Chapter 2
Emergence and Reduction

2.1 Introduction

This book concerns the relationship between spacetime and the high-energy theory that we believe underlies it. Although this relationship has often been termed "emergence", there are a variety of things going on in the different approaches to quantum gravity. In this chapter, I consider the philosophical literature on emergence in order to see how the term applies and decide whether it is a potentially useful one to appeal to in making sense of the emergence-claims in the physical examples. I find that, although the word "emergence" has many different uses, it is preferable that we do not, in fact, begin with any strict definition of it. Instead, as I explain, the better option is to explore the different relations in the physical examples on their own merits rather than as candidates for a relation of emergence according to any particular philosophical conception. Of course, this does not mean that I reject any possible correspondence or comparison of these relations with other philosophers' conceptions of emergence—rather, given the many different conceptions of emergence available, working with a general framework instead of a strict definition should facilitate a clear and open discussion.

If we were to begin with an aim of interpreting the physical examples in terms of a strict definition of emergence, this would place us in a tight spot. On the one hand, we would need to capture enough of what philosophers take to be important in defining a conception of emergence for the concept to still be understandable as emergence, but, on the other hand, we would not want to be so tied to a prior conception of emergence that we'd be able to learn nothing significant from the physical examples (other than to what extent they may be said to embody the conception of emergence we begin with). The difficulty would be compounded by the fact that it is very hard to provide an overarching definition of emergence (as we shall see); indeed, the most sensible philosophical stance is to admit that there is no single "best" definition of emergence that applies across the board, but rather many different conceptions, each with its own advantages and domain of applicability.

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Even though "emergence" is so widely-used as to elude a precise general definition, it is typically associated with the ideas of supervenience and reduction. I find that, while these concepts may be useful in framing an understanding of emergence, they are not necessarily related to the idea. Also, at the heart of emergence-discussions in philosophy lies a distinction between ontological- and epistemological-emergence. This forces us to focus on the ideas of deduction and derivability, which, I argue, is an unhelpful (or at least uninteresting) perspective to take when considering the physical examples. Owing to these facts, this chapter (Sect. 2.4) presents the conception of emergence used in this book as only a vague skeleton, and one that does not rely on the idea of reduction. It might seem, at first, that this conflicts with my claim that the GCP is taken as a principle of quantum gravity, given that the GCP utilises the idea of reduction. In fact, we can uphold the GCP while maintaining that there are conceptions of emergence in quantum gravity that do not rely on reduction. As will be argued in this chapter, there are many ways of defining reduction and derivation, and separating these issues from our account of emergence is useful. Also, the conception of emergence used in this book is not exclusive, and the physicists' sense of emergence may still hold. The skeleton conception introduced here (Sect. 2.4) is inspired by the physical examples explored in the later chapters, and each of these examples "fleshes out", or embodies the idea of emergence in a different way.

The conclusions I arrive at in this chapter are not completely alien. A number of authors endorse pluralism regarding emergence, and eschew a definitive definition of the term. Butterfield and Isham (1999), for instance, after a thorough exploration of three different candidate relations for emergence (reduction understood as definitional extension, and supervenience), find a "heterogeneous picture of emergence", and suggest that it is best to bear in mind the variety of different ways in which theories may be related (with particular emphasis on limits and approximations), rather than seek an overarching definition. Also, Silberstein (2012, p. 637), in reviewing three large recent edited collections of articles on the topic, states that different cases require different conceptions of emergence, and that it is absurd for philosophers to try and argue otherwise.

This chapter proceeds as follows: I begin by attempting to give some indication of what philosophers mean by "emergence", and, in doing so, reveal emergence-talk as a vast and thorny thicket. Next, I outline the difficulties with typical accounts of emergence, being those that are somehow linked to reduction and/or derivation, and explain that the tendency to think of emergence as a failure of reduction (or derivation) is related to the desire to classify cases of emergence as either ontological or epistemological. I argue that we are better to consider the science first, rather than immediately getting tangled up in questions regarding how our theories relate to the world. This explains the approach taken in the following chapters, which focus primarily on exploring the physical examples and the relations of emergence they suggest, unequipped with a exact prior definition of the term.

I then explain how the term "emergence" is typically used by physicists, which involves the idea of reduction. I argue that defining reduction is as difficult as defining emergence—and that taking this path, by choosing a particular definition of reduction, also necessarily means closing the door on many other, incompatible, views.

Thus, we risk ending up with a conception of emergence with restricted applicability and interest. Rather than attempt the long, exclusive—and possibly treacherous—route of seeking out a particular definition of reduction whose failure best characterises emergence, it is better, when considering the physical examples that I do in this book, to focus on a positive definition of emergence, unconcerned with reduction. I then attempt to indicate the features of the positive accounts of emergence.

Following this, I introduce the "physicists' debate" that sparked much of the recent interest in the topic of emergence, at least in philosophy of science. I am not so interested in examining the debate itself, but the physical examples that were appealed to in making the claims of emergence are very similar to (or even representative of) those that I am concerned with; as is shown in later chapters, these physical cases exemplify some interesting aspects of emergence and other inter-theory relations. Most importantly, the lessons that can be drawn from them are also applicable to modern approaches to spacetime and quantum gravity. I fear that much of what is interesting about these cases (i.e. those that are involved in the "physicists' debate", not quantum gravity) has been neglected precisely because it does not match-up to philosophers' prior conceptions of what counts as emergence. Finally, I outline the implications of this discussion for the conception of fundamentality, i.e. what it means for a theory to be *fundamental*.

