spectrum, these details are lost in the hydrodynamic limit where the EFT completely describes the low-energy physics. The EFT is characterised by the universality class, which itself depends only on symmetry and topology (Volovik 2003, p. 5).

Because of the universality of the low-energy theory, we are unable to reconstruct the micro-structure of the underlying condensed matter system from the low-energy collective modes (for example, we cannot reconstruct the atomic structure of a crystal from its low-energy acoustic waves because all crystals have similar acoustic waves describe by the same equations of the same EFT). Quantising the low-energy collective modes produces phonons, not atoms; in other words, the QFT produced by quantising the classical effective fields is still an EFT, and does not provide information on the high-energy theory, except for its symmetry class. What is important for $\mathcal{L}'$, describing the effective dynamics, as well as the low-energy properties and degrees of freedom, is not the details of the micro-physics, but only the symmetry and topology of the condensed matter system (Volovik 2003, pp. 6–7). This is essentially the example of superfluidity presented earlier (Sect. 4.6).

In order to produce the Einstein–Hilbert Lagrangian of GR, Volovik follows an approach similar to that of Sakharov's (1967) "induced gravity" proposal, in which the Lagrangian density (5.4) is expanded in small fluctuations in the effective metric $g_{\mu\nu}$ about the ground state and then the high-energy terms are integrated out. Unfortunately, in the case of the $^3\mathrm{He} - \mathrm{A}$ effective metric, the result contains higher-order terms dependent on the superfluid velocity, v_i, and these dominate the Einstein–Hilbert term. This is a consequence of the fact that the Fermi points arise from a spontaneously broken symmetry.

In order to reproduce the Einstein–Hilbert action, the effects of the broken symmetry must somehow be suppressed (Volovik 2003, pp. 8, 113). Because the superfluid velocity is inversely proportional to mass, Volovik (pp. 130–132) considers the limit in which the mass of the $^3\mathrm{He} - \mathrm{A}$ atoms goes to infinity, and thus $v_i \to 0$. In such a system the terms dependent on v_i are suppressed and the Einstein–Hilbert action recovered. Unfortunately, such a system does not represent a superfluid. Volovik thus states that the physical vacuum cannot be completely modelled by a superfluid—a conclusion reasserted by Bain (2008).

5.2.2 The Quantisation of Gravity

The major implication of spacetime emergent through EFT is that any attempt to construct a quantum theory of gravity by quantising some aspect of general relativity is mistaken.[7] If spacetime is emergent in this way, quantising it will not help us identify the fundamental (i.e. high-energy) degrees of freedom—by analogy, we would arrive at a theory of phonons rather than a description of the underlying atoms of the condensate. The typical sentiment is expressed by Visser,

> There is a possibility that spacetime itself is ultimately an emergent phenomenon, a near-universal "low-energy long-distance approximation", similar to the way in which fluid mechanics is the near-universal low-energy long-distance approximation to quantum molecular dynamics. If so, then direct attempts to quantize spacetime are misguided—at least as far as fundamental physics is concerned. In particular, this implies that we may have totally mis-identified the fundamental degrees of freedom that need to be quantized, and even the fundamental nature of the spacetime arena in which the physics takes place. (Visser 2008, p. 1)

If programs involving the quantisation of the metric tensor produce theories of particles analogous to phonons, then it is unsurprising that they should break down at high-energy. Their breakdown can motivate the search for a high-energy theory beyond GR, but we cannot say that the degrees of freedom of the high-energy theory would themselves need to be quantised in order to produce a theory of quantum gravity.

5.2.3 Analogue Models of Gravity?

Notice that the analogue models of gravity do not actually contain "gravity". These models produce an effective Lorentzian curved spacetime geometry, but not the Einstein field equations. For this reason, Barceló et al. (2001, p. 799) state that we have analogue models *of* general relativity rather than *for* general relativity. The conceptual picture we arrive at is an unusual one: we are used to obtaining the metric as a solution to the Einstein equations, which, in turn, are supposed to describe the dynamics of GR. Instead, in this picture we obtain the metric field as part of an EFT from an underlying condensate which itself defines an approximately flat (non-relativistic) spatiotemporal structure.

