Chapter 1
Introduction: Spacetime and Quantum Gravity

The search for a theory of quantum gravity is the pursuit of a more unified picture of the world. It is a quest to push beyond what is known—one that perhaps leads into the inaccessible. It is a journey guided by principles rather than experiment: principles gleaned from known physics, but which we cannot be sure will carry us as far as we want to travel. One of these principles states that we must be able to return from our journey—if we reach a theory from which we cannot arrive back at the firm ground of established physics, then, whatever we have reached, it is not quantum gravity.

Moving to a theory of quantum gravity might represent the breakdown of spacetime, in the sense that it is possible that our current understanding of spacetime, as described by general relativity, will not feature in the fundamental description of such a theory. If spacetime does not appear fundamentally in quantum gravity, but is to be recovered at some large distance/low energy scale (compared to that at which the theory has been formulated), then general relativity is an *effective* theory, and spacetime is *emergent*. The "return" to current physics will represent the process of recovering spacetime. This book discusses the nature of such a breakdown, the process of recovery, and the conception of emergence that it might entail.

The framework of effective field theory describes a particular class of effective theories. A faithful interpretation of effective field theory is essential for understanding the lessons of modern physics, including—especially—high-energy physics and the place of quantum gravity. The conception of emergence that features in effective field theory is associated with this philosophy, yet it also applies usefully across many different branches of physics. It is the main—but not the only—idea of emergence explored in this book.

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1.1 Quantum Gravity: What Is It and Why Do We Want It?

There are two perspectives from which to view the problem of quantum gravity; this fact reflects the great divide in physics, which is, essentially, the origin of the problem itself. On the one hand, we have the “particle physicists’ perspective”. According to this view, the problem of quantum gravity is that our best theory of gravity is not a quantum field theory—the *standard model* of particle physics, which uses the framework of quantum field theory (QFT), supplies an account of all the known fundamental forces of nature *except for gravity*. Perhaps the most familiar of the fundamental forces, gravity is the dominant force at large distance scales. The theory that describes gravity, general relativity (GR), is not only incredibly accurate, but conceptually elegant and remarkable in its achievements. By identifying gravity with spacetime geometry, GR transported space and time from the realm of the absolute and unchanging into the realm of motion, affectedness and interaction. According to GR, spacetime is not a fixed entity that stands as a background, not a stage for physics to play out upon. Instead, spacetime may be understood as a dynamical entity that influences matter and which itself is influenced by matter.

And thus, from the “general relativists’ perspective”, gravity is not really a force at all—it does not “act” on objects. Rather than conceiving of gravity as a field that deflects objects from their inertial paths, GR tells us to understand that an object’s inertial path is determined by the curvature of spacetime. This contrasts with QFT, which is a theory of fields defined on a static, background spacetime. Basically, the theory says that all matter is composed of particles, which are understood as local excitations of quantum fields; the fundamental forces are themselves represented by quantum fields, whose corresponding excitations interact locally with the other particles, depending on their type.[1] Any dynamical field, according to QFT, is quantised. Incorporating gravity into this framework would entail treating gravity as a field whose force is mediated by a particle called the graviton.

The development of GR and quantum theory each represented a conceptual revolution, transforming our understanding of all aspects of the physical world: space, time and matter. The problem is that they each did so in ways that are incompatible with one another—their contradictory accounts of spacetime being a prime example. Quantum gravity is the domain of research[2] whose aim is to find a theory that *in some sense* unifies GR and quantum theory.[3] There are many different ways in which this may be interpreted. For example, a QFT that describes gravity would be a candidate theory of quantum gravity—this attempt to incorporate gravity into the framework of QFT is known as the “particle physicists’ perspective” (or the “high-energy theorists’ perspective”) of quantum gravity, since it privileges QFT over the insights of GR (through its use of a background spacetime, for example, as is clarified in Sect. 6.4).

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[1] The idea of locality in QFT is necessary in order to make sense of the axioms of the framework (i.e. unitarity, micro-causality and the Poincaré-invariant vacuum), and is discussed in Sect. 3.2.

[2] In this book, however, I will often use the term “quantum gravity” simply to refer to the theory being sought. Thus, “quantum gravity” is typically shorthand for “a *theory* of quantum gravity”.

[3] A more precise definition of quantum gravity is presented shortly, on p. xxx.

Another candidate would be a theory produced by quantising GR (using standard quantisation procedures, or perhaps some inventive techniques and additional ideas). Quantum geometrodynamics (discussed in Sect. 1.5) is an example of this approach, as is loop quantum gravity (Chap. 7).

There are more creative approaches, too, and these form the main focus of this book. Quantum gravity could be a theory that is neither a QFT nor a quantisation of GR: it may be a theory that is quantum in some sense, but which does not rely on a background spacetime. It might represent a "small-scale" ("micro", or high-energy) theory of spacetime, but without any standard conception of spacetime appearing within it. In such a case, the theory would describe the micro-constituents, or "atoms" of spacetime, rather than spacetime itself. If spacetime thus "breaks down" at some scale, then familiar quantum theory and QFT breaks down with it. The desire to unify gravity and quantum theory may well result in a theory of neither.

The belief that we require a unified theory is one of the strongest motivations for quantum gravity. Unification is a traditional "guiding principle" in physics, and is often viewed as means of producing successful theories. Familiar examples of this—representing various different ideas, or degrees, of "unification"—include Maxwell's theory of electromagnetism, which "unified" light as well as the electric and magnetic forces; the electroweak theory, which "unified" the electromagnetic force and the weak force; and even GR, with its identification of inertial mass with gravitational mass, and spacetime with gravity. For those inclined towards unification, the current situation in physics—the dualistic, split picture of the world it presents—is unsettling, and calls us to question the fundamental nature of both GR as well as the framework of quantum theory.

As indicated above, unification is typically taken as forming essentially the definition of quantum gravity, yet what is meant by "unification" is left open. On a strict definition of unification, quantum gravity would be a theory that completely *replaces* both GR and quantum field theory at very high energy scales.[4] If this were the case, then GR would need to be recovered (as an approximation) at the relevant (low) energy scales, and quantum gravity would, in some sense, "explain" why quantum field theories provide the appropriate description of the world in the domains where they apply. It should already be clear, however, that such a strict definition of unification is not standardly adopted in quantum gravity research. As mentioned above, quantum gravity could be a QFT that describes gravity, and it could be a theory of a quantised gravitational field; in both these cases, QFT is not necessarily completely replaced, but could instead have been incorporated, or made use of in some way. So, what is meant by unification in quantum gravity research needs clarification. Rather than pursue this further here, however, I will instead (shortly) propose a new definition of quantum gravity that is more useful for our purposes.

Another reason why unification is not ideal to use in a definition of quantum gravity is because it prompts a confusion between a theory of quantum gravity (understood as a theory that, in some sense, unifies GR and the framework of QFT) and a "theory of everything", which is a theory that unifies gravity with the other fundamental forces

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[4] See the definition of "perfect unification" in Maudlin (1996).

(i.e. particular QFTs, rather than the framework of QFT). Although quantum gravity need not represent a "theory of everything" in this sense, such a theory would count as quantum gravity—string theory being the primary example. If the main conceptual motivation for quantum gravity were unification, then it would seem as though we would want a "theory of everything" in this sense. There are reasons, however, for questioning the perceived need to unify gravity with the other forces. Gauge field theories, such as those that describe the fundamental forces in QFT, explain forces as due to the action of fields; objects couple to a particular field only if they have the appropriate charge (that serves as the coupling constant, see Sect. 3.2). According to GR, though, gravity is not really a force at all—as Maudlin (1996, p. 143) states, objects do not couple to the gravitational field—they simply exist in spacetime. So, one argument against seeking to unify gravity with the forces described by QFT, is that by doing so, we would be refusing one of the great conceptual insights offered by GR.

As a side note here, I mention that there are two ways of responding to this suggestion while respecting GR as providing our best theory of spacetime, and seeking to preserve its lessons. (1) We might believe that it is a mistake to seek a theory that unifies gravity with the other forces, because we know, from GR, that gravity is not on the same footing as these forces. According to this view, any attempt to reveal the fundamental forces as stemming from some common origin is misguided, and will not be successful. This view entails, however, that the teachings of GR hold at inaccessible energy scales—ones at which GR is not known to apply. This could itself be a mistake. We should question whether the lessons of GR—as valuable as they are—must necessarily carry-over into unknown realms. It could be that these features "emerge" along with GR, and exist only at larger energy scales than those where quantum gravity is thought to be important. So, (2) is that we remain open to the possibility that physics changes radically at extremely high energy scales.[5] We should not seek to preserve particular features of GR simply because they are features of GR; instead we need additional evidence or justification for supposing that these aspects of the theory will also be present in quantum gravity.[6]

The search for quantum gravity is driven by both conceptual and technical (or physical) motivations. Unification is an example of a conceptual motivation; it is not the only one, however. The main conceptual motivation driving the search for quantum gravity is the more general desire to make sense of the world. We want a science that provides a coherent account of space, time and matter; we expect physics to provide a picture of the world that does not conflict with itself. This conceptual motivation is easily confused with the dream of unification, but, as should be clear now, this motivation does not require, nor necessarily seek, a unified theory.

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[5] This suggestion of "high energy agnosticism" is explored in Sect. 3.8.

[6] One important feature of GR that is supposed to also be present in quantum gravity is *background independence*, discussed in Sects. 1.2, 1.5 and 6.4.