2.2 Emergence

In philosophy, the topic of emergence is currently a very popular one; just some evidence for its "academic trendiness" is the recent publication of three large edited collections on emergence (Bedau and Humphreys 2008; Corradini and O'Connor 2010; Howhy and Kallestrup 2008) as reviewed by Silberstein (2012). The vast literature on emergence is almost matched in size, though, by the wildly diverse range of uses (and definitions) of the term itself. As Silberstein (p. 627), with some apparent vexation, notes: philosophers tend to bristle upon hearing the word "emergence", feeling it "too multifaceted, vague or ambitious to be coherent". Working from the articles in these edited volumes—which range in subject from the emergence of classical physics from quantum physics, emergence associated with singular limits and phase transitions, emergence of life from chemistry, emergence of embodied cognition, emergence of group cognition, emergence of consciousness, to the emergence of souls—Silberstein (2012) develops a taxonomy of emergence comprising a total of seven different claims.

The basic expression of emergence, "X is emergent with respect to Y", is the idea, very crudely, that Y is some presumably more fundamental property (phenomenon, system, theory, etc.), upon which X depends in some sense and from which X has autonomy in some sense; the emergent X is typically understood as being *in some sense* less fundamental than its base Y, and *in some sense* not reducible to its base Y A general definition of emergence may thus be taken as comprising two claims. Bedau

(1997, p. 375) puts them thus (although the labels "Dependence*" and "Autonomy*" are my additions),

Dependence* (or Linkage) Emergent phenomena are somehow dependent on, constituted by, generated by, underlying processes. (A less-fraught term is *Linkage*, where we might say that the emergent phenomena is, in some appropriate sense, linked to the underlying system or processes).[1]

Autonomy* Emergent phenomena are somehow autonomous from underlying processes.

Typically, the first of these claims, *Dependence**, is relatively uncontroversial, and it is the second claim that serves to distinguish different conceptions of emergence. In the vast majority of cases, *Autonomy** involves ascribing one or more of the following features to the emergent phenomenon (property, system, theory, etc.): irreducibility, unpredictability, causal independence, or unexplainability given its base. In other words, the claim that some phenomenon is emergent is usually understood as the claim that the phenomenon is *in some sense* not reducible to (i.e. deducible from) its base.

This leads us to the core distinction in the emergence literature. *Ontological emergence* is the thought that this failure of reduction (in whatever sense is meant) is a failure *in principle*: that there are genuinely emergent phenomena (properties, systems, theories, etc.). It is emergence in a strong sense. This stands in contrast to *epistemological emergence*, which is a failure of reduction *in practice*, meaning that the apparent emergence is (somehow) really only an artefact of our computational limitations. Epistemologically emergent phenomena are not "genuinely emergent", but, for whatever reason, it is very difficult for us to explain, predict or derive them on the basis of their underlying system(s). This leads to epistemologically emergent properties being termed *predictive* or *explanatory* emergent properties.

There are two general classes that fall under the category of explanatory emergence in Silberstein (2012) taxonomy. One of the definitions that comes under the first of these classes is Bedau's "weak emergence" (See e.g. Bedau 1997, 2002, 2008). In developing this conception of emergence, Bedau is interested in complexity science, which deals with systems that are extremely sensitive to their initial conditions. Given the micro-details of such a system (including the micro-dynamics), together with the initial conditions plus all other external conditions, the macro-description of the system can be derived but only by *simulation*. This involves inputting a continual stream of successive boundary conditions into the equations governing the micro-dynamics.

These boundary conditions, Bedau (1997, p. 379) emphasises, are extensively contingent, and derivations that depend on simulations are "awash with accidental information". Such derivations are too detailed and unstructured to impart any sort of understanding of the relation between the micro- and macro-levels, and may in fact obscure simpler macro-level explanations of the physics, but, nevertheless, the

[1]My definition of Dependence is provided on p. xxx, and is the claim that the emergent theory is related to the theory it emerges from via the RG and EFT techniques.

macro-level description is able to be derived from the micro-level description plus external conditions. This is equated with "explanatory incompressibility" (Bedau 2008).

The second class of explanatory emergence is associated with the representational resources needed to understand some phenomena.[2] As Silberstein puts it:

> Certain wholes (systems) exhibit features, patterns, behaviors or regularities that cannot be fully represented and understood using the theoretical and representational resources adequate for describing and understanding the features and regularities of their parts and reducible relations. Even when the properties of the whole are metaphysically or otherwise determined by the properties of the proper parts of the whole, we might not be able to model the properties of the whole in terms of the vocabulary that we use to model the properties of the parts (Silberstein 2012, p. 633).

I've presented these two conceptions of explanatory emergence because they demonstrate, clearly, just how complicated and nuanced the focus on derivability can be (and typically is). The difficulty in articulating a conception of Autonomy* usually becomes the difficulty in articulating the conception of reduction that is not being exemplified. This is not a helpful shift, because the use of the term "reduction" is as equally ubiquitous and heterogeneous as "emergence". Rather than stressing the relation of emergence as a failure of reduction (in any sense) I want to focus on the other, positive, aspects of the idea.

The following three sub-sections are intended to motivate the shift from thinking in terms of reduction to utilising a positive conception of emergence (introduced in Sect. 2.4). They present very general problems rather than definitive arguments.

