**On the Independent Emergence of Space-time**

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**§1 Introduction**  Space and time have been fundamental to metaphysics and physics since the pre-Socratics. Their union remained fundamental after Minkowski’s pronouncement that special relativity doomed each separately to fade away as a mere shadow, and Einstein’s declaration that space-time itself exists only as a structural quality of the gravitational field described by general relativity. But difficulties in meshing general relativity with quantum theory have prompted a widespread conviction that space-time is not fundamental but emergent. This raises a difficult ontological question: What is there more fundamental than space-time from which it might emerge? Rather than try to answer this question I suggest we reject its presupposition that emergence demands a precisely characterized ontological basis.

 Jeremy Butterfield (2011a,b) took emergence to mean properties or behavior of a system which are novel and robust relative to some appropriate comparison class. Karen Crowther (2016: p.50) added a dependence requirement based on Bedau’s (1997: p.375) condition that emergent phenomena are dependent on, constituted by, or generated by underlying processes. Together, these criteria would make space-time emergent just in case spatiotemporal phenomena display novel and robust behavior relative to some comparison class of underlying non-spatiotemporal processes on which they depend. This chapter explores the possibility that space-time emerges in the domain of a quantum theory of gravity in a way that does not so depend on objects, properties or processes represented by that theory.

 The possibility is suggested by two relational approaches to quantum theory: Carlo Rovelli’s (1996) relational quantum mechanics and my (2017) pragmatist view, according to which any assignment of a quantum state is relative to the physical situation of an actual or hypothetical agent. By contrast, Rovelli takes the assignment of a state to a system in quantum theory always to be relative to some other physical system―a view he deploys (Rovelli & Vidotto, 2015) to secure the conceptual foundations of a theory of loop quantum gravity from which (general-relativistic) space-time emerges only as a classical limit. But can a quantum theory of gravity help itself to talk of physical systems or situations without representing them in space-time? In the rest of this chapter I show how it can in a pragmatist view of quantum theory (Healey, 2012, 2017): I consider Rovelli’s relational approach elsewhere (Healey, forthcoming).

 The following section offers a preliminary analysis of the relation between fundamentality and emergence. This exposes two problems in evaluating the suggestion that space-time is not fundamental but rather emerges within a quantum theory of gravity. Leaving the actual construction of such a theory in the capable hands of physicists, I introduce a strategy for attacking the second, conceptual, problem.

 Section 3 illustrates this strategy by applying it to theories of the free electromagnetic field, for which we have a successful quantum theory from which a corresponding classical theory emerges—Maxwell’s theory of electromagnetic radiation. I argue that this provides an example of the emergence of a phenomenon within a quantum theory that describes no underlying physical processes.

 The argument depends on the pragmatist view that a quantum state is not what Bell (2004) called a beable, even when a statement assigning that state is objectively true. So while it is not the function of |*ψ*> to represent a physical object or magnitude (“an element of physical reality”), some quantum states are objectively real. Section 4 explains why this view does not conflict with recent results such as those of Pusey, Barrett & Rudolph (PBR), (2012) and Colbeck & Renner (2012).

 Applying the pragmatist view to the states of a conjectured quantum theory of gravity,

Section 5 presents a resolution of the conceptual problem diagnosed in section 2. This shows how space-time might emerge within a quantum theory of gravity that describes no more fundamental physical structure. Section 6 says why this emergence would be independent.

 Finally I draw some morals of this resolution for the relation between metaphysics and fundamental physics. Even if there is such a thing as ultimate reality, fundamental physics need not describe it and much that is real (even in physics) is not grounded in it.

**§2 Fundamentality and Emergence**  ‘Fundamentality’, an ugly word used almost exclusively by philosophers, purports to designate a monadic property of a fundamental object. But the adjective ‘fundamental’ is implicitly relational: It is preferable to use the relational term ‘fundamental to’ from which it derives. This reframes discussion of fundamentality as a question of whether *x* is fundamental to *y*, for suitable instantiations of the variables *x*, *y*.

 Their prominence in everyday, scientific and philosophical thought about the world suggests replacing *x* by space and by time. Three salient instances for *y* then yield the theses

 *UsS,T* Space, time are fundamental to us.

 *RealityS,T* Space, time are fundamental to reality.

 *PhysicsS,T* Space, time are fundamental to physics.

These theses are by no means mutually exclusive: indeed, some may be taken to imply others. But *UsS,T* does not imply *PhysicsS,T*. Though in some sense fundamental to us, life, air, water, food, clothing, housing, each other, language, sanitation, antibiotics, government, law, colors, causation, probability, atoms, the force of gravity are not (all) fundamental to physics. There are naturalistically-inclined philosophers who would deny that any of these are fundamental to reality. Some physicalist philosophers may endorse this conditional statement:

*If x is not fundamental to physics, then x is not fundamental to reality*

Insofar as life, air, water, food, clothing, housing, other people, language, sanitation, antibiotics, government, law, colors, causation, probability, atoms, the force of gravity are not fundamental to physics they may conclude that none of these are fundamental to reality. I’ll raise doubts about this conditional statement later (see §7). But note that anyone interested in the foundation of reality who accepts the conditional is then led to ask whether space and time are fundamental to physics.