Although it sounds strange, it could perhaps be possible to effectively model a background independent theory (within a certain low-energy range) using a background dependent one (just as, for example, we are able to effectively model a discrete system at low-energy as a continuous one). What is important here is just that the emergent, low-energy physics is able to be treated independently of a background spacetime *in a particular low-energy regime*—meaning that, at low-energies, the

[7] Barceló et al. (2001), Hu (2009), Visser (2008), Volovik (2003).

theory appears background independent, but may be revealed as background dependent at higher-energy scales. There are some attempts along these lines, for instance Barcelo, Visser and Liberati's (2001) demonstration that something suggestive of an effective dynamics can be produced by the inclusion of one-loop quantum effects, along the lines of Sakharov's (1967) "induced gravity" proposal, and recent work by Sindoni et al. (2009), Sindoni (2011).

Bain (2008), however, argues that the analogue models fail to replicate not just the dynamical, but also the kinematical aspects of GR. The analogue models have Lorentzian spacetime emerge from a prior spacetime structure and depend, in some way, on the properties of the background structure (for instance, the velocity dependence of $\mathcal{L}_{eff}$ in (5.1)). Bain (p. 308) thus claims that insofar as general solutions to the Einstein equations are background independent, they will not be modelled effectively by analogue models that are background dependent. Bain does not explain specifically what idea of background independence he has in mind, but it is not obvious that the dependence of the effective theory on some aspect of the underlying system would preclude us from effectively modelling general solutions to the Einstein field equations.[8]

Further, Bain (2008, p. 308) claims that, to the extent that the Einstein equations are diffeomorphism invariant, they will not be modelled effectively by an analogue spacetime, insofar as the EFT of the latter is not diffeomorphism invariant. The background geometry of the condensed matter system provides a privileged coordinate frame, so it is natural to suspect that diffeomorphism invariance is not preserved. However, just as we could potentially model a background independent theory effectively, so too we could potentially model a diffeomorphism invariant theory effectively.

Barceló et al. (2011, p. 105) point out that active diffeomorphism invariance is maintained for a low-energy observer "within" the system, (i.e. an observer who can only perform low-energy experiments involving the propagation of the relativistic collective fields). Invariance under active diffeomorphisms is equivalent to the claim that there is no prior geometry, or that the prior geometry is undetectable. In this case the prior structure is undetectable to an internal observer, and so, in this sense, diffeomorphism invariance is effectively maintained at low-energy scales (even though, at high-energies, the theory is revealed as not diffeomorphism invariant).

One difficulty with interpreting the analogue models, however, is that if we are to accept that they give us emergent spacetime, we must identify spacetime with the Lorentzian metric structure. If we have some other conception of spacetime, for instance, an equivalence class of diffeomorphism invariant four-geometries, the analogue models fail to give us emergent spacetime.

[8]The idea of background independence is discussed further in the next chapter (Sect. 6.4).

5.2.4 Emergence

The sense in which the EFT describing spacetime in the analogue models is autonomous from the micro-theory of the condensed matter system is related to the conception of autonomy relevant to EFT more generally (Sect. 3.9); as is typical of EFT, the low-energy theory depends on very little of the high-energy theory, and so the high-energy theory is underdetermined by the low-energy physics. Furthermore, however, in models such as Volovik's $^3\text{He} - \text{A}$, it is only the symmetry and topology of the high-energy system that is important in determining the low-energy physics. These determine a universality class, and any system within this universality class will exemplify the same low-energy physics. For those models where this is the case, we can say that the EFT describing spacetime does not depend on the details of the high-energy theory at all.

The strength of the condensed matter approaches to quantum gravity is that they are able to demonstrate the limitations of any quantum gravity theory that conceives of GR as an EFT. As Volovik (2003, p. 7) states, because we are familiar with the condensed matter structure at many different scales (including the inter-atomic spacing, which is taken to be analogous to the Planck length in quantum gravity), the condensed matter approaches to quantum gravity may help indicate which quantities in quantum gravity are able to be calculated within EFT, and which quantities depend essentially on the details of the trans-Planckian physics.