2.2.1 Distinguishing in Principle from in Practice

One reason we might be tempted to shift (or, at least, be open to shifting) from talking about a definition of emergence based on reduction to talking about a definition based in other notions is that emergence is wounded by the great cut that runs through it, dividing it into ontological and epistemological cases. The main problem with distinguishing emergent phenomena as either ontologically or epistemologically emergent is that, in many interesting cases, it is unclear whether our failure to derive, explain or predict them given their base is a failure *in principle* or merely *in practice*. Indeed, it is unclear even how the distinction is supposed to be decided in most cases when we are talking about successful scientific theories. It seems like we would require an account of the relationship between a scientific theory and ontology. The question of how—or whether—our theories represent the world is an extremely interesting and important one. But it is also one of the most difficult questions that there is. If we are

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[2]As we shall see, 3 explanatory emergence is one conception of emergence that may be said to apply to EFT: for instance, we would, presumably, want to say that the effective theory describing the hadronic states is explanatorily emergent from the "underlying" quantum chromodynamics—it is derivable in principle (we believe), but nevertheless necessary for imparting any understanding of the low-energy phenomena.

concerned, as I am in this book, with the humbler task of explicating the relationships between physical theories, then the question of whether these represent ontological or epistemological relationships is one, I submit, we are not automatically compelled to address. In fact, it seems preferable to avoid engaging with this issue if it would mean locking horns with the question of how our theories connect to the world.

The purpose, or legitimacy, of placing so much weight on the distinction between a derivation that is not possible *in practice* from one that is not possible *in principle* should also be contested, given the obscurity of these statements. Consider an attempt to derive molecular structure from the Schrödinger equation. Although we might take this as being possible *in principle*, it would require infinite computational power: if the amount of computer memory necessary to represent the quantum wavefunction of one particle is N, then the memory required to represent the wavefunction of k particles is N^k (Laughlin and Pines 2000). The idea of the derivation being possible in any meaningful sense threatens to evaporate. So, when a claim is made that something is possible *in principle*, whoever is making the claim needs to explain exactly what they mean by it. We need to be careful, too, when asserting that a derivation is (not) possible *in practice*—presumably we do not simply mean that we are (un)able to make the deduction from micro-theory to macro-physics unaided as humans, but then we shift the question into one about computational limitations (which are potentially arbitrary, and possibly subject to change in the future). And, of course, we need to keep in mind that a derivation not being possible in practice is no indication that it is, or is not, possible "in principle". Again: issues of modality are certainly interesting and important, but we do not necessarily need to engage with them for the purposes of better understanding the relationships between our physical theories.

In spite of these difficulties, however, it is of course entirely plausible that one could find a definition or a some other means of distinguishing ontological from epistemological cases of emergent scientific theories. Yet, the inclination and cost of doing so should be queried. We are not doing metaphysics or philosophy of mind, and do not need to carry over certain concepts unless they are useful. A focus on the question of whether an account of emergence is ontological or epistemological is potentially distracting, and, in spending our time trying to make sense of the categories given the physical theories, we risk overlooking or ignoring more interesting and tangible relations; we end up going metaphysics-first rather than science-first in our methodology. Therefore, as stated earlier, the accounts of emergence presented in this book are supposed to apply to theories (or models), and the question of whether they are to be understood as epistemological or ontological is not properly addressed.

2.2.2 The Problem of Defining "Derivation"

The problem of defining "reduction" is one I return to shortly (Sect. 2.3.1), however, there is a similar problem in defining "derivation". As we shall see in considering effective field theory (Chap. 3), it is tempting to relate emergence to a failure of derivation *in practice*, and even to attempt to strengthen this account by stressing the derivational independence of the theories in question. Bain (2013a, b), for instance, argues that the use of approximations and heuristic reasoning in arriving at the macro-theory from the micro-theory, together with the fact that specification of the equations of motion (plus boundary conditions) for the micro-theory will fail to specify solutions to the equations of motion for the macro-theory, mean that there is no sense in which we can arrive at the macro-theory by means of a *derivation* from the micro-theory.

Clearly this conception of emergence then just depends on what we would permit to count as a derivation. Typically in physics, derivations *do* involve some use of approximation and/or additional assumptions (even if it it just those involved in defining the "correspondence principles" that are required in addition to the theory), so it perhaps becomes a matter of degree. However, the question of how strongly a derivation in physics must rely on approximation or additional assumptions before it ceases to count as a derivation and instead is to be classed as something else, is one that I feel is irrelevant to the question of emergence, or, at least irrelevant to the important or interesting aspects of the relation. Again, appealing to Sect. 2.2.1, it may be difficult to tell whether, in any particular case, the use of approximation is necessary in principle or merely in practice, and, again, we might question the point of even attempting to distinguish between the two scenarios.

2.2.3 A Varied Landscape Where Less Is Different

I am not the only one to claim that emergence may be separated from reduction. Butterfield (2011a, b, 2012) have written a series of papers in which the independence of emergence and reduction is demonstrated, using an assortment of physical examples, including phase transitions. These show that we can have emergence with reduction, as well as emergence without reduction. Emergence is defined simply as novel and robust behaviour relative to some comparison class, and reduction is defined as deduction aided by appropriate definitions or bridge principles (i.e. Nagelian reduction).[3] I view Butterfield's results as evidence that we should step aside from defining emergence in terms of reduction, and finally stop debating the issue of "emergence *versus* reduction".