Another conceptual motivation is the desire to solve the *measurement problem* of quantum theory.[7] This is the question of why it is that any measurement on a quantum system finds the system in a definite state even though the system evolves as a superposition of different states (i.e. the evolution is unitary and linear—more detail in Sect. 1.7.1). This is a serious difficulty for quantum mechanics, and different interpretations of the theory have been developed to address it.[8] Yet, we might feel that none of the solutions proposed are satisfactory. For many people, there is the expectation that the problem will only be solved, or explained, by the new physics promised by quantum gravity. Most notably, Roger Penrose maintains that the resolution of the measurement problem is the clearest reason for seeking quantum gravity. He argues that quantum theory must be modified by gravity, and that these gravitational effects are responsible for the "collapse" of the superposition into a definite state.[9]

There is one further, distinct, conceptual motivation: the simple wish to advance physics and expand the scope of human knowledge.[10] This motivation is the hope to understand more of the universe, to push to higher and higher energies beyond what is known, and to explore territory hitherto-unexplored. Adding even more potency to this motivation is the tantalising suggestion that quantum gravity promises to profoundly alter our worldview—a suggestion that engenders a strong sense of "natural curiosity", and certainly acts as a lure toward investigating quantum gravity (Rickles 2008, p. 284). Even without considering quantum gravity specifically, there is a common thought that our current theories are not the final word: this idea comes from some dissatisfaction with QFT as a fundamental theory, due to perceived problems of mathematical coherency and renormalisation, as well as the feeling that certain patterns and parameter values in the standard model are in need of explanation (or point toward a deeper explanation). This might mean a new theory or framework is required at current energies, to replace QFT and the standard model, or it might mean a new theory is required at higher-energies—such as axiomatic QFT (Sect. 3.8.3).[11]

The physical reasons for seeking a theory of quantum gravity are less clear-cut than the conceptual motivations. This is because there is simply no phenomenon that can be uniquely identified as the result of some combination of general relativity and quantum theory. To make matters worse, as Butterfield and Isham (2001) explain, not only are there no data, but there is not even any agreement as to the *sort* of data that would be relevant to quantum gravity. The lack of data is typically cited as being due to the extreme inaccessibility of the domains in which quantum gravity is expected to be applicable. Thus, although distant, there are certainly parts of the

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[7] It may be argued that this represents a technical—or physical, problem—rather than a conceptual one, depending on your understanding of what constitutes a "conceptual" versus "physical" problem.

[8] Examples include the Copenhagen interpretation, Bohmian mechanics (also known as the de Broglie–Bohm theory) (Bohm 1952), GRW theories (Ghirardi et al. 1986), and the Everettian interpretation (also known as the "many worlds" interpretation) (Everett 1957, 1973).

[9] Penrose (1996), Penrose and Marcer (1998), Penrose (1999, 2002).

[10] Ashtekar and Geroch (1974, p. 1213) express this sentiment, for example.

[11] The remarkable success of the QFTs of the standard model makes the latter scenario more likely.

world for whose descriptions quantum gravity is thought to be necessary—these are the domains where general relativity intersects with quantum theory.

Most characteristically, GR and quantum theory are both necessary in order to describe the case in which a particle of mass m has its Compton wavelength, $l_C = \hbar/mc$ equal to its Schwarzschild radius, $l_S = Gm/c^2$, where G is Newton's gravitational constant, $\hbar$ is the reduced Planck's constant, and c is the speed of light. This equality occurs when the mass is the *Planck mass*: $m = m_P = \sqrt{\hbar c/G}$. A particle's Compton wavelength is a prediction of quantum field theory (discussed in Sect. 3.2), which states that localising m to within l_C uses enough energy to create another (identical) particle of mass m, which results in an indeterminacy in the number of particles present. The Schwarzschild radius is a prediction of general relativity; it states that compressing m to within the distance l_S will result in the formation of a black hole.

Other phenomena whose full explanations are expected to be provided by quantum gravity include spacetime singularities, such as black holes and the cosmological singularity of the big bang. There are two reasons for this. One reason is that regions of spacetime near a singularity have extremely high curvature (in the case of a black hole, however, this may be hidden from us by an event horizon), and the approximation of QFT in curved spacetime ceases to be valid in such regions. When the radius of curvature becomes smaller than the Compton wavelength of particular species of particle, then particle creation occurs. Stephen Hawking (1975) argued the possibility that a black hole creates and emits particles at the rate it would if it had a temperature of $T_H = \kappa/2\pi$, where κ is the *surface gravity* of the black hole. This phenomenon is known as Hawking radiation. The idea that the surface gravity of a black hole be identified with temperature is one aspect of a fascinating parallel between the laws of black hole mechanics and the laws of thermodynamics—in fact, all four laws of thermodynamics are supposedly mirrored in black hole mechanics (Bardeen et al. 1973). In one of these, thermodynamics and black hole physics are actually combined: the *Generalised Second Law* states that the sum of a black hole's area and the entropy of a system can never decrease.

The Generalised Second Law is a result of Jacob Bekenstein's work in the early 1970s (e.g. Bekenstein 1973) that suggested that a black hole possesses entropy proportional to the surface area of the event horizon. This is now known as Bekenstein entropy, and it implies that there is a fundamental limit on how much entropy a region can contain. This brings us to the second reason why singularities are of interest to quantum gravity: the intriguing results here are a combination of quantum theory, GR and thermodynamics, and thus seem to indicate there is something more fundamental underlying these theories. In particular, this work has led to the development of the *holographic principle*, which was proposed by Gerard 't Hooft (1985), and says that the complete physical description of a volume of space can be provided by a description of the physics on the boundary of that region.[12] The principle was inspired by the curious implication of Bekenstein entropy—that the maximal entropy of any region

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[12] Bousso (2002) provides a review. For more discussion on the holographic principle as a principle of quantum gravity, see, e.g. Bigatti and Susskind (2000), Sieroka and Mielke (2014).

scales with its radius squared, rather than radius cubed. This is surprising because usually we would expect the number of degrees of freedom within a certain region to depend on the volume of the region, rather than its area. Like Hawking radiation, the holographic principle has not been experimentally confirmed, and remains conjectural. In spite of this, however, it is taken to be a key principle of quantum gravity, and is expected to be explained by the theory. I discuss the holographic principle in the context of string theory, in (Sect. 1.9).

Nevertheless, while a radical new theory (quantum gravity) might be necessary for an explanation (or understanding) of the extreme domains where quantum gravity is thought to be necessary, we might question whether a completely new theory is strictly needed in order to make predictions, or to describe the aspects of these domains that are (even potentially) experimentally accessible. A semiclassical "hybrid" theory, or some other approximation to a full theory of quantum gravity, may be suitable for these purposes.[13] These are, typically, theories that do not involve a quantised gravitational field, and instead couple a classical spacetime to quantum matter fields. While it is possible that such an approximation could fulfil the "technical requirements", it would not sate the desire for understanding, unification or a fundamental theory. Nor, perhaps, would it be equipped to address the deep conceptual questions raised by the holographic principle, or explain black hole thermodynamics. Thus, I submit, the main motivations for a full theory of quantum gravity (as a fundamental theory of spacetime, that unifies GR and QFT) are conceptual.

Of course, however, the distinction between "full (new) theory" and "semiclassical hybrid" is one that needs addressing—what counts as a theory, as opposed to an approximation? The issue of fundamentality obviously plays a role, so, without supplying an appropriate definition of "theory of quantum gravity", it is not fair of me to say that a hybrid theory should not count as a theory of quantum gravity simply because it does not appear to be fundamental. This brings us back to the problem of defining quantum gravity. We seem to have two options here: either adopt a broad understanding of quantum gravity, that includes semiclassical hybrids, or take a more restrictive definition, which excludes semiclassical hybrids. The restrictive definition might state that quantum gravity is a fundamental theory of spacetime that unifies GR and quantum theory (upon some specification of what counts as "fundamental" and "unified"). In this book, however, we will take a more inclusive definition. This is helpful because, as mentioned above, it is not clear that the different approaches to quantum gravity share a common understanding of unification—yet, we do not want to exclude any of them from discussion here. The issue of fundamentality will arise again when discussing emergence in (Sect. 2.6).

Thus, the most useful definition of quantum gravity at this stage is *a theory that supersedes GR at (some) high energy scale*. In other words, it is a theory of the "small distance" physics that is responsible for the emergence of gravitational phenomena at

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[13] This is discussed further in Sect. 5.3, along with some other "hybrid" approaches that aim to reproduce the results of quantum gravity within accessible energy scales. See also Callender and Huggett (2001), Wüthrich (2005), Mattingly (2009, 2014).

large distances (or, equivalently, low energies, since energy is inversely proportional to length). This definition takes into account the possibility that quantum gravity may not be a theory involving a quantised gravitational field, or discrete spacetime.

1.1.1 Correspondence and Emergence

Regardless of the conception of spacetime that features in quantum gravity—or, indeed, even if a conception of spacetime is lacking in quantum gravity—the fact that it is a theory that replaces GR means there is a perceived need to "recover" GR from quantum gravity in the regimes where GR is known to hold as a valid description of the world. The idea is that, by establishing a link between quantum gravity and GR, whereby GR is shown to be a large-distance approximation to quantum gravity, we explain how it is that GR was so successful, in spite of "not being correct" (in the light of the new theory). This appeals to our expectation of what science should be like: we want physics to provide us with a coherent picture of the world, rather than a sequence of disconnected snapshots. Such motivation is evident in the problem of quantum gravity, being an attempt to describe phenomena at the intersection of two disparate theories. Another reason why establishing a link between the theories is viewed as important is the belief that a new theory should not render inexplicable any phenomena that had been explained by its predecessor.[14] The thought is that if a theory of quantum gravity cannot account for the same phenomena as GR (by effectively "reducing to" or "recovering" GR in the appropriate domains), then the theory is inadequate as a replacement for GR.

This principle is an instance of a more general one that is typically understood as a criterion of theory acceptance—the *generalised correspondence principle*.[15] It can be stated as, "the requirement that any acceptable new theory L should account for the success of its predecessor S by 'degenerating' into that theory under those conditions under which S has been well confirmed by tests" (Post 1971, p. 228). The principle may also be framed in terms of reduction, and it is perhaps more typical to do so,

Generalised correspondence principle (GCP) any acceptable new theory S should account for the success of its predecessor L by *reducing* to L in the domain of applicability of L

The newer theory is broader in scope than the theory it replaces (i.e. it has a larger domain, makes more predictions, or contains additional insights compared to the older theory). The idea of reduction says that the older theory can be "mapped" to

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[14] In practice (as any historian of science will tell you), this is not always the case.

[15] The generalised correspondence principle takes inspiration from *the correspondence principle*, which states (roughly) that quantum mechanics should reproduce the results of classical mechanics for systems involving large orbits and large masses (While this principle is typically attributed to Bohr, it is worth noting that it is not what Bohr intended as "the correspondence principle"—see Bokulich 2014).

the newer theory, or shown to be part of it. Some familiar examples of the GCP in action include the "reduction" of special relativity to classical mechanics for velocities small compared to the speed of light, and GR "reducing to" Newtonian gravity in the limit of weak gravitational fields. This ties in with the *physicist's sense of emergence*, which holds that the old theory, L is *emergent* from the new theory, S, if S and L satisfy the GCP.[16] (This is not an exclusive definition—there are other senses of emergence in physics).