Conceiving of these approaches heuristically, while remaining conscious of their limitations, accords with the philosophy of EFT more generally, as described in Sect. 3.8. In particular, we should be cautious in speaking of specific properties of BECs as though they are necessarily required for emergent spacetime. We are thus warned against following Hu (2005), for example, who is willing to bite the bullet and accept any "radical conclusions" that result from pushing the analogy between condensed matter physics and spacetime.[9] Instead, when we refer to the underlying "condensate" we should do so in a symbolic sense, taking it to refer to whatever (unknown) entity it is that possesses the relevant symmetries and mathematical structure.

5.3 Bottom–Up: GR as an EFT

The bottom–up approach to GR as an EFT is a highly pragmatic exercise. Instead of worrying about what happens at high-energies, people engaged in this program attempt to quantify the effects of the unknown physics upon GR at experimentally accessible energies. In this case, the EFT framework is embraced in the spirit described in Sect. 3.8—it is not in competition with those approaches to quantum

[9] These include considering the Planck temperature (1032 K) as "low temperature", given that BECs only exist at very low temperatures and spacetime is supposed to exist at this temperature in the early universe, for example.

gravity that seek a final theory or new physics, indeed, it could assist such searches by providing quantitative predictions that any other quantum gravity approaches would be expected to reproduce. On the other hand, however, it may well be that we continue with the EFT approach, and that new physics is not found (again, as stated in Sect. 3.7.3). This latter suggestion gains support from the observation, yielded by treating GR as an EFT and calculating the quantum corrections, that GR shows no signs of breakdown as far as we can see: the quantum corrections are small, and there is no (urgent) problem of quantum gravity in this respect.

Similarly, Weinberg (2009) has suggested that there may not be new physics beyond the standard model and GR; it is possible that the appropriate high-energy degrees of freedom just are the metric and matter fields, including those of the standard model, and, in this case, there is no "underlying theory" (this will be discussed shortly Sect. 5.4). The point that I wish to emphasise here is that the bottom–up approach to GR as an EFT simply means remaining open-minded in regards to physics at high-energies, as Donoghue (1997, p. 218) states,"We have no reason to suspect that the effects of our present theory are the whole story at the highest energies. Effective field theory allows us to make predictions at present energies without making unwarranted assumptions about what is going on at high energies."

The main problem with treating GR in the same way we treat other QFTs has been the non-renormalisability of gravity, that is, there is no renormalisable theory of the metric tensor that is invariant under general coordinate transformations.[10] However, the non-renormalisability is not actually a problem at the low-energies we are familiar with, thanks to the framework of EFT. Recall from Sect. 3.4.1, that at low-energy the non-renormalisable interactions are highly suppressed. Hence, we are not prevented from making meaningful predictions; rather, predictions in this range are well-controlled due to the heavy mass in the low-energy expansion E/M. Choice of the heavy mass M is dependent on the situation being studied. Although we might usually expect to use the Planck mass, $m_P = (\hbar c/G)^{1/2}$ (with G being Newton's gravitational constant), in other cases it is more appropriate to choose a different scale.[11]

The low-energy Lagrangian, $\mathcal{L}_{eff}$, consists of a sum of all possible interactions which are consistent with the symmetries of the GR (general covariance and local Lorentz invariance). The Einstein–Hilbert Lagrangian, $\sqrt{g}R$ (where $g = det(g_{\mu\nu})$ is the determinant of the metric tensor, and R is the Ricci scalar) appears simply as the first (i.e. least suppressed) term in the expansion $\mathcal{L}_{eff}$. Although a complete quantitative analysis of the size of quantum corrections remains a work in progress, the leading and next-to-leading quantum corrections can be calculated, and have been shown to be negligible. This is as we expect, given the success of GR in its familiar applications.

[10]The gravitational coupling constant (Newton's constant), G, has mass dimension -2 in units where $\hbar = c = 1$, recalling from footnote (10) this means that we expect conventional perturbative QFT to be applicable only for energies $E^2 \ll 1/G$.