However, apparently not everyone who considers the demonstrated reconciliation of emergence and reduction in Butterfield (2011a, b) has the same response. Callender (2013), for instance, follows Butterfield in exploring the example of phase

[3]This conception of emergence is essentially similar to the one I propound here. As will be shown in Sect. 2.4 however, my account features an additional aspect (Dependence). Also, I go further than Butterfield in articulating the basis for novelty and autonomy (I do this using the ideas of underdetermination and universality, which are not part of Butterfield (2011a, b) account); and, unlike Butterfield (2011a, b), my account here does not make reference to limits. Another important contrast is that my account is supposed to apply to EFTs in general, while Butterfield (2011a, b) considers only specific examples of EFTs.

transitions, but is concerned with the claims of several authors who argue that, because reduction fails in some sense (between the thermodynamic description of the phenomena and the statistical mechanical one, owing, in some way, to the thermodynamic limit), phase transitions represent emergent phenomena. For each of these claims, Callender (2013) finds a different way in which reduction does not fail. So, while Butterfield argues that emergence and reduction are logically independent (i.e. we can have emergence with reduction, as well as emergence without reduction), Callender (2013, p. 32) argues that there is no sense of emergence that poses a threat to "the reductionist program broadly construed". Callender's conclusion is revealing of philosophers' willingness to engage in the grand battle between 'emergentists' and 'reductionists', and the sad fact that any claim of emergence is often only of interest for its consequences regarding reduction. The point I want to make is that, if we are interested in understanding our physical theories and the relationships between them, we do not need to take up arms—we can explore emergence without having to engage with issues of reduction (*even though* there may be various ideas of reduction in the vicinity). Indeed, the shift in focus promises to enable us to see new questions in the philosophy of physics that we otherwise would overlook.

2.3 Emergence in Physics

Usually in physics the idea of one theory, T_1, being emergent from another, T_2, is taken to mean that T_1 approximates (i.e. approximately reproduces the results[4] of) T_2 within a certain limited domain of T_2's applicability. Physicists' terminology runs backwards to the philosopher's, as physicists would say that in this case the "more fundamental" theory T_2 *reduces to* the emergent theory T_1 within the domain where the latter is applicable. An example is Newtonian mechanics emergent from special relativity: the latter "reduces" to the former in the classical limit, $(v/c) \rightarrow 0$ or (where v is the velocity of the system and c the speed of light), which is just to say that the emergent theory, Newtonian mechanics, can be derived from the more fundamental theory, special relativity, within the domain (i.e. for particular values of pertinent quantities) where the former is known to hold.[5] In philosopher's jargon: Newtonian mechanics is reducible to special relativity.

The physicists' conception of emergence in such cases is thus very different to that of the philosophers, being more akin to reduction rather than to a failure of reduction. A nice illustration of this conception is provided by Fig. 2.1, adapted from Butterfield and Isham (2001, p. 79) This figure represents a "tower of theories", where each emerges from the one above it (we might think of the theories toward the top of the tower—i.e. closer to the "ultimate" theory—as being applicable at higher energies

[4]As Butterfield and Isham (2001) note, "results" here can include theoretical predictions as well as larger structures such as derivations and explanations.

[5]This relates to the GCP (1.1.1), which I am taking as a principle to uphold in the search for quantum gravity.

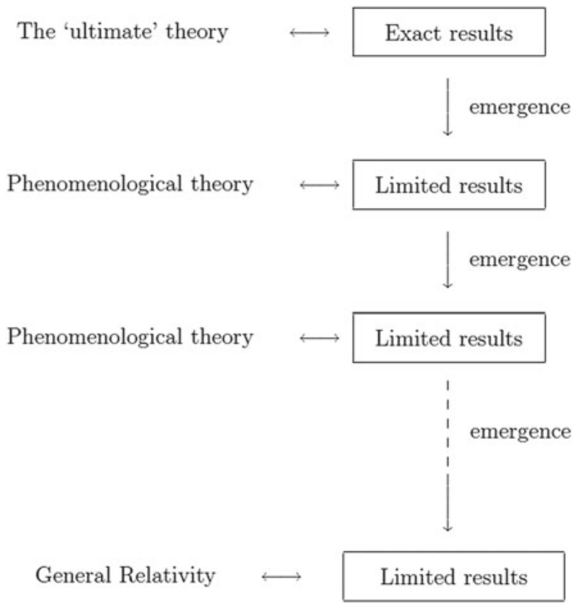

Fig. 2.1 Tower of emergent theories (Adapted from Butterfield and Isham 2001, p. 79)

than those at the bottom—i.e. the phenomenological theories), essentially the same as the hierarchy described by Anderson (below, in Sect. 2.5) and his fellow New Emergentists Laughlin and Pines (2000, p. 30), who state that "Rather than a Theory of Everything we appear to face a hierarchy of Theories of Things, each emerging from its parent and evolving into its children as the energy scale is lowered". These ideas are made more precise in considering effective field theory (Chap. 3), where the idea of a tower of theories is very natural, yet much-debated. Although Fig. 2.1 makes reference to "the ultimate theory", we needn't be committed to its existence in order to comprehend or utilise this conception of emergence. Also, although Fig. 2.1 shows only a single tower, we expect that, in general, there will be many different towers branching off from any given theory (Butterfield and Isham 2001 p. 79).

Unfortunately, it is almost as difficult to articulate the physicists' conception of emergence as it is the philosophers'; Butterfield and Isham (1999) attempt to make it precise in terms of *reduction*, and then in terms of *supervenience* and find that neither is able to do the job. Here I will consider only their exploration of reduction.

2.3.1 Reduction

Butterfield and Isham (1999) exploration of reduction as a candidate for emergence is made from the perspective of the physicists' sense of emergence. Nevertheless, if we take the philosophers' conception of emergence as a failure of reduction, then this discussion is of relevance, as it demonstrates the difficulty in articulating an appropriate definition of reduction. This may be taken as presenting a further difficulty for those approaches to emergence that attempt to define the concept as a failure of reduction, and another reason for suggesting that we abandon the tradition of doing so.