The idea of correspondence is a prevalent one in physics, and many successful theories exhibit it in some sense. Yet, it lacks a precise definition; there is no strict, uniform way in which a newer theory recovers its predecessor, and the account of "reduction" is debatable in many cases.[17] Rather, there are myriad types of correspondence. Radder (1991) identifies three different forms, and Hartmann (2002)—working from a large collection (French and Kamminga 1993) of case-studies inspired by the essay in which Post introduced his GCP (Post 1971)—adds another four, producing a list that is not supposed to be exhaustive.

What we find, generally, is that S and L are often incompatible, so a straightforward deduction of S from L is typically not possible. Instead, *idealisations*, *approximations*, and *meta-level arguments* are involved (Radder 1991). Most familiar of these are the limiting relations whereby the characteristic constants of L are taken to their previously-assumed values, effectively masking their presence in S. But limiting relations are not involved in all instances of the GCP. Also, correspondence is not a relation that holds between entire theories. Not all equations, predictions or laws in L will correspond to equations, predictions or laws in S. This is because L is novel and more broadly applicable than its predecessor. However, this also goes the other direction—typically, the older theory is not fully recovered by the newer one. And this is the case even if we restrict S to S^*, being just the parts of the theory that were responsible for its success.[18] Finally, although correspondence is an important heuristic tool that aids in theory construction, it may only be properly established post hoc, once a theory is (more or less) fully-developed.

The GCP has been widely (though not explicitly) adopted in quantum gravity research: that quantum gravity recover GR as a low-energy approximation is viewed as a requirement of the theory. Actually, correspondence takes on unparalleled significance in quantum gravity research. As stated above, the domains where quantum gravity is supposed to be necessary are extreme, and experimentally inaccessible. Although a theory of quantum gravity might (one day) make unique, testable predictions, it could be the case that the most readily obtainable "link" to the empirical realm is by having the theory make contact with known physics.[19] This means that GR must emerge from quantum gravity according to the physicists' sense of emer-

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[16] This idea is discussed in Sect. 2.3.

[17] The thorny issue of reduction is returned to in Chap. 2.

[18] See Radder (1991) and the case-studies in French and Kamminga (1993).

[19] There is also the possibility that this "link" provided by quantum gravity's reduction to GR could serve in the absence of any experimental test of the theory, prompting interesting questions about the "scientific" status of such a theory. See also Dawid (2013).

gence.[20] There is no definite prescription as to what this must entail, though it is commonly assumed that a limiting relation will be involved. In the chapters that follow, I describe the different attempts at correspondence by several approaches to quantum gravity—considering how these aspire to uphold the physicists' sense of emergence.

The physicists' sense of emergence is not the only conception of emergence that is of interest in quantum gravity, however, and it is not the primary one of concern in this book. Essentially, we want to know what we can learn about unknown physics—quantum gravity—from known physics—the (comparatively) large scale theories that are supposed to emerge from it, including GR and the QFTs of the standard model. Asking this question, however, entails recognising the profundity of the apparently mundane situation we find ourselves in: even though we believe that quantum gravity is somehow ultimately responsible for current physics (i.e. observed gravitational phenomena), we can do physics without knowledge of quantum gravity. So, we need to understand how it is that small (distance) scale processes are able to give rise to large scale physics and yet leave us so little indication of what these small scale processes are. In other words, we seek to discover how it is that familiar (low energy) physics could emerge from high energy physics, in such a way as to be effectively autonomous from (the details of) the high energy theory. The conceptions of emergence that are explored in this book are ones that address these questions. And, as will be demonstrated, these conceptions actually need not be associated with the idea of reduction (in any sense).

Before considering the idea of emergence in quantum gravity, it is enlightening to investigate these questions in the context of familiar areas of physics. I do this (Chaps. 3 and 4) after first more thoroughly looking into the meaning of "emergence" in philosophy and physics (Chap. 2). Specific quantum gravity approaches are considered (in Chaps. 6 and 7). I also discuss models of emergent spacetime that are not models of quantum gravity, and in which spacetime emerges *without* GR (Sect. 5.2). First, however, I finish this chapter with a summary of some of the main conceptual issues in QG and necessary background to the idea of emergent spacetime. This begins with a brief explanation of what is meant by spacetime in this book (Sect. 1.2), and an outline of the general arguments that (are typically taken to) motivate the suggestion that spacetime "breaks down" at some scale, together with an indication of the different senses of emergence this could suggest (Sect. 1.3). The possibility of quantum gravity being a non-spatiotemporal theory, as well as its supposedly extreme experimental inaccessibility, lead to concerns regarding its status as a viable physical theory at all (Sect. 1.4). Another important issue in understanding the fundamental nature of space and time—or, rather, their breakdown—is the "problem of time", introduced in Sect. 1.5.

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[20] Similarly, if quantum gravity is a theory which replaces the QFTs of the standard model, then these must also emerge in the domains where they have proven successful as a description of the phenomena.

As stated, the emergence of spacetime is related to the idea of "recovering" spacetime from quantum gravity (Sect. 1.6); there are two different "transitions" that are involved in this, the quantum/classical transition and the micro/macro transition (Sect. 1.7). This book mostly focuses on the micro/macro transition. In regards to the quantum/classical transition, though, it may be that the idea of decoherence plays a role (Sect. 1.7.1). One of the challenges to the idea of emergent spacetime (and gravity) is the Weinberg–Witten theorem (Sect. 1.8). The idea of emergent spacetime suggested in the AdS/CFT correspondence in string theory, is briefly explored in Sect. 1.9. A theme running throughout this book is the relationship between different theories in physics: particularly the cross-fertilisation of high-energy particle physics and condensed matter physics. This is discussed in Sect. 1.10. Finally, Sect. 1.11 provides a chapter-by-chapter overview of the rest of the book.

1.2 Spacetime

The best description of spacetime is provided by GR—a theory which famously identifies it with the gravitational field. Spacetime, according to GR, is a dynamical entity that both affects matter and is affected by matter. In this book, "spacetime" is typically used to denote spacetime as described by GR, i.e. the gravitational field, but I occasionally speak of background spacetime of QFT, or of other theories (when this is done, the context should prevent confusion).

A model of GR is specified as $\mathrm{M} = \langle \mathcal{M}, g, T \rangle$ where $\mathcal{M}$ is a four-dimensional manifold of spacetime points, encoding the topology and differentiable structure, g is the Lorentzian metric tensor, encoding the geometry, and T is the energy-momentum tensor. The two tensors satisfy Einstein's field equations,

$$G_{\mu\nu} \equiv R_{\mu\nu}[g] - \frac{1}{2}g_{\mu\nu}R[g] + \Lambda g_{\mu\nu} = -8\pi G_N T_{\mu\nu}[\Phi] \tag{1.1}$$

where $G_{\mu\nu}$ is the Einstein tensor describing the curvature of spacetime, $R_{\mu\nu}$ is the Ricci curvature tensor, G_N is Newton's gravitational constant, and Φ represents the source(s) of the gravitational field, whose energy-momenta is described by $T_{\mu\nu}$.

It is not immediately obvious which structure should be identified as spacetime in such a model. One, naïve, approach is to take the manifold as spacetime, seeing that it is the set of points on which all the fields—matter and metric—are defined. The motivation for this is based in the belief that matter and spacetime are two separate entities—an intuitive view that comes from recognising the way that we use the concepts of space and time to describe the behaviour of objects. We tend to think of matter as "existing in spacetime", and thus imagine spacetime to be purely the container of events. The desire to preserve this view entails conceiving of the manifold alone as spacetime, because the metric tensor can be interpreted as carrying energy, and thus blurs the line between "spacetime" and "matter".

Of course, the problem with this view is that the manifold unequipped does not possess any of the properties that it seems like spacetime should possess according to GR. For example, the light-cone structure is not defined, past and future cannot be distinguished, and no distance relations exist. For this reason, spacetime is better identified as the manifold *plus metric*, rather than the manifold alone. This suggests that spacetime and matter, as they feature in GR, are intertwined. Although it is true that we use the concepts of space and time to understand the behaviour of objects, this does not imply that spacetime and matter must be conceived of as totally distinct from one another. The fact that our only access to spacetime is through the behaviour of matter means that the geometry of spacetime should be interpreted as reflecting the relationship between spacetime and matter, rather than the intrinsic nature of spacetime.

Even this, however, isn't the whole story, because there is a claim to be made that different (diffeomorphically-related) manifold-plus-metric structures correspond to the same spacetime. This is a consequence of the diffeomorphism invariance of GR.[21] While the idea of general covariance is perhaps familiar as the statement that the laws of the theory are unaffected by a change of coordinates, it can also be understood as an *active* transformation. Instead of relabelling the structures on the manifold with new coordinates, we can imagine that these structures (fields) have actually been dragged along to new positions on the manifold, so that their coordinates are the same as those which they would have possessed had we moved to the new coordinate system. Models related by a diffeomorphism transformation are physically indistinguishable as they agree on all invariant quantities.[22]

The fact that a spacetime does not uniquely correspond to a particular field configuration is the *problem of space*; it has an analogue *problem of time* that also owes to the difficulties of interpreting gauge theories.[23] This is discussed below (Sect. 1.5). Diffeomorphism invariance means that, in order to specify a model of GR, a gauge-invariant *equivalence class* of gauge-variant structures is required, rather than a single tuple of $(\mathcal{M}, g, T)$. Nevertheless, when considering the idea of emergent spacetime, several quantum gravity approaches present, or are interested in, only an emergent *metric* structure (e.g. in Sect. 5.2). This doesn't completely fly in the face of the lesson of diffeomorphism invariance, however; although a given spacetime will not correspond to a particular manifold-plus-metric combination, a given metric may be said to uniquely pick out a spacetime.

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[21] This is also related to the idea of background independence, discussed in Sect. 6.4.

[22] This is the basis of the *hole argument* (Earman and Norton 1987; Norton 1988).

[23] Rickles (2006).

1.3 Motivations and Indications for the Breakdown of Spacetime

Our definition of quantum gravity (as the theory that supersedes GR) means that if quantum gravity is discovered then there is a sense in which our conception of spacetime (according to GR) will break down—it will cease to hold in the domains where quantum gravity is shown to apply, and instead will appear as an approximation valid at large distance scales. But, depending on how radically the new theory departs from the description of spacetime provided by GR, there may be different—stronger—senses in which spacetime breaks down.[24]

In this book, I discuss four ways in which the structures described by quantum gravity may depart from spacetime: the condensed matter approaches Sect. 5.2, which may be interpreted as telling us that relativistic spacetime results from collective excitations of entities analogous to the particles which compose a superfluid (which itself exists in a spacetime); causal set theory (Sect. 6.5), which holds that spacetime emerges from discrete basic elements lacking internal structure, but partially ordered by a special causal relation; pre-geometric approaches (Sect. 6.7), which maintain that spacetime is a consequence of a phase transition undergone by a quantum-mechanical system of basic elements; and loop quantum gravity (Chap. 7), according to which space might be viewed as an extremely fine fabric or network "woven" of finite loops, and spacetime a superposition of such states. All of these are thought to involve the *continuous* geometry of spacetime being abandoned in favour of discrete structures (which may or may not themselves be spatiotemporal in some sense).