[11]Burgess (2004); Donoghue (1994, 1997).

5.3.1 Kinetic Theory Approach

Another, distinct, bottom–up approach is Hu's kinetic theory (Hu 2002). Although this theory is based on a strong analogy between condensed matter physics and spacetime, Hu explains his idea of GR emergent from a condensate by analogy with hydrodynamics as emergent from molecular dynamics: the metric and connection forms are, according to Hu, hydrodynamic variables. Rather than treating GR as an effective quantum field theory, the kinetic approach takes semiclassical gravity as its starting point (i.e. the coupling of the classical spacetime metric with the expectation value of the stress-energy tensor, where this tensor represents quantum matter fields).

Hus stochastic gravity is the "next level up" from semiclassical gravity and involves the two-point function of the stress-energy tensor (Hu 1999; Hu and Verdaguer 2008). The kinetic approach then builds on this, being a hierarchy, or "staircase", of equations which take into account the higher correlations of the stress-energy tensor and describe their effect on the higher-order induced fluctuations of the metric. Mattingly (2009, p. 393) describes how this relates to the high-energy theory from which GR emerges, "We know that any good [quantum gravity] theory will have to give correctly the correlations between the quantum fluctuations of matter at every order, and we hope that by accounting for these correlations by hand some new important insights will be found into the nature of that underlying theory."

5.3.2 Emergence

The relation of emergence between GR and the high-energy theory beyond would mean that the only "insights" we can find using bottom–up approaches will be in the form of approximate, quantitative predictions. Using the EFT framework to work bottom–up, we are restricted by the availability of experimental input required to set the parameters of the theory. Also, there is the risk that perhaps the assumptions of the framework (e.g. the existence of well-separated heavy mass scales) are not fulfilled at high-energies. The bottom–up approach, in both examples, sustains no illusions, however: it is explicitly heuristic. It is not aimed at producing an elegant final theory, but is just a means of combining GR and QM to make predictions in the regimes where we are able to.

The physical and conceptual aspects of the theories in the bottom–up approach are not supposed to resemble those of the underlying theory, so we should not be concerned if, for example, these theories neglect background independence. They are not themselves appropriate candidates for a quantum theory of gravity. As Mattingly (2009) and Burgess (2004) both express, the philosophy of the bottom–up approach entails a recognition that quantum gravity is not an immediate issue. Using the ideas of EFT, we are able to press on, slowly inching our way up until we hit crisis point.

5.4 Asymptotic Safety in Quantum Gravity

Treating GR in the bottom–up EFT framework, the effective action, S_{eff}, may be expressed as,[12]

$$S_{eff} = -\int d^4x\sqrt{-detg}[f_0(\Lambda) + f_1(\Lambda)R + f_{2a}R^2 + f_{2b}R^{(\mu\nu)}R_{(\mu\nu)} + f_{3a}(\Lambda)R^3 + \cdots], \tag{5.5}$$

where Λ is the ultraviolet cutoff, and the $f_n(\Lambda)$ are coupling parameters with a cutoff dependence chosen so that physical quantities are cutoff-independent. We can replace these couplings with dimensionless parameters $g_n(\Lambda)$,

$$g_0 \equiv \Lambda^{-4}f_0;\ g_1 \equiv \Lambda^{-2}f_1;\ g_{2a} \equiv f_{2a};\ g_{2b} \equiv f_{2b};\ g_{3a} \equiv \Lambda^2 f_{3a};\ \cdots . \tag{5.6}$$