The intuitive idea of reduction that Butterfield and Isham (1999) work with is that one theory T_1 is reduced to another T_2 if T_1 is shown to be a part of T_2. Reduction is taken as deduction of one theory from another, typically with the reducing theory being augmented with appropriate definitions or bridge-principles linking the two theory's vocabularies, i.e. as *definitional extension*.[6] This basic idea of reduction, as deduction aided by definitions or bridge-principles, is essentially the traditional account of reduction proposed by Ernest Nagel (1961).[7] In order to use this idea, however, we must understand theories via the *syntactic* conception, that is, we must treat the postulates of a theory as sets of sentences closed under deduction. This contrasts with the *semantic* conception, according to which theories are classes of models satisfying the axioms. So, already, by taking this path we are forced to justify closing the door not only on conceptions of emergence as a relation between *things other than theories*, but also on a very popular rival view of theories as sets of models.

Butterfield (2011a, pp. 926–927) goes to some length to justify his choice of working with the syntactic conception, including arguing that it is capable of describing perfectly well the phenomena in scientific theorising that advocates of the semantic view tout as the merits of models, but, nevertheless, also emphasising that he does need, for his own purposes in making a crucial point about supervenience, to later switch to the semantic conception and use the idea of a class of models that is not the set of models of a given (syntactic) theory. Mainwood (2006, p. 32), on the other hand, points out optimistically that we may assume that nothing hangs on the choice of taking the syntactic conception rather than the semantic one, other than that the former provides a neat definition of reduction. Without going into the depths of details—it thus seems, simply, that we could perhaps avoid all this trouble if we were to avoid talking about reduction.

Next, having taken the syntactic conception of theories in order to get our nice definition of reduction, we define definitional extension; T_1 is a definitional extension of T_2 iff one can add to T_2 a set D of definitions, one for each of T_1's non-logical symbols, in such a way that T_1 becomes a sub-theory of the augmented theory $T_2 \bigcup D$. In other words, in the augmented theory we can prove every theorem of T_1 The issues then regard the construction of the definitions: these are chosen with a view to securing the theorems of T_1, and can require a great deal of creativity and skill. Also, there is no requirement that the definitions be brief: "A definition or deduction might be a million pages long, and never formulated by us slow-witted humans" (Butterfield 2011a, p. 932). Finally, if we take a definition, for a predicate, to be a

[6]This is also how Butterfield (2011a, b) articulates his idea of essentially-Nagelian reduction.

[7]Nagel's account of reduction is not uncontroversial, as Butterfield points out. Various objections have been raised against it, but it has also been defended by many philosophers, including: Dizadji-Bahmani (2010); Endicott (1998); Klein (2009); Marras (2002); Needham (2010).

statement of co-extension (and for a singular term, co-reference), then this scheme does not obviously extend the domain of quantification (i.e. there are objects in T_1 distinct from those of T_2), and so Butterfield (p. 932) describes three tactics, which I will not go into, for dealing with this problem.

Definitional extension, while being a nice candidate for reduction because it is both intuitive and precise, is, unfortunately, sometimes too strong and sometimes too weak to do the job. Both of these points, which are apparently widely-recognised, are made by Butterfield and Isham (1999, p. 118). In regards to definitional extension sometimes being too weak for reduction, the problem has to do with the fact that, even though T_1 and T_2 are strictly co-extensive in their predicates, we might think that there are some aspects of T_1 that "outstrip" T_2, for instance that T_1 might have aspects to do with explanation, or modelling, or heuristics, that aren't captured by T_2, and definitional extension is inadequate to capture these.

Of course, however, we could then perhaps choose to label these additional aspects "novelty", which case we might say that their presence indicates a failure of reduction, rather than that definitional extension is insufficient for reduction. Such a tactic might be taken by an advocate of explanatory emergence, described earlier. More typically, however, the move is to add supplementary conditions to definitional extension in order to bolster it as a candidate for reduction, Nagel himself, for instance, included some additional clauses regarding explanation, i.e. that T_2 should explain T_1, where explanation is understood in deductive-nomological terms. In some cases, authors choose to add clauses that prohibit other candidates for novelty, so that it becomes controversial which supplementary clauses are correct (see Butterfield 2011a, p. 930).

In regards to definitional extension sometimes being too strong for reduction, the criticism is that, on taking reduction as deduction aided by appropriate bridge principles, there are intuitive cases of T_2 reducing T_1 in spite of there being considerable conceptual and explanatory disparities between the two theories. Butterfield and Isham (1999, p. 120) quote Feyerabend's (1981) example of Newtonian gravity theory reducing Galileo's law of free fall: although the reduction goes through, the Newtonian theory is inconsistent with Galileo's law because it says (contrary to Galileo's law) that the acceleration of a body increases as it falls towards the earth. There are other standard examples, namely, special relativity and Newtonian mechanics, or statistical mechanics and thermodynamics: as Butterfield and Isham point out, while some authors cite these examples as paradigmatic of reduction, others cite them as examples of replacement or incommensurability. The moral is that reduction often requires approximation: in many cases, reduction involves T_2 including some sort of analogue, $(T_1)^*$, of T_1, where $(T_1)^*$ is required to be close enough to T_1 that we are happy to say that T_2 reduces T_1.[8]

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[8]Following their discussion of reduction, Butterfield and Isham (1999) turn to the relation of *supervenience* as a candidate for emergence, which some metaphysicians have found promising, given its apparent ability to sidestep controversial issues such as property-identity and explanation that, as we have seen, have to be addressed in order to provide an analysis of reduction. They find that, although supervenience promises the advantages of being weaker than reduction (it allows for definitions that are infinitely long as well as finitely long) though also quite precise, these advantages are often illusory; firstly, it is not clear whether supervenience is, indeed, weaker than definitional