There are several arguments, or "hints" that spacetime will break down in a serious way at some high-energy scale, and they may be grouped into two categories: *definitional considerations* and *external considerations*. As the examples presented here demonstrate, the definitional considerations are dependent upon taking a particular definition of quantum gravity, i.e. they come about as a result of adopting certain principles (or sets of principles), which, of course, we cannot be sure will be useful, or will feature in quantum gravity. On the other hand, external considerations are problems, concerns or observed features of the world that could be neatly explained or solved by the discreteness of spacetime, but are not necessarily related to quantum gravity. An external consideration, on its own, cannot be treated as evidence of spacetime discreteness, especially without investigating other possible explanations for its appearance. The temptation to "tally-up" external considerations in order to make a case for the breakdown of spacetime is potentially dangerous because it invites us to take the (relatively) "easy way out"—ascribing to a single, (otherwise) unproven, origin many different concerns with possibly disparate origins. The history of the luminiferous ether should serve to caution against such moves.

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[24] See Huggett and Wüthrich (2013).

The most familiar justification for the breakdown of continuous geometry is the argument from dimensional analysis for the existence of a fundamental (i.e. minimal) length scale, which is also taken as evidence for the scale at which quantum gravity is expected to be important. Dimensional analysis is a common and important tool in physics, used for order of magnitude estimations and finding appropriate units for various physical quantities. In the context of quantum gravity it involves combining the characteristic constants of GR and quantum theory. Famously, Max Planck demonstrated in 1899 that there is a unique way (apart from numerical factors) to do so, in order to provide fundamental units of length, time and mass. Here, they are designated l_{P}, t_{P} and m_{P}, respectively,

$$l_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^3}} \approx 1.62 \times 10^{-35}\,\mathrm{m} \tag{1.2}$$

$$t_{\mathrm{P}} = \sqrt{\frac{\hbar G}{c^5}} \approx 5.40 \times 10^{-44}\,\mathrm{s} \tag{1.3}$$

$$m_{\mathrm{P}} = \sqrt{\frac{\hbar c}{G}} \approx 1.22 \times 10^{19}\,\mathrm{GeV} \tag{1.4}$$

As mentioned (Sect. 1.1), m_{P} is the mass at which a particle's Compton wavelength is equal to its Schwarzschild radius. Based on the predictions of GR combined with those of quantum theory, we expect there to be microscopic, rapidly-evaporating black holes at this scale. John Wheeler, in the 1950s, spoke of a "quantum foam" at the Planck scale, where quantum fluctuations of spacetime (or fluctuations affecting spacetime) would become significant—geometry at this scale is thought to be ill-defined, or "fuzzy" (Wheeler and Ford 1998). Thus, we are led to the suggestion that the Planck length is a minimal length—meaning that, on this picture, no distances smaller than the Planck length exist. The arguments based on dimensional analysis are definitional considerations, since they arise from taking as a definition of quantum gravity that it be a theory that combines GR and quantum theory in this way.

Another definitional consideration is the problem of time, which is a single title used to designate a cluster of problems. These problems stem from the dissimilar ways in which GR and quantum theory treat space and time: attempting to combine the theories leads to conflict and strange consequences! These results have been taken as suggesting that time does not exist in quantum gravity. More generally, and less controversially, the problem of time does suggest that at least some of the concepts and structures featured in quantum theory and GR will perhaps not be useful in quantum gravity, though it is difficult to determine what these are.

As discussed below (Sect. 1.5), there is a particular manifestation of the problem of time in an approach to quantum gravity that proceeds by quantising the gravitational field (canonical quantum gravity); the equation that is supposed to describe the dynamics of the theory does not feature a time parameter. This context demonstrates how the problem of time may be considered an example of a definitional problem—it stems, in this context, from taking quantum gravity as a theory of a quantised GR.[25]

One external reason for thinking that continuous spacetime might break down is the fact that many quantum field theories go awry at high-energies (Sect. 3.2), and that this could be avoided if there was a natural high-energy cutoff provided by a fundamental length. This suggestion, historically, arose in the context of studying quantum electrodynamics, and today many of the quantum gravity approaches that describe a fundamental length recognise the utility of doing so in regards to solving the high-energy difficulties of QFT (Hagar 2014). Nevertheless, as argued in Sect. 3.8.3, the interpretation of QFT is not uncontroversial. Furthermore, although the existence of a fundamental length would help explain the necessity of renormalisation, the necessity of renormalisation does not, on its own, imply the existence of a fundamental length—there are other possible explanations and ways of understanding QFT that do not involve spacetime discreteness.

Another, similar, external consideration is the non-renormalisability of gravity: again, there are ways of "solving" this that do not suggest spacetime discreteness (but are not incompatible with spacetime discreteness, Sect. 5.4). GR may be treated in the same way as QFTs are (Sect. 5.3), and the same philosophy is applicable. This view, which I introduce in Sect. 3.8, is a pragmatic one which entails recognising that there are many different high-energy scenarios that could be responsible for observed low-energy physics, and avoiding making assumptions about which (if any) of these is correct.

Some additional—though also inconclusive—arguments for discreteness are presented in Sect. 6.2.

1.4 Quantum Gravity as a Physical Theory

The experimental inaccessibility of quantum gravity (in the absence of novel low-energy predictions made by particular approaches) is suggested not only by arguments from dimensional analysis and black hole thermodynamics, but also from the great success of GR at all accessible energies (Sect. 5.3). If scientific theories are supposed to make contact with the empirical realm through predictions and experiment, then this leads to questions regarding the status of quantum gravity as a scientific theory at all: questions such as those that have most publicly been levelled at string theory, for example Smolin (2007), Woit (2007).

A potentially more serious objection to quantum gravity as a physical theory is raised by Maudlin (2007) and concerns those approaches to quantum gravity that do not feature spacetime. Maudlin claims that, for a theory to be "physically salient" it must have spatiotemporal entities as part of its fundamental ontology; otherwise, it is difficult to see how such a theory could ever make contact with the empirical

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[25] To emphasise: this is only one particular aspect of the problem of time. It is explained in a little more detail below (Sect. 1.5), along with some other aspects of the problem.

realm. The idea of spatiotemporal entities as being the basic ontology of our scientific theories, ultimately constituting what we observe, comes from Bell's idea of "local beables" (Bell 1987). The worry is that, because all observations are observations of local beables—things that exist *somewhere* in space and time—a theory without local beables is unable to account for any observations, and is thus *empirically incoherent*.

However, a lack of fundamental local beables in a theory does not mean that such a theory is unable to recover local beables in some limit or approximation, and, thus, be testable at that level. On such an account, the local beables would emerge along with spacetime.[26] Maudlin (2007) anticipates such a reply, however, and claims that the empirical contact made by the derived local beables does not establish the "physical salience" of the fundamental theory. The argument then turns on what is meant by a theory being "physically salient". I stand with Huggett and Wüthrich (2013) in maintaining that we should look to the theory in question itself, the procedure by which the local beables are derived, and its empirical success in order to determine what is physically salient, rather than begging the question against theories that do not feature space and time. This prescription accords with a broadly useful attitude to adopt when studying quantum gravity: that we should first attempt to develop and examine particular approaches toward a theory rather than seek general arguments as to their physical salience. Given the diverse range of potential approaches, based on different motivations and guiding principles, any general arguments that do not take these into account are themselves unlikely to be salient.

1.5 The Problem of Time

The "problem of time" in quantum gravity is neither a single problem, nor exclusive to quantum gravity—instead, it is a cluster of problems, at least one of which (the "problem of change", discussed below) arises even in classical GR, where it is linked to the interpretation of gauge invariance (Sect. 1.2). Other versions of the problem stem from the disparate way in which time is treated in GR compared to quantum theory. Time, according to quantum theory, is external to the system being studied: it is *fixed* in the sense that it is specified from the outset and is the same in all models of the theory. In GR, however, time forms part of what is being described by the theory. Time in GR is subject to dynamical evolution, and it is not "given once and for all" in the sense that it is the same across all models (Butterfield and Isham 1999). Reconciling these two treatments of time is not possible, and any attempt at formulating a quantum theory of gravity will thus face the problem of time in some form or another.

The problem of time also manifests itself in different guises depending on the different approaches to quantum gravity. The problem is easiest to appreciate in the canonical quantisation programs of GR (I here discuss one such example, *quantum geometrodynamics*), where it surfaces in several forms, including the one related to

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[26] Huggett and Wüthrich (2013) and Oriti (2014) also make this point.

the definition of observables and the interpretation of the gauge invariance of GR (the problem of change).[27] The aim of these programs is to produce a straightforward quantisation of GR. To this end, the strategy is to cast GR in Hamiltonian form and then to quantise this Hamiltonian theory using the canonical quantisation procedure.

Casting GR in Hamiltonian form involves splitting spacetime into space and time, so that the theory describes the evolution in time of the geometry of a three-dimensional spacelike hypersurface, Σ, i.e. a spacelike "slice" of the spacetime manifold. This splitting violates the gauge invariance (general covariance) of GR, with the result that the dynamical equations of the Hamiltonian formulation are not (alone) equivalent to Einstein's field equations. Additional constraint equations are thus imposed on the Hamiltonian system in order to mend the symmetries of GR.

The form, and number, of constraints depends on the choice of variables that the theory is formulated in; I here use the metric variables.[28] In this form, there are two types of constraint required in Hamiltonian GR: the diffeomorphism (or momentum) constraint and the Hamiltonian constraint. These constraints have a geometrical interpretation in terms of motions of Σ.[29] The diffeomorphism constraint generates (via infinitesimal transformations) diffeomorphisms *on* Σ: it shifts information tangentially to the slice. The Hamiltonian constraint generates (again, via infinitesimal transformations) symmetries *off* Σ: it pushes information (in a direction normal to the slice) from the slice to onto one that is infinitesimally close to it. The full Hamiltonian of canonical GR (not the constraint) is the sum of the diffeomorphism and Hamiltonian constraints, which together are needed in order to impose full diffeomorphism invariance (general covariance). Taking the Poisson bracket of the full Hamiltonian then gives the "time evolution" of the theory, which is just a combination of the two motions, tangential and normal, to Σ (because these transformations are symmetries, the motion is unphysical).