Because these parameters are dimensionless, they must satisfy a RG equation of the form,

$$\Lambda\frac{d}{d\Lambda}g_n(\Lambda) = \beta_n(g(\Lambda)) \tag{5.7}$$

In perturbation theory, all but a finite number of the $g_n(\Lambda)$ diverge as $\Lambda \to \infty$. Thus, we are apparently prevented from calculating anything at high-energy. As mentioned earlier (Sect. 3.8.2), this proliferation of infinities at high-energies is typically taken to presage the ultimate failure of our theory in this regime. It is usually assumed that, when Λ reaches some very high energy, that new physics will come into play: the appropriate high-energy degrees of freedom are not the metric and Standard Model fields. However, as Wüthrich (2012) points out, "these difficulties—at least in general relativity—simply result from insisting on forcing general relativity on the Procrustean bed of perturbation theory".[13] Weinberg (1979, 2009) has proposed that perhaps the couplings do not actually blow up at high-energy, but rather that they are attracted to a finite value $g(n*)$, i.e. that they approach a UV fixed point. The suggestion is, thus, that gravity is *asymptotically safe*, indicating that the physical quantities are "safe" from divergences as the cutoff is removed (taken to infinity).[14]

The research program focused on exploring this "asymptotic safety scenario in quantum gravity" aims to place quantum gravity within the framework of known physics principles (this includes treating GR as a QFT, as above Sect. 5.3), so that we may use these familiar principles to explore the behaviour of the theory. Although doing this involves using our familiar low-energy degrees of freedom (metric and matter fields on a continuous. four-dimensional manifold), it is not (and needn't

[12]Following Weinberg (2009).

[13]This sentiment is also expressed by many proponents of so-called "discrete" approaches to quantum gravity, as discussed in the next chapter.

[14]This is similar to QCD, except that QCD is also asymptotically free, having a fixed point of zero; usually, in asymptotic safety, the fixed point is finite, but not zero.

be) presupposed that these low-energy degrees of freedom will be appropriate at high-energy.[15]

Instead, the strategy focuses on "backtracking", using the RG, toward the high-energy "origin" of these degrees of freedom. In particular, it is not supposed that the Einstein–Hilbert action (or a discretised form of the Einstein–Hilbert action) is the appropriate micro-action. However, unless the theory becomes purely topological at some scale, a metric will always be involved, and, from general covariance arguments, it will almost unavoidably contain an Einstein–Hilbert action. For this reason it might be thought that the Einstein–Hilbert action will play a role in the high-energy limit.

The arena on which the RG is applied is a space of actions; a typical action has the form $\sum_\alpha u_\alpha P_\alpha$, where P_α represent the interactions, and u_α are scale-dependent coefficients, or couplings.[16] Using the Wilson-Kadanoff approach, the RG may be understood as a sequence of coarse-graining operations (as explained in Sect. 3.3.1). It is stipulated that the dominant effect of the interactions in the extreme UV is *antiscreening*, so that, by analogy with QCD (Sect. 3.3.2) the interactions become weaker at high-energy. The RG thus flows toward a fixed point on the critical surface, and, recalling the description in Sect. 4.5, relevant couplings are repelled from the fixed point, while irrelevant ones flow, under the RG coarse-graining operation, towards it. The flow lines, known as renormalisation group *trajectories*, emanating from the fixed point, sweep out a manifold that is defined as the *unstable manifold*.

The points on these flow lines correspond to actions from which we are able to obtain a *continuum limit*: this is the limit in which we are able to calculate physical quantities that are strictly independent of the high-energy cutoff, independent of the form of the coarse-graining (RG) operation, and invariant under point transformations of the fields. That is, we have continuum properties even in the presence of a high-energy cutoff (which might otherwise be interpreted as "discretising" spacetime, as in Sect. 3.8.2). The continuum limit represents a *universality class* of scaling limits that give us continuum quantities, where a scaling limit is constructed by 'backtracking' along an RG trajectory emanating from the fixed point. Any action on an RG trajectory describes identically the same physics on all energy scales lower than the one where it is defined. Because of this, if we follow the trajectory back (almost) into the fixed point, we can in principle extract unambiguous answers for physical quantities on all energy scales. Thus, the presence of the fixed point guarantees universality.

The main drive for the asymptotic safety approach to quantum gravity is its potential for being able to "propagate down" the strongly-suppressed effects of the high-energy physics through many orders of magnitude toward experimentally accessible energies. Because of the *universality* secured by the presence of the fixed point, the asymptotic safety approach to quantum gravity is not concerned with identifying the nature of the "fundamental" (i.e. high-energy) degrees of freedom: it is only the universality class that matters. Within this picture, even sets of fields or other variables that are non-locally and non-linearly related to one another may describe the same universality class, and, hence, the same physics.