Butterfield and Isham (1999, p. 125) conclude that rather than seeking a definition of emergence framed in terms of reduction (or supervenience), we should instead bear in mind the variety of ways in which one theory may be emergent from another, particularly focusing on the notions of limits and approximations. I believe that this is correct. I have presented Butterfield and Isham's exploration of reduction simply to illustrate that even a logical cut-and-dried formulation of reduction can be quite thorny and quickly lead us into difficulties. I do not mean to say that it is impossible to formulate a workable conception of reduction upon which to base a conception of emergence, but simply that it appears not an easy task: if we can avoid having to take this route in defining emergence, it seems preferable to do so. It is not at all clear what there is to be gained from it.

2.4 Emergence as Dependence Plus Novelty and Autonomy

So far I have presented a case for working with a vague, skeleton conception of emergence, one that is inspired by the physics, but does not rely on reduction. Here is an explicit statement of the conception that is used in this book. It will be made more precise when considering the physical examples in the following chapters.

Dependence The low-energy theory is related to the high-energy theory via the physics of the RG and EFT techniques (this relation may or may not be classed as a derivation, see Chap. 3). Alternatively, if one is not averse to the concept of supervenience, we might understand Dependence as involving supervenience: the system described by the low-energy (macro-) theory *supervenes* on that of the high-energy (micro-) theory, where supervenience is understood as the claim that there cannot be two objects that are alike in all high-energy respects (i.e. two systems that are the same as described by a particular, appropriate, high-energy theory), but differ in respect to their low-energy physics.[9] (This use of supervenience requires a little more explanation, given Butterfield (2011a) demonstration that we can have emergence without supervenience, so I comment on it again shortly).

Independence The low-energy physics is *novel* and *autonomous* with respect to the high-energy description.

I take emergence to be a relation between physical theories. When I speak of "systems", I mean just the systems (putatively) described by the (models of the) theories.

(Footnote 8 continued)
extension, and, secondly, it is sometimes too weak for emergence. Butterfield (2011a) finds other difficulties with the notion, and argues that it is unrelated to emergence. I work with these results.

[9]The most basic characterisation of supervenience states that a set of properties A supervenes upon another set B just in case no two things can differ with respect to A-properties without also differing with respect to their B-properties (see, e.g. McLaughlin and Bennett (2011).).

I leave aside the question of how the theories are related to the systems they describe; discussions of scientific realism are beyond the scope of this book.[10]

A note regarding my admittance of the concept of supervenience as potentially a part of my definition of emergence: although Butterfield (2011a) demonstrates that we can have emergence (with or) without supervenience, supervenience (as I have stated it above) holds in all of the cases I consider in this work. As I have put the claim above, it states that two systems that are the same according to a particular high-energy theory (whatever the appropriate one may be for the system and energy under consideration), can be described as having the same physics (as one another) by the appropriate low-energy theory. Butterfield (2011a, Sect. 5.2.2) has two examples of emergence without supervenience. Briefly: the first example involves recognising the work of philosophers such as Silberstein and McGeever (1999), who present entangled quantum states as cases of emergence without supervenience (i.e. the entangled states are emergent and do not supervene on the states of the entangled particles individually). This involves a different notion of supervenience (mereological supervenience) than the one I've admitted here, and emergence is taken as a failure of supervenience. Accounts of quantum gravity that describe entanglement could potentially represent emergence and a failure of supervenience in the sense argued for by Silberstein and McGeever (1999); the exploration of this possibility is an avenue for future work.

The second case that Butterfield (2011a) presents as an example of emergence without supervenience is counterfactual, and involves the possibility of "configurational forces": fundamental forces that come into play only when the number of bodies (or particles, or degrees of freedom) exceeds some number, or when the bodies etc. are in certain states. Although we know of no such forces (science does not describe any such forces), and Butterfield (2011a) acknowledges that physics does not require any configurational forces, it is possible that configurational forces are required to explain some chemical or biological phenomenon or phenomena. If this were the case, then, Butterfield (2011a) argues, we would again have emergence without supervenience, because the emergent chemical or biological facts would not supervene on the micro-theory (quantum mechanics of the particles), instead also requiring the facts about the configurational forces.

The existence of configurational forces would represent a problem for basing the notion of Dependence (part of my definition of emergence) on supervenience. This is because such forces would mean that we could have two systems which were the same according to the particular high-energy theory appropriate for describing them, yet which differed according to the low-energy physics—if the low-energy physics depended in some way on the configurational forces, and these differed for the two systems. Configurational forces would not feature in the high-energy theory, but would need, presumably, to be described according to some new theory, applicable at some "intermediate" energy scale, between the domains of the high-energy and low-energy theories being considered. As it stands, however, we have no reason for

[10]These questions are, of course, non-trivial! And my stance described here is not unproblematic, as will be particularly evident in Chap. 4, where I discuss the thermodynamic limit.

thinking that there are such forces at work in the physical examples I consider in this book, or, indeed, in physics at all. Thus, because my definition of emergence is only meant to apply to the physical examples are explored here, the counterfactual example of Butterfield (2011a) presents no problem.[11]

Novelty is taken as robust behaviour exhibited by the macro-system (appropriately described by the emergent theory) but not present in the micro-system (described by the micro theory).[12] The emergent theory is novel compared to the theory it emerges from if it is formally distinct from the latter, describing different physics and different degrees of freedom. The idea of novelty is further clarified by considering the physical examples, as in Chaps. 4–6.