The quantisation procedure involves promoting the canonical variables of the classical Hamiltonian theory to quantum operators which satisfy the canonical commutation relations. Because these constraint operators generate the gauge symmetries of the theory, every operator that represents a genuine physical observable must commute with them.[30] In other words, the constraints determine the physical Hilbert space of the theory, and only the states which satisfy both constraints are physical states.

The diffeomorphism constraint is able to be readily interpreted as imposing a "canonical analogue" of (3-d) diffeomorphism invariance, indicating that points in

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[27] For detailed reviews on the problem of time, see Isham (1993), Kuchař (1992, 1999). For more philosophical introductions to the problem, see Belot and Earman (2001), Huggett et al. (2013), Rickles (2006).

[28] This is done for the sake of clarity. However, the canonical approaches that use the metric variables are no longer active lines of research; instead, most work is focused on the use of Ashtekar variables (see, e.g., Ashtekar 1986) and loop connections (see , e.g., Ashtekar et al. 1992)—these are discussed in Chap. 7.

[29] This is true for a given a shift vector N^a and a lapse function N.

[30] Part of the definition of a "physical observable" is that it be a gauge-invariant quantity.

space are not themselves physically meaningful.[31] The Hamiltonian constraint, however, is very difficult to make sense of. In quantum geometrodynamics, it is the Wheeler–deWitt equation,

$$\hat{H}|\psi\rangle = 0 \tag{1.5}$$

where $\hat{H}$ is the Hamiltonian operator, and $|\psi\rangle$ are the quantum states.

Since, in a classical theory, the Hamiltonian generates the dynamical evolution of the states, we might expect the Wheeler–deWitt equation to express the dynamical content of quantum geometrodynamics. Indeed, (1.5) resembles the familiar time-dependent Schrödinger equation that describes the evolution of states in quantum theory—except, of course, the right-hand-side of (1.5) has *zero* in the place of the time derivative. This absence of time in the "dynamical" equation of the theory is the primary form of the problem of time.

A second form of the problem of time, which arises even at the classical level of GR, is the *problem of change*.[32] In the context of quantum geometrodynamics, it comes about because, as mentioned above, the constraints generate the gauge symmetries of the theory, and all physical observables (being gauge-invariant quantities) described by the theory must satisfy the constraints. For an observable to satisfy (1.5), however, it must be a "constant of the motion"—conserved through all (gauge) motions and thus unchanging over "time". The second form of the problem of time, then, is that all physical observables do not change: the dynamics of the theory is "frozen". Any change described by the theory is only a gauge redundancy: an artefact of the mathematical description rather than a reflection of the physics.

It must be emphasised, however, that the Wheeler–deWitt equation is not only hard to make sense of in this respect, but that there are additional interpretative difficulties regarding the quantum state $|\psi\rangle$ (which will be briefly touched on in Sect. 1.7.1). Furthermore, (1.5) is difficult to deal with mathematically as well—it has no known solutions. Yet, we cannot just dismiss the Wheeler–deWitt equation as inconsequential, and nor can we ignore the problem of time. Quantum geometrodynamics represents the most straightforward attempt at formulating a quantum theory of gravity; it uses standard, proven methods to quantise GR. To simply stand back and declare that these methods must be inapplicable in this particular case, given the problems with (1.5) would be unjustified. If quantum gravity is construed as a theory that combines quantum theory and GR, then quantum geometrodynamics will be of interest because it reveals something about this very combination. (Also, again, it should be noted that at least one form of the problem of time is already part of the interpretation of GR itself, and this takes on new significance when considered in the context of the quantum version of the theory). Thus, we may be tempted to take the problem of time as evidence that time will not appear in quantum gravity.[33]

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[31] See Butterfield and Isham (1999, pp. 149–150) for a little more detail on the momentum constraint.

[32] See Wüthrich (2006), Rickles (2006).

[33] There is an additional problem of time in quantum gravity involving the idea of a "trajectory". In GR there is no preferred time variable, and time coordinates have no intrinsic meaning (and, since evolving from one slice to another is a symmetry, or a re-labelling, it too has no intrinsic meaning).

However, the absence of time in the Wheeler–deWitt equation cannot be interpreted so directly so as to be indicative of the lack of time quantum gravity. This is because quantum gravity needn't be a quantisation of GR.[34] In this book, quantum gravity is defined as a theory that applies at high-energy and which describes structures "beyond" GR. The picture suggested by several of the examples considered herein is that GR is a low-energy approximation to quantum gravity, and according to this conception, quantising the structures of GR will *not* in fact lead us to quantum gravity (Chaps. 3 and 5). On this view, quantum gravity is not a quantum version of GR—it is a quantum (in some sense) theory that GR approximates in a certain domain, a domain in which the quantum effects of the "underlying" theory are able to be neglected.

1.6 The Recovery of Spacetime

If we take quantum gravity to be the micro-theory of spacetime, and we are to uphold the GCP (p. xxx), then spacetime is to be understood as an *effective* structure, and GR an *effective theory*, meaning it is supposed to be valid only at length scales that are large compared to the characteristic length scale of quantum gravity (perhaps the Planck length). An effective theory is one that systematises what is irrelevant for the purposes at hand, and enables us to generate useful predictions with a finite number of input parameters.[35] On such a definition, we acknowledge that *all* our current physical theories are effective. We do not have a complete theory of everything; rather, we have theories that apply within particular domains, and serve us "for all practical purposes".

The fact that we do not have a complete physical theory of everything (i.e. one that would describe the effects of everything upon anything, and would enable us to calculate whatever we wished to calculate) is conceptually worrisome because we know that there are no isolated systems in nature. Whatever the system we are interested in studying, its behaviour is, strictly speaking, influenced by forces from innumerable other objects in its extended environment, which may extend as far as the observable universe. We are fortunate, then, that—for all practical calculations—we do not *need* to know the effects of everything upon the system of interest: we are

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(Footnote 33 continued)
In classical canonical GR, time is used to parametrise a "trajectory" (in configuration space) of the three-geometry Σ, and this is done in an arbitrary way. The quantum version of this theory has no explicit time parameter, and the trajectories thus "disappear". The analogy with the quantum description of a particle is easy to draw (as is done by, for instance, Kiefer 2000, p. 171 and Rovelli 2004, p. 30): while a classical description of a particle involves a trajectory, there is no such thing as a trajectory in the quantum description (although, of course, the description of the quantum particle involves a background spacetime, and this is not the case for canonical quantum gravity).

[34] For more discussion regarding this point, see Mattingly (2009), Wüthrich (2005) and the neat review in Weinstein and Rickles (2011).

[35] Wells (2012).

able to determine the effects that are the most relevant for describing the behaviour of the system to a given degree of precision, and ignore the rest. We do not need to know the position of Uranus in order to compute the trajectory of a cricket ball. This mundane fact is actually truly remarkable. Its familiarity is testament to its incredible power—were we not able to study a given phenomenon without having to understand all of the rest of the world, science would be impossible.

As explained above (p. xxx), however, this blessing also comes with a curse: the flipside to being able to describe familiar phenomena without knowledge of quantum gravity is that our current theories reveal very little of the high-energy physics from which they emerge. As human beings with a particular cultural background, we have adapted and become accustomed to dealing with events as existing in space and time—it is through the constructions of space and time that we interact with the world. These conceptions are basic to our experience. In order to imagine how—or even *that*—spacetime could emerge from something else—something possibly non-spatiotemporal—it seems as though we would need to be special sorts of visionaries, mystics, or on hallucinogens. It is difficult, as well, to technically demonstrate how a theory of spacetime could be recovered from a theory that describes non-spatiotemporal degrees of freedom; usual approximations and limiting procedures make use of the idea of spacetime. In keeping with the attitude that it is (at this stage) more useful to look at particular approaches to quantum gravity rather than consider general arguments in the abstract, this book will explore the techniques used in several different approaches to quantum gravity toward obtaining a low-energy limit, a spatiotemporal structure or some approximation to GR.

1.7 Two Transitions

Quantum gravity is not only supposed to be a small-scale (high-energy) theory—it is supposed to be a quantum (in some sense) theory. Thus, the recovery of spacetime from quantum gravity is likely to be a two-step process: there is the procedure by which the “classical appearance” is recovered, and there is the process of arriving at the low-energy limit of the theory, in which we return to known energy scales. The former is known as the quantum/classical transition, while the latter is called the micro/macro transition. While both of these transitions address the question of why we do not use quantum gravity to describe familiar gravitational phenomena, they are distinct, and may or may not be related to one another.

The quantum/classical transition occurs in familiar quantum theory. Quantum mechanics is not itself restricted to certain scales, but it is understood as a universal framework in physics; the “appearance of classicality”, justifying our ability to accurately describe much of our everyday phenomena using classical theories, is to be explained using some additional principles, hypotheses, interpretation or theory. This is connected to, but not exclusively about, the measurement problem. It may, for instance, involve the idea of decoherence, which is touted simply as “standard quantum theory with the environment included". This is explored shortly, in Sect. 1.7.1.

Decoherence, as well as the other ways of understanding the non-appearance of superpositions, is supposed to be something that *happens*—an occurrence in time.[36] On the other hand, the processes involved in the micro/macro transition are not supposed to be dynamical—they are theoretical or mathematical procedures used to obtain a low-energy (or large-scale) description of the physics. The micro/macro transition is not something that *happens* to a system. It is the "zooming out" to a coarser-grained theory, and showing how—and when—it becomes appropriate, or necessary, to use a new theory, that describes different degrees of freedom. The micro/macro transition may be represented by an approximation procedure, a limiting process (the "continuum limit"), or the renormalisation group flow and the other methods of effective field theory, as described in Chap. 3. Treating GR within this framework, for instance, may help us understand it is that GR could emerge as a low-energy theory, from a high-energy theory that describes the "micro" constituents of spacetime.

Additionally, is worth pointing out that there is another sort of transition that may be related to the emergence of spacetime: a phase transition. This is a dynamical process (even if instantaneous in some cases). The conceptions of emergence applicable to phase transitions, in particular second-order phase transitions, are explored in Chap. 4. In the context of quantum gravity and the emergence of spacetime, the phase transition has been termed "geometrogenesis", as discussed in Sect. 6.7.