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[15] And so accords with the philosophy of "effective EFT".

[16] This explanation is based on Niedermaier and Reuter (2006), Percacci (2009).

This leads us to the sense of *emergence* appropriate to the asymptotic safety scenario. By direct comparison with the idea of emergence associated with universality and fixed points, we may tie our conception of emergence to the underdetermination of the high-energy degrees of freedom. The asymptotic safety scenario demonstrates that different choices of micro-action and dynamical micro-variables all lead to the same low-energy physics. In other words, the low-energy degrees of freedom, including the GR metric and Standard Model matter fields, are robust and autonomous from their high-energy counterparts, dependent only on the universality class.

As in other examples of EFT, the novelty of the low-energy theory in the asymptotic safety scenario is expected to be synchronic. However, there may also be diachronic novelty, if the fixed point is associated with second-order phase transitions (Sect. 4.12). In such a case the fixed point would represent a dynamical change of state of the universe, and the low-energy degrees of freedom could be seen as emergent compared to the universe before the phase transition. As will be discussed in the next chapter, there is some evidence, coming from the use of Regge calculus and causal dynamical triangulations (Sect. 6.6), that the fixed point may indeed correspond to a second-order phase transition.

Evidence for the existence of a UV fixed point in quantum gravity has come from calculations based on a number of different approximation techniques.[17] These include the $2 + \epsilon$ expansion,[18] the $1/N$ approximation,[19] lattice methods,[20] and the truncated exact renormalisation group equations (ERGE).[21]

5.5 Conclusion

The analogue models of spacetime and the treatment of GR as an EFT represent two different directions in describing spacetime as an EFT. Both approaches exemplify the philosophy of EFT espoused in Sect. 3.8: that EFT is itself an effective, pragmatic description of physics. The top–down approaches considered here serve to demonstrate the limitations on any approach to quantum gravity that conceives of GR as an EFT.[22] I argued that these limitations are essentially tied to the conception of emergence appropriate to these models.

Two types of analogue models were examined: the general case of an effective Lorentzian metric arising from the linearisation of a field theory around a non-trivial

[17] For a brief overview, see Percacci (2009).

[18] Weinberg (1979), Kawai et al. (1993), Kawai et al. (1996), Niedermaier (2003), Niedermaier (2010).

[19] Smolin (1982), Percacci and Perini (2003), Percacci (2006).

[20] Ambjørn et al. (2004, 2005).

[21] Reuter and Saueressig (2002); Reuter and Weyer (2009); Lauscher and Reuter (2002); Codello and Percacci (2006). For an extended list of references see Weinberg (2009).

[22] However, recall from discussion in Chap. 1 that there is more to recovering GR than simply an emergent metric and an effective dynamics for spacetime, and it is not clear that these models are capable of representing these extra features, see Carlip (2014).

background, and Volovik's model in which a dynamical curved metric arises at low-energy in a condensed matter system of a particular universality class. The spacetime that arises at low-energy in both these models is strongly robust and autonomous from the high-energy physics, owing to the fact that the emergent spacetime depends only on the symmetries and general features (in the case of Volovik's model, the topology) of the condensed matter system rather than on any particular micro-details.

Coming from the other direction, the bottom–up approaches to GR as an EFT treat gravity as if it were a QFT, and are valuable in that any and all testable predictions of quantum gravity can be calculated in this framework. These approaches tell us that quantum gravity is not an immediate concern, and also that new physics is not required at any energy scale accessible to experiment. The asymptotic safety scenario for gravity draws an analogy between GR and QFTs, and is the claim that we do not need new physics at *any* energy scale in order to describe quantum gravity. If the fixed point postulated by the asymptotic safety scenario represents a second-order phase transition, then the situation is one in which spacetime as an EFT is diachronically novel as well as strongly autonomous from the high-energy physics underlying it. This suggestion is realised by several of the discrete approaches to quantum gravity discussed in the next chapter.

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