The idea of novelty, free of any implications concerning reduction, might strike many philosophers as uninteresting, or "too weak" to represent a conception of emergence. Morrison (2012, p. 148), for instance, wants to distinguish emergent phenomena from "resultant" ones. Emergence carries connotations of "the whole being greater than the sum of its parts"—the suggestion being that, again, an emergent structure must be one that is somehow irreducible to its components or underlying description. As emphasised throughout this chapter, I do not feel the need to restrict our conception of emergence in physics by tying it to ideas carried over from metaphysics or the philosophy of mind—the idea of emergence as a failure of reduction is not helpful in all cases. We can have a conception of emergence that features novelty with or without reduction.

In regards to *autonomy*, we may say that a particular level of the "tower" is autonomous from the one above it (i.e. the higher-energy theory underlying it) if it is *robust* and impervious to changes in the high-energy system. Usually there is not *absolute* autonomy, but rather *quasi*-autonomy, meaning that the level is independent of *much* or *most* of the high-energy physics. This idea is made more precise in the discussion of the physical examples, but it may be characterised as the high-energy theory being *severely underdetermined* by the low-energy physics. Like novelty, autonomy is a feature that, divorced from issues of reduction and deduction, philosophers would be reluctant to class as emergence. Again, consider Morrison (2012, p. 413), who says that this sort of autonomy is a necessary but not sufficient condition for emergence, because "the fact that we need not appeal to micro phenomena to explain macro processes is a common feature of physical explanation across many systems and levels" (I return to discuss these views in Chap. 4.). In the physical examples considered in this book, the idea of autonomy is certainly a pervasive one, but I do not think it should be overlooked simply for this reason; if anything, the

[11]Butterfield (2011a) also emphasises one major reason for reservation regarding the use of the concept of supervenience. This is the necessity of being very careful in actually applying it: a supervenience claim needs to define precisely what properties or predicates are in the subvening set (i.e. the set A).

[12]I use the term "macro" just to contrast with "micro" here: I mean these only as relative terms (i.e. not to imply that the emergent phenomena must always be confined to the macro-realm), and will often say "upper-level" or "low-energy" to denote the same thing, being the phenomena that emerge from the "lower-level", "underlying" or "high-energy" system.

pervasiveness should inspire us to examine the relation more closely and ask why it is so widely exemplified in nature. In particular, autonomy is very important, and its explanation certainly not trivial, in the literature on EFT, as explored in (Chap. 3).

2.5 The Anderson/Weinberg Debate

The tradition of discussing emergence in physics that is of interest here began with Philip Warren Anderson's classic 1972 article *More is Different*, which was written expressly to defend the intrinsic value of condensed matter physics, against Steven Weinberg's claim (which encapsulates an attitude very common even today) that high-energy (i.e. particle) physics is somehow "more fundamental" than other areas of science. This "physicists' debate" was provoked by the issue of funding: particularly, the issue of funding the proposed (but never built) Superconducting Super Collider, upon which scientists from various disciplines were called to testify.[13] It was in this context that Weinberg famously stated,

> In all branches of science we try to discover generalizations about nature, and having discovered them we always ask why they are true. I don't mean why we believe that they are true, but why they *are* true. Why is nature that way? When we answer this question the answer is always found partly in contingencies, that is partly in just the nature of the problem we pose, but partly in other generalizations. And so there is a sense of direction in science, that some generalizations are "explained" by others [...]
>
> There are arrows of scientific explanation which thread through the space of all scientific generalizations. Having discovered many of these arrows, we can now look at the pattern that has emerged, and we notice a remarkable thing: perhaps the greatest scientific discovery of all. These arrows seem to converge on a common source! Start anywhere in science and, like an unpleasant child, keep asking "Why?" You will eventually get down to the level of the very small.
>
> [...] All I have intended to argue here is that when the various scientists present their credentials for public support, credentials like practical values, spinoff, and so on, there is one special credential of elementary particle physics that should be taken into account and treated with respect, and that is that it deals with nature on a level closer to the source of the arrows of explanation than other areas of physics (Weinberg 1987, p. 434).

In response, Anderson defended the view that the laws and principles he studied as a condensed matter physicist were emergent: entirely different from, yet of no lower status, than those studied in particle physics.

> The reductionist hypothesis may still be a topic of controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the animate or inanimate matter of which have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain conditions we feel we know pretty well.
>
> [...] The main fallacy in this kind of reasoning is that the reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple

[13] For more on the physicists' debate, see Cat (1998), Schweber (1993).

> fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.
>
> The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behaviour of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.
>
> [...] But this hierarchy does not imply that science X is "just applied Y". At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry (Anderson 1972, p. 393).

Many authors have attempted to flesh out Anderson's views into a clear philosophical position, but most, after a degree of struggle, conclude, with some bewilderment, that Anderson has made a simple mistake of confusing epistemological emergence with ontological emergence (Mainwood 2006). Nevertheless, I'm not concerned with pinning down exactly what Anderson had in mind, nor am I interested in arguing over the best interpretation of his text. Rather, I want to look at the *physical examples* that inspired Anderson and his colleagues—whom, following Mainwood (2006), I will refer to as New Emergentists[14]—to speak of emergence, and the physical mechanisms that underlie these. The reason I am interested in these examples is because they demonstrate how theories emerge from one another at different energy scales—and, if we conceive of quantum gravity as a small-scale theory of spacetime (i.e. a theory that is supposed to replace GR at high-energies), then this idea of emergence is important.