As other authors have pointed out, taking the semiclassical limit of quantum gravity (as a means of representing the micro/macro transition) is not sufficient on its own to understand the emergence of the classical behaviour of spacetime.[37] This is because, if the superposition principle holds in quantum gravity, as it is typically assumed to do, then superposition states of spacetime (or the "atoms" of spacetime) will be the generic ones of quantum gravity, and a limiting procedure, on its own, will never resolve a quantum superposition. The order in which we consider (or apply) the two transitions may be important, too, depending on the relationship between them (Oriti 2014, for example, argues this point from the perspective of quantum gravity approaches that make use of the idea of geometrogenesis).

To summarise: In order to understand the emergence of spacetime from quantum gravity we require both a quantum/classical transition as well as a micro/macro transition. Although it is possible that the two transitions be somehow intertwined, they are conceptually distinct and can be discussed (more or less) independently of one another—indeed, at this stage, it seems preferable to do so. It may be that decoherence is involved in the quantum/classical transition in quantum gravity—yet it seems plausible that just as we can explore the relationships between known theories in physics (even quantum theories) and their low-energy limits without needing to invoke the idea of decoherence (or any other interpretation of the quantum/classical

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[36] For a discussion of decoherence in a non-dynamical context, see Wüthrich (Forthcoming).

[37] Kiefer (2000), Landsman (2006), Wüthrich (Forthcoming).

transition), so too we can explore the relationship between (a theory of) spacetime and (a theory of) its micro-structure.[38]

1.7.1 Decoherence

The process of *decoherence* was proposed in order to explain why it is that we typically describe most of our familiar, macroscopic physical systems using classical, rather than quantum, theories, in spite of the fact that such systems are themselves supposed to be quantum systems. It goes some way towards explaining how the classical picture emerges from quantum theory (because decoherence does not solve the measurement problem, however, it cannot provide the full explanation). If spacetime itself is ultimately a quantum entity, then decoherence might help us understand the emergence of its classical appearance.

The central dynamical equation of quantum mechanics is the (time dependent) Schrödinger equation,

$$i\hbar\frac{\partial}{\partial t}|\psi\rangle = \hat{H}|\psi\rangle \tag{1.6}$$

where $\hbar$ is the reduced Planck's constant, $\hat{H}$ is the Hamiltonian operator, and ψ is the wavefunction describing the system. This equation is linear and deterministic: given an initial state of the system, $|\psi\rangle$, we can compute the state at any time t. The linearity of (1.6) means, however, that if $|\psi_1\rangle$ is a solution and $|\psi_2\rangle$ is a solution, then the superposition state,

$$|\psi_3\rangle = \alpha|\psi_1\rangle + \beta|\psi_2\rangle \tag{1.7}$$

is also a solution (α and β are coefficients signifying the relative amplitudes, or "weighting" of each contribution, the sum of their squares being unity). Equation (1.6) tells us that a system described by any initial state, $|\psi\rangle$ will naturally evolve into a superposition. In other words, a superposition is the generic state of a quantum system. Of course, however, superpositions are never directly observed: when we make a measurement on the system, we find it to be in a state associated with a definite value of the property being measured (and superposed states cannot be characterised this way).

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[38] Anastopoulos and Hu (2008, 2007) make a similar point, though perhaps do so by downplaying the significance of the role of decoherence.

The most common way of understanding this phenomenon is via the Copenhagen interpretation,[39] which utilises the idea of non-linear wavefunction collapse.[40] This interpretation states that if we make a measurement on a quantum system in a superposition (1.7), then the superposition is destroyed as the wavefunction ψ collapses into a definite state that depends on what property was measured. A simple example is to imagine a system in a state of superposition where a single particle is localised about two different positions, i.e. the wavefunction is "peaked" in two different regions. Performing a measurement in order to determine whether the position of the particle is within a certain region will result in one of the peaks of the wavefunction (the one outside the region in question) collapsing to zero, and the particle being located at a definite position.

Collapse is instantaneous and irreversible. Many interpretations making use of the idea of collapse thus claim a discontinuity: they describe the evolution of a system as smooth and unitary according to (1.6), until the act of measurement abruptly collapses the wavefunction. Decoherence aims to address this disjointed description of a system's dynamics. Rather than an instantaneous, irreversible collapse, the process of decoherence describes how the coherence that characterises pure quantum states becomes heavily suppressed and no longer observable.[41] The process is supposed to describe a strictly unitary interaction, and thus be only *practically* irreversible (Schlosshauer and Fine 2007).[42] It calls on us to recognise that the vast majority of macro systems are not isolated, but are continually interacting with other entities surrounding them; for instance, a very simple macroscopic system comprising a single dust particle will have molecules (from the air) bouncing off it,[43] and it will have photons (from sunlight) bouncing off it. Such external entities not being taken as part of the system are called the *environment*. Decoherence says that interactions with the environment are responsible for suppressing the quantum nature of a system.

In quantum theory, when we need to express our ignorance of the state of the system before measurement, we use a *density matrix*. It describes the probability distribution for the alternative outcomes of a measurement on the system. For a system characterised by $\psi(x)$, the density matrix is,

$$\rho(x, y) = \psi(x)\psi^*(y) \tag{1.8}$$

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[39] Although it should be emphasised that many authors do not consider the Copenhagen interpretation to be consistent, nor even a complete "interpretation". Footnote 8 lists some other interpretations of quantum mechanics.

[40] Although there may be a variant of the Copenhagen interpretation which makes use of the idea of decoherence rather than wavefunction collapse. Also, there are (perhaps more viable) interpretations of quantum mechanics that make use of collapse, other than the Copenhagen interpretation.

[41] The description of decoherence in this section is based on Halliwell (2005), Joos et al. (2003), Zurek (1991).

[42] Other authors go on to tie its irreversibility to an increase in entropy and the second law of thermodynamics (e.g. Kiefer 2000; Zeh 2007; Zurek 1991).

[43] This system is considered in the calculation by Joos and Zeh (1985): one of the original papers on decoherence.

This density matrix corresponds to a *pure state*, also known as a coherent state: it corresponds to a system that can only be described by quantum mechanics. On the other hand, a system that involves both quantum and statistical mechanics is called a *mixed state*. The density matrix for a mixed state where we don't know exactly which quantum state the system is in, but we know the probability p_n that the system is in quantum state ψ_n is given by,

$$\rho(x, y) = \sum_n p_n \psi_n(x)\psi_n^*(y) \tag{1.9}$$

For a superposition state, as in (1.7), the density matrix is (with $\alpha = \beta = \frac{1}{\sqrt{2}}$, for normalisation),

$$\rho^c(x, y) = \frac{1}{2}[\psi_1(x)\psi_1^*(y) + \psi_2(x)\psi_2^*(y) + \psi_1(x)\psi_2^*(y) + \psi_2(x)\psi_1^*(y)] \tag{1.10}$$

where the superscript c stands for "coherent". The last two terms represent the interference effects, and it is these that prevent us from saying that the system is either in state $|\psi_1\rangle$ or $|\psi_2\rangle$. In order to describe classical probabilities, these off-diagonal terms (of the density matrix) need to be cancelled to produce the *reduced density matrix*,

$$\rho^r(x, y) = \frac{1}{2}[\psi_1(x)\psi_1^*(y) + \psi_2(x)\psi_2^*(y)] \tag{1.11}$$

The reduced density matrix ρ^r expresses classical ignorance (equating to the statement that the system is either in state $|\psi_1\rangle$ or $|\psi_2\rangle$). Decoherence is the process by which the pure, or coherent, state described by ρ^c becomes (to a good approximation) the mixed state ρ^r. A large system comprising many degrees of freedom is more strongly coupled to its environment than a small system with fewer degrees of freedom, and so decoherence occurs much faster for larger systems. Since macroscopic objects (being systems with a large number of degrees of freedom) are difficult to isolate from their environments, decoherence tells us that the interference effects rapidly "leak" out as the system goes from being in a pure state to a mixed state with its environment. In other words, the coherence is "distributed" over a large number of degrees of freedom characterising the system-plus-environment, making it unobservable (heavily suppressed) at the level of the system itself. The local suppression of interference is the reason why quantum effects are typically not observed for macroscopic objects.

If we believe that spacetime itself is a quantum entity, then—once we have an account of the micro-degrees of freedom—the idea of decoherence may be thought to play a role in explaining the absence of (detected) quantum effects; the quantum properties of spacetime may be suppressed via decoherence. As explained above (Sect. 1.5), quantising spacetime leads to the Wheeler–deWitt equation (1.5). Like the Schrödinger equation (1.6), the Wheeler–deWitt equation is linear and so admits solutions that are superpositions. The aim of decoherence is to explain why these superpositions are not observed in our universe (Padmanabhan 1989).

Here, we need to introduce an important distinction between *quantum gravity*, which describes spacetime as a quantum system, and *quantum cosmology*, which describes the entire universe as a quantum system. Motivation for quantum cosmology also comes from decoherence and the universality of quantum theory: for instance, Kiefer (2000, p. 167) states that if a system is coupled to its environment, and this environment is itself coupled to an environment, then it seems that the only closed system is the entire universe. Understanding decoherence in the context of the entire universe seems immediately problematic for exactly this reason, however, as the universe (by definition) does not exist in an environment—there can be no interactions with external degrees of freedom. Nevertheless, philosophers interested in quantum cosmology have argued that there are ways to define decoherence in this context, and that the idea of decoherence offers a better explanation of the non-appearance of universal superpositions than its alternatives.[44]

While research on decoherence in quantum cosmology often intersects with (or conflates quantum cosmology with) quantum gravity (see, e.g. Craig and Singh 2010; Halliwell 1989; Kiefer 2000; Seidewitz 2007), it should be clear that this book is only concerned with quantum gravity. Rickles (2008, p. 267) demonstrates the logical independence of quantum cosmology and quantum gravity by pointing out that the fact that our universe contains gravity is *contingent*. There could be another universe in which gravity is not present, and, although it would be a very different type of universe, we could still talk about quantum cosmology in that universe, even though gravity does not exist.[45]

Because the decoherence of spacetime is supposed to have occurred soon after the birth of the universe, quantum gravity—being necessary for understanding the conditions of the early universe—will need to say something about (or take into account) this process. Yet, decoherence is also important to the role of quantum gravity as a description of the micro-structure of spacetime as it is at present. It might seem odd that decoherence could be relevant to the current micro-structure of spacetime, when decoherence is thought to have occurred so long ago. However, this concern overlooks one of the features of decoherence compared to collapse interpretations—decoherence doesn't "turn" a quantum system into a classical one, instead the coherence "dissipates" over a large number of degrees of freedom. The interference effects might still be relevant at extremely small distance scales—say, the Planck scale. Also, we might expect that if we were to appropriately isolate some quantum gravitational system (or micro-spacetime system) that the quantum properties (i.e. interference effects) would be manifest. Decoherence would then

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[44] See, e.g. Kiefer (2000), Ridderbos (1999), Wüthrich (Forthcoming).