I have mentioned the Anderson/Weinberg debate and the tradition of the New Emergentists not just because references to their claims pervade the philosophical literature on emergence in physics, but because the physical examples and mechanisms the New Emergentists were inspired by are exactly those that continue, today, to inspire physicists to speak of emergence. The emergence-claims have flowed along the direction of Weinberg's arrows, however: no longer are they confined to the level of condensed matter physics, but, as we shall see, they appear even in the domain of high-energy physics.

[14]Other condensed matter theorists who presented views similar to Anderson's include Robert Laughlin, David Pines and Piers Coleman. See, e.g. Laughlin (2005), Coleman (2003), Laughlin and Pines (2000). Mainwood (2006) refers to these, and their followers, as the "New Emergentists".

2.6 Fundamentality

As indicated by even the initial, very crude statement of emergence provided at the start of this chapter—that an emergent phenomenon is in some sense less fundamental than its base, and in some sense not reducible to its base (52)—discussions of emergence typically involve some reference to the idea of fundamentality, and the discussion in this chapter has some implications for our understanding of the notion. Anderson (1972) suggestion, as we have seen, Sect. 2.5 is to treat the basic laws that govern each of the levels in the tower as each being as fundamental as any other.[15] Similarly, Cao (2003), argues that the definition of a fundamental theory as being one from which all other theories can be derived, has lost its meaning thanks to the ideas of effective field theory and the renormalisation group (Chap. 3).[16]

I am sympathetic to these views, which favour the condensed matter theorists' perspectives on the world, rather than the particle physicist's ones. Even though I think the idea of the renormalisation group is enough to define a meaningful sense of "direction" in the way Weinberg conceives, the levels are novel and autonomous enough that seeking an explanation of one in terms of the one above it (in energy) seems an exercise in futility: such an explanation imparts no understanding of the important physics that characterises the level of interest (in other words, there is emergence, even if it is just "explanatory emergence").

It is tempting, because of the "direction" imparted by the RG (pointing in the opposite direction to "emergence" in Fig. 2.1), to follow Weinberg and take "more fundamental" to simply mean "higher-energy". This is not a useful view to have, though, since it is suggestive of there being a single "source of the arrows", a "final theory" (to again use Weinberg's terms), and taking this ultimate theory to be just the one that is valid at the highest-possible energy scales. Recognising that such a theory would simply be a theory that is valid at the highest-possible energy scales (it is an open question whether the RG-based arguments for "direction" would be applicable at such scales, see Sect. 3.8) rather than one that *explains* all low-energy physics, would, I think, make the attribution of fundamentality uninteresting.

Of course, equating "more fundamental" with "higher-energy" does not necessarily carry the implication that there is a "most fundamental" level, but neither does it make the idea of fundamentality particularly useful. Because I am not sure

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[15] Although I must point out that Anderson bases this view on our inability to derive the laws of any one level from those of the one beneath it; and it is left to Mainwood (2006) to explicate the relevant sense of "ability".

[16] Instead, Cao (2003, p. 28) proposes a new definition of a fundamental theory, as being one which can be derived from no other theory. This definition enables GR and the QFTs of the standard model to be classed as fundamental theories. I am not convinced that we are justified in classifying these fundamental theories, however—certainly they are *currently* unable to be derived from anything, but, as outlined in Chap. 1, we have reasons for believing there may be quantum gravity, in which case, if the GCP applies, then GR will cease to be fundamental. Similarly, there are reasons (discussed in Sect. 3.8) for not viewing QFT as fundamental—not just in the sense that there may be a theory "underlying" it, from which it may be derived, but perhaps that the framework itself is flawed or incomplete (as adherents of Axiomatic QFT argue).

what we should take "fundamental" to mean, I prefer to just avoid using the term. Instead, I will endeavour to simply distinguish between levels based on their relative energy-scales, using the phrasing micro- and macro-, with the disclaimer made above (Footnote 12) regarding their use simply as contrastive labels.

2.7 Conclusion

As explained in the previous chapter, the purpose of this book is to explore the relationship between quantum gravity and GR (or, perhaps, the structures described by GR). In beginning this exploration, I am taking the GCP (defined on p. xxx) as a principle to be upheld by quantum gravity. This means that quantum gravity and GR are supposed to be related by the "physicists' sense of emergence"—in other words, it is taken as a requirement of quantum gravity that GR is able to be *derived* from it. In other words, according to the GCP, reduction is supposed to hold *in some sense*. Yet, the idea of emergence in philosophy is typically taken as a failure of reduction *in some sense*.

Rather than attempting to make sense of these different senses, I leave aside the conception of emergence as a failure of reduction, and join Butterfield and Co. in accepting the diversity of emergence and other relations. Emergence can hold with or without reduction, and we have no good reason to restrict our attention to either case. Indeed, I have argued that we have motive for keeping an open mind in our investigation of the physics. So, instead of focusing on articulating the relevant failure of reduction, I look at the ways in which GR (and the structures it describes) might be said to be novel and autonomous from quantum gravity (while still being related to quantum gravity, through the notion of Dependence defined on p. xxx). The idea of treating novelty and autonomy as bases for a conception of emergence is natural given the physics—not just the approaches to quantum gravity, but other examples of EFTs.

This chapter gave a very brief, very general overview of the philosophical understanding of emergence, on the advice that we proceed via the science-first approach rather than dragging excess weight in the form of previous metaphysical debates regarding ontological and epistemological emergence. Several suggestions of the potential difficulties with applying an account of emergence in terms of reduction were made, intending only to motivate the shift from holding a restrictive prior understanding of emergence to adopting one that is more flexible.

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