[45] Also, quantum gravity is usually taken to include a kind of vacuum state that would, at least in some sense, correspond to a world without gravity. To emphasise: quantum gravity and quantum cosmology, while distinct fields of research, certainly (and very importantly) inform one another.

explain why it is that such interference effects are not (relevantly) present in non-isolated quantum-gravitational systems.[46]

1.8 Weinberg–Witten Theorem

The Weinberg–Witten theorem is a constraint that is often cited as presenting an insurmountable obstacle for the formulation of emergent gravity (Weinberg and Witten 1980). If gravity is to be treated as a QFT, then its associated particle, the *graviton*, is massless and of spin-2. Consider $|p>$ and $|p'>$, being one-particle, spin-2, massless states labelled by their 4-momenta, and having the same Lorentz-invariant helicity ±2. If $T^{\mu\nu}$ is a Lorentz covariant, conserved current, and (hence) the matrix elements $< p'|T^{\mu\nu}|p >$ Lorentz covariant, then the Weinberg–Witten theorem states,

$$\lim_{p' \to p} < p'|T^{\mu\nu}|p >= 0 \tag{1.12}$$

The case of importance, of course, is where $T^{\mu\nu}$ is the stress-energy tensor, and in this case (1.12) states that the graviton cannot carry observable energy or momentum.[47] Thus, naively, this theorem seems to rule out any theory, including GR, in which the gravitational field carries energy.

Obviously, GR gets around the Weinberg–Witten theorem, and it does so thanks to a subtle interaction between gauge invariance and Lorentz invariance that means the matrix elements $< p'|T^{\mu\nu}|p >$ are non-covariant.[48] There are other means of avoiding getting caught by the Weinberg–Witten theorem; in particular, a theory will get around the theorem if it:

(a) lacks a stress-energy operator, or
(b) has non-relativistic gravitons, or
(c) has emergent (effective) gravitons, with emergent gauge invariance, propagating in an effective spacetime distinct from the background spacetime.

The emergent (effective) gravitons must exist in an effective spacetime, since a spin-2 gauge invariance in the background spacetime would prevent the gravitational energy from being locally observable. This would be a problem given that an array of separated mass scales is a requirement for formulating an effective field theory (as will be discussed in Sect. 3.4.1). First-quantised string theory falls under category

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[46] It is worth pointing out, too, that the relationship between decoherence and quantum gravity is not limited to the use of decoherence in attempts to recover the appearance of spacetime. Quantum gravity may help reveal new insights about decoherence: it might demonstrate that certain interpretations of quantum theory are better than others (as in e.g. Ridderbos 1999; Singh 2009), and perhaps gravity itself is involved in the decoherence of quantum systems that aren't exclusively quantum gravitational Gambini et al. (2004), Kok and Yurtsever (2003).

[47] See Barceló et al. (2011), Carlip (2014), Jenkins (2009).

[48] For details, see Carlip (2014).

(a), since $T^{\mu\nu}$ is unable to be defined.[49] The AdS/CFT correspondence (discussed below, Sect. 1.9) falls under category (c).

Many of the approaches to quantum gravity that are inspired by condensed matter physics feature emergent gravitons and fall under category (b). In the case of the general condensed matter approaches discussed in Chap. 5, there are no emergent gravitons, but only an effective geometry (a curved Lorentzian metric), and so the Weinberg–Witten theorem has nothing to say. However, for the condensed matter approaches in Sect. 5.2 that do consider gravitons (i.e. quantum fluctuations of the effective geometry), namely Volovik's superfluid models, the escape route is via (c). Still, those models in which the dynamics is implemented via the inclusion of quantum effects (along the lines of Sakarov's "induced gravity") are explicitly excluded from the Weinberg–Witten theorem, which "clearly does not apply to theories in which the gravitational field is a basic degree of freedom but the Einstein action is induced by quantum effects" (Weinberg and Witten 1980, p. 61). This is also the case in several of the discrete approaches considered in Chap. 6.

1.9 AdS/CFT Duality

A *duality* is an (exact or approximate) physical equivalence, which may hold between two different theories (featuring very different structures), or between two different regions of the parameter space of a single theory, e.g. a gauge freedom. The existence of dualities holding between theories with different pictures of spacetime has led to the suggestion that spacetime may not be fundamental.[50]

Perhaps the most significant example of such a duality is the *AdS/CFT duality*. This comes from superstring theory, which describes the fundamental constituents of matter as extended one-dimensional objects (strings) propagating on a ten-dimensional background spacetime. The strings can be open (i.e. lines), in which case they correspond to gauge particles, or closed (with ends joined to form a loop), in which case they correspond to gravitons. The AdS/CFT duality is an exact physical equivalence between a string theory that describes gravity and a Yang-Mills theory (i.e. a gauge theory) in which gravity does not feature among the fundamental degrees of freedom; hence, the AdS/CFT duality is also called a gauge/gravity duality. This conjecture was first presented by Juan Maldacena (1998).

The AdS/CFT duality is a concrete example of the holographic principle. As explained above, the holographic principle states that, for a gravitational theory defined over some region of spacetime, called the *bulk*, a complete description of the physics can be provided by a theory defined on the *boundary* that contains the bulk spacetime. The boundary will be of lower dimension than the bulk region of spacetime, for instance a two-dimensional surface bounding a three-dimensional

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[49] There is no consistent, off-shell definition of the string action S in the background spacetime with metric g_{ab}, so the object $T^{ab} = \frac{1}{\sqrt{-g}}\frac{\delta S}{\delta g_{ab}}$ is undefined (Jenkins 2009, p. 4).

[50] For instance, this claim is made by Seiberg (2007).

spacetime region. The application of the holographic principle to string theory came from Susskind (1995), owing to work by t Hooft (1993) and Thorn (1992).

The holographic principle is embodied in the AdS/CFT duality, since the gravitational theory involved describes closed strings propagating on a spacetime, while the physically equivalent gauge theory is defined on the boundary of this spacetime. More technically, the AdS/CFT duality states that the physically observable properties of a particular string theory in anti-de Sitter space (AdS) are equivalent to those of a particular conformal field theory (CFT) defined on the (conformal) boundary. The claim that dual theories are physically equivalent means there exists a bijection between states, operators, and correlation functions of the two theories.[51] Symmetries are preserved across the dual theories.[52]

Even though the relationship between the two theories is symmetric, and the duality is considered to be exact,[53] many authors take the AdS/CFT duality as implying that the gauge theory on the boundary is fundamental, while the higher-dimensional bulk spacetime is *emergent* from it.[54] This—unjustified—interpretation is even implicit in the use of the term "holography" to refer to the principle: although a (traditional) hologram is two-dimensional, it encodes information about all three dimensions of the object it represents, and the holographic image is apparently emergent from its (more fundamental) two-dimensional surface. The fallacious line of reasoning that leads to the suggestion that the gravitational theory is emergent is that an exact formulation of it has not been found, whereas we do have an exact formulation of the gauge theory, and so (the thought is that) the gauge theory is more fundamental.[55]

Instead, an appropriate interpretation of the duality would be one that treats the dual theories as being on equal footing. Although the duality apparently features two (very) different theories, we should view them as describing the same physical quantities, just using different concepts. In other words, we should imagine them as two formulations of the one theory, in some sense akin to a gauge transformation, or a change of variables in a single theory. Describing one theory as emergent from the other, on this picture, is misguided.[56] In order to defend the interpretation that

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[51] Note: this is a restricted definition of what it means to have dual theories. Different, or more general, definitions may be used in other cases.

[52] Though the theories can have different gauge redundancies, since the gravitational theory is diffeomorphism invariant while the gauge theory is not.

[53] Calculational results such as Aharony et al. (2000) contribute to the general acceptance amongst physicists that the duality is exact, in spite of no proof having (yet) been found Dieks (2015).

[54] Horowitz and Polchinski (2009), Horowitz (2005), Seiberg (2007).

[55] de Haro (2015), Dieks (2015) also expose this shoddy reasoning, and Rickles (2013) points out that calling one theory more fundamental than the other is inconsistent with the (correct) interpretation that both theories are physically equivalent.

[56] de Haro (2015), however, argues that an interesting notion of emergence is possible if the duality between AdS/CFT is rendered *approximate*—modifying each of the theories by a suitable coarse-graining operation leads to new structures and physical quantities appearing, and enables us to claim that GR emerges from the string theory side of the duality. If this were done, there would also be emergence on the QFT side.

the dual theories represent the same physics, we can appeal not only to the existence of the duality mapping (by which one theory is mapped to the other), but also to the fact that the theories share the same symmetries (Rickles 2013, p. 8). These shared symmetries represent a *deeper structure* which underlies the two representations, and which will only be fully revealed by yet another theory—one that would be more suited to being called “fundamental”. If we accept this interpretation, then, it seems that we might again have a basis for the claim that the AdS/CFT duality implies emergent spacetime—in fact, we might say that it implies two different emergent spacetimes (as approximations, or representations, of the more fundamental physics).

1.10 The World in a Grain of Sand

A theme running throughout this book is what Nambu, in his 2008 Nobel Prize speech, referred to as the “cross-fertilisation” of high-energy physics and condensed matter physics (Nambu 2008). The cross-fertilisation considered here spreads even further, though, as we move into the realm of quantum gravity, and draw inspiration (as well as techniques) from not only particle physics and condensed matter physics, but statistical physics and thermodynamics as well. This book represents, in its approach, an attempt at cross-fertilisation between physics and philosophy, exploring what we can learn of the notion of emergence by considering its use in both domains, and hopefully, in doing so, enriching the philosophy of emergence as well as moving toward understanding the emergence of spacetime in quantum gravity.

As described in Sect. 2.5, the idea of emergence in physics that I am interested in gained the attention of philosophers following Anderson’s “More is Different” (1972), which argued that there are multiple “levels” in science, defined by the energy scales at which different theories or descriptions are applicable; and one level is no less fundamental, or important, than another simply by virtue of its applying at higher-energy. According to Anderson (1972), a small-scale description of a physical system is not usefully applied at large-scales, because new degrees of freedom emerge at large-scales—describing the emergent phenomena requires new laws and new concepts not featured in the higher-energy theory and not easily obtained from the higher-energy theory. Anderson’s views are well-supported by the examples considered in this book. We find that low-energy theories are not only importantly novel compared to the high-energy description (having different equations of motion and describing distinct degrees of freedom), but also robust under changes in the high-energy physics—they depend, for the most part, only minimally on the small-scale happenings at the “level below” (in length scale).

Yet, in spite of this, we find that there is much that is “carried over” between levels. The techniques of the renormalisation group and the formalism of effective field theory were developed in quantum field theory, then shown to usefully apply in condensed matter physics. Nowadays, the renormalisation group is used in fluid mechanics, nanotechnology and cosmology (and, in this book, the ideas of the renormalisation group and effective field theory are explored in the context of quantum gravity). The universe at large, it seems, shares some features (even if only structural features) in common with the world at the smallest scales. What is particularly interesting about the renormalisation group is that it explains its own success across these different levels with their very different laws and concepts. As described in (Chaps. 3 and 4), the renormalisation group reveals that only minimal aspects of the high-energy physics need to be accounted for at low energies, and that the means of "taking into account" these interactions disguises their origins in terms of the robust low-energy degrees of freedom.

The approaches to quantum gravity discussed in this book not only utilise the ideas of the renormalisation group and effective field theory, but also share inspiration, techniques and principles with statistical physics, thermodynamics and hydrodynamics. Again, the aspects that are selected owe their power to the way they "pick out" certain features of the high-energy physics and demonstrate how these translate, very generally, to low-energy phenomena: they do so in a way that leaves the details of the high-energy system *underdetermined* by the low-energy physics. In other words, the high-energy system contains far more information than is required in order to explain the *emergent* features of the low-energy physics.[57]

There are tantalisingly strong analogies between quantum field theory and condensed matter physics, and exploring how these might extend into quantum gravity is interesting as well as exciting. Volovik (2003) demonstrates how we might understand the standard model of particle physics as emergent, at low-energies, from superfluid helium, and, as discussed in Chap. 5, other condensed matter approaches can produce the effective curved spacetime (metric) of GR. Yet, in attempting to make sense of the success of these analogies, in order to potentially learn something of the unknown high-energy realm, it is frustrating to understand the reason for their success as also being a tremendous hinderance to our gaining insight into the details of this realm.

1.11 Synopsis

Chapter 2: Emergence

The relationship between spacetime (or GR) and quantum gravity has often been called "emergence", yet the term is notoriously ill-defined. In light of this, the second chapter of this book is dedicated to exploring the meaning of the term in philosophy and in physics. Rather than canvassing the many different uses of "emergence" in philosophy, the focus is on understanding emergence as it is used to describe an inter-theoretic relation in the philosophy of science and the philosophy of physics. Accounts of emergence in philosophy typically appeal to the ideas of reduction and derivation; after explaining this, I outline the difficulties with such accounts and begin to give an indication of why I do not find these ideas useful (at least not

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[57] I apologise for the vagueness of these remarks: they will be made concrete in the rest of the book.

for the current project). I also discuss Jeremy Butterfield's work on emergence (i.e. Butterfield 2011a, b, 2012).

Following this, I introduce the debate between physicists Steven Weinberg and Philip Anderson (and others) that was responsible for sparking much of the recent curiosity in the topic of emergence in the philosophy of science. While I do not engage with the debate directly, it is of interest because the physical examples that were appealed to in making the claims of emergence are essentially the same as those that I am concerned with. Having already attempted to discourage thinking about emergence in terms of reduction, I present some indication of how we might understand emergence without appeal to reduction. This alternative sense of emergence is based in the *novelty* and *autonomy* of the emergent physics given the theory it emerges from. After explaining this, I briefly look at how the term "emergence" is used in physics; finally, I consider the idea of fundamentality (i.e. what it means for a theory to be fundamental) in regards to the new conception of emergence being advocated.

Chapter 3: *Effective Field Theory*

As stated above, an effective theory is one that is supposed to be valid only within a particular domain—typically, at energy scales that are much lower than the energy scale taken to characterise the successive theory. The framework of *effective field theory* is a means of formalising this idea for a certain class of theories under certain assumptions. An effective field theory (EFT) may be said to be emergent from the micro-theory that underlies it. The idea of emergence in EFT is non-standard and has been controversial in the philosophy of physics literature, so the purpose of this chapter is to explore the idea of emergence in EFT independently of quantum gravity.

The chapter comprises two parts: in the first, I provide a basic introduction to EFT and its development, which stemmed from "the problem of renormalisation" in QFT and the discovery of the renormalisation group (RG). The second part of the chapter deals with the philosophy of EFT, including the idea of emergence. Because much of the philosophy of EFT has centred around some controversial claims made in the presentation by Cao and Schweber (1993), I begin by examining these. I argue that the controversy stems from a confusion between EFT as it applies *in principle* and EFT as it actually applies *in practice*.

I then go on to propound a philosophy of EFT based in how the formalism applies in practice, emphasising that we are not justified in asserting that many of the "in principle" claims hold true in physics—especially when it comes to inaccessibly high-energy scales. I explain how this view has consequences for our understanding of QFT and the physics beyond our current theories. Finally, I present an account of emergence in EFT compatible with this philosophy. Owing to a subtlety in the necessity of EFT, I find that a conception of emergence defined by reduction is inadequate in this case. The appropriate account is one based simply on the novelty and autonomy of an EFT compared to its high-energy theory.

Chapter 4: Universality, Higher-Organising Principles and Emergence

Inspired by two recent accounts of emergence in physics (Batterman 2011; Morrison 2012) associated with phase transitions and critical phenomena (in which the RG plays a crucial role), I turn to explore the conception of emergence applicable in these physical examples. This is significant given that some of the approaches to quantum gravity imply, or claim, that spacetime geometry emerges following a phase transition. There are bases for emergence, I find, in the ideas of *universality* and *higher-organising principles*.

Universality in critical phenomena is the fact that large classes of different systems exhibit the same behaviour when undergoing a second-order phase transition. This idea is essentially related to that of *multiple realisability*, which has itself featured in discussions of emergence, so the chapter begins with a brief summary of the relationship between these ideas. Following this, the idea of a higher-organising principle is introduced, with symmetry-breaking in phase transitions presented as an example.

The case of critical phenomena is then outlined, and I argue that we can associate a conception of emergence both with the idea of symmetry-breaking as a higher-organising principle and with the idea of universality associated with fixed points in the RG flow (i.e. they each furnish an account of emergence). Following this, I consider the conceptions of emergence of Robert Batterman (2011) and Margaret Morrison (2012). Although each account has its own nuances—with Batterman emphasising the role of limiting relations and mathematical singularities, and Morrison stressing the importance of symmetry breaking in addition to the RG-based explanation—I argue that the interesting aspects of emergence are actually provided simply by the idea of universality.

The idea of universality is tied to several other examples of emergence in physics, including EFT and hydrodynamics, and so I explore the relationship between these as well. Such investigation is important given the suggestions (explained later in Sect. 5.4) that gravity is asymptotically safe (meaning it is represented by a fixed point in the RG flow and has an associated notion of universality), as well as other claims that GR is analogous to hydrodynamics (these are examined in Chaps. 5 and 6).

Chapter 5: Spacetime as Described by EFT

This chapter examines the possibility of treating GR as an EFT, and, drawing from the ideas presented in the previous three Chaps. 2–4, explores what we might learn of emergent spacetime through the framework of EFT. The idea of treating GR as an EFT is natural not only from the acceptance of the GCP (as argued above), but because of the desire for unification that the search for quantum gravity represents. This desire for unification leads us to attempt to incorporate gravity into the framework of QFT and treat it as we do other fields. There are two perspectives from which we can approach GR as an EFT—“top-down”, where we start with a high-energy theory and attempt to recover GR as a low-energy EFT, and “bottom-up”, where we start with GR as the low-energy EFT and seek to discover the micro-theory—and I look at examples of each in this chapter.

Firstly, I consider examples of "analogue models of GR" which present the metric structure of GR (described by an EFT of quasi-particles) emergent from a condensed matter system. These provide concrete examples of spacetime emergent as the low-energy collective excitations of very different micro-degrees of freedom. I explain how (and to what extent) these models illustrate the conception of emergence (as novelty and autonomy) in EFT outlined in the previous chapters. Interestingly, these models provide us with emergent spacetime, rather than emergent GR. I also argue that, in accordance with the philosophy of EFT propounded in Chap. 3, we should be wary of drawing too much from the analogy between condensed matter physics and QFT.

Secondly, I look at 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. I finish the chapter by outlining the asymptotic safety scenario, which is an important conjecture that comes from treating GR in the same way we treat other QFTs, and relates not only to the idea of a fixed point, but has inspired many different "discrete" or "background-independent" approaches to quantum gravity, some of which will be discussed in the next chapter.

Chapter 6: Discrete Approaches to Quantum Gravity

In this chapter I consider several examples of "discrete" approaches to quantum gravity—including causal set theory, causal dynamical triangulations, quantum graphity and quantum causal histories. These are approaches that describe discrete basic elements that, in some sense, constitute spacetime at high energy. In many of the approaches, spacetime is conceived of as an effective, low-energy manifestation of very different high-energy degrees of freedom.

After briefly outlining each approach, I examine the means by which each attempts to recover spacetime (and/or GR) as well as the potential bases for emergence that they present. I find that the conceptions of emergence that these approaches suggest are similar to those already considered in this book. Interestingly, many of them also provide evidence of a phase transition, and, by analogy with the conceptions of emergence explored in the previous Chap. 4, may provide examples of diachronic novelty as well as autonomy.

Chapter 7: Loop Quantum Gravity

Loop quantum gravity (LQG) is one of the most well-established quantum gravity programs (along with string theory). Proponents of LQG hold that the greatest lesson of GR is that the gravitational field is diffeomorphism invariant, and so LQG seeks to preserve diffeomorphism invariance at the high-energy level of quantum gravity. Like the discrete approaches, LQG describes the small-scale structure of spacetime as being discrete. However, the proponents of LQG claim that, rather than being a *postulate* of the theory (as it is in the discrete approaches), fundamental discreteness is a *prediction* of the theory. It is not clear that this is indeed the case, though, because the discrete operators described by LQG are not physical observables as they stand.

This chapter is concerned with the conception of spacetime described by LQG: I explore the micro-structure of space, as well as that of spacetime, suggested by the theory. I then consider the semiclassical limit and the attempts to recover spacetime in LQG, before discussing the potential bases for emergence in the theory.

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