 That question is easily answered. Space and time have not been fundamental to physics at least since Einstein (1905) published his special theory of relativity. As Minkowski (1908) put it three years later

“Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.”

Indeed, even before relativity theory there was a strong scientific case that space-time is more fundamental to physics than space and time individually. So space and time are not fundamental to physics insofar as *space-time* is fundamental to physics, but space and time are not. This motivates revising *PhysicsS,T* to read

 *PhysicsS-T* Space-time is fundamental to physics.

 Acceptance of Minkowski space-time as the basic geometric setting for special relativity seemed to close the case; and general relativity (the theory that succeeded

it ten years later) merely introduced a host of alternative structures this space-time might take, depending on how matter and energy are distributed in it. Many philosophers have come to believe that space-time is fundamental to physics, even though space and time are not.

 But this was not Einstein’s own view. As he put it (Einstein, 1961)

“Space-time does not claim existence on its own but only as a structural quality of the [gravitational] field” p.155

He came to think of the gravitational field, (represented by the four-dimensional metric tensor *gμν*), as more fundamental than space-time, so that

 “If we imagine the gravitational field, i.e. the functions *gμν* to be removed, there does not remain a space, but absolutely nothing, and also no "topological space". ....There is no such thing as an empty space, i.e. a space without a field.” *ibid*.

 Physics has moved on since Einstein. Even without an agreed, successful theory of quantum gravity, we have reason to believe that neither space-time nor a (classical) gravitational field will be fundamental to physics. The following quote (Rovelli & Vidotto, 2015) expresses a common (though not universal) attitude amongst contemporary physicists.

“G[eneral] R[elativity] is not just a theory of gravity. It is a modification of our understanding of the nature of space and time. Einstein’s discovery is that space-time and the gravitational field are the same physical entity. Space-time is a manifestation of a physical field. All fields we know exhibit quantum properties at some scale, therefore we believe space and time to have quantum properties as well.” p.6

 The idea is to follow Einstein’s lead into the quantum realm by considering space-time to arise as a manifestation of a *quantum* gravitational field. This idea could be made to work if we could find something underlying space-time—some entity *x* that is fundamental to space-time to instantiate the expression ‘*x* is fundamental to *y’*, with ‘y’ instantiated by ‘space-time’. But how might we instantiate ‘x’? We don’t know!

 But the progress of physics over the past half century suggests at least the form of an answer to this question. Einstein thought space-time is the same physical entity as a classical gravitational field: but today we should expect it to arise as a manifestation of a quantum gravitational field. If so, from the perspective of a theory of quantum gravity, space-time will appear as an emergent phenomenon, (a structural quality of) a classical gravitational field that emerges in some appropriate limit of that theory.

 Indeed, philosophers of physics often speak of the emergence of space-time in a quantum theory of gravity. Like fundamentality, emergence is best thought of as a relation: *x emerges from y*. One might assume this is simply the converse of the relation *x is fundamental to y*. But while metaphysicians typically regard *is fundamental to* as an ontological relation, philosophers of science typically take *emerges from* to relate theories rather than things. So there are ample opportunities for confusion here!

 In a pair of recent papers, Jeremy Butterfield (2011a,b) has taken emergence to mean properties or behavior of a system which are novel and robust relative to some appropriate comparison class. He investigates such emergence by analyzing possible relations (e.g. reduction, supervenience, limiting case) between a theory T2 describing such properties or behavior and a second theory T1 taken to be applicable to the same system. On this approach, space-time would emerge in a quantum theory of gravity if and only if theoretically-described spatio-temporal phenomena count as novel and robust relative to a class of (presumably) non-spatiotemporal phenomena described by a quantum theory of gravity.

 An emergence relation between theories generally involves an inverse relation between their ontologies. The emergence of geometric optics from wave optics depends on the identification of a ray with an element of a propagating wave-front. Butterfield (2011a) gives the example of the emergence of the theory of thermodynamics (for an isolated gas in equilibrium) from the theory of statistical mechanics, which depends on the identification of a gas with a vast number of particles. In such cases the emergence of T2 from T1 requires the ontology of T1 to be fundamental to that of T2.

 Two problems arise if we try to take this approach to the emergence of space-time within a quantum theory of gravity:

 1.We have no agreed quantum theory of gravity to serve as theory T1.

2. We don’t know how any such theory could be applied to a system without assuming that system is in some sense spatio-temporal.

These problems are nicely illustrated in the following figure, copied from (Rovelli & Vidotto, 2015), p.8.

The figure sketches three approaches toward the hoped-for theory of quantum gravity. The left side depicts a conventional attempt to craft a theory of gravity as a quantum field theory on an assumed space-time background (possibly with more than three spatial dimensions). The center depicts an attempt to create a quantum theory of gravity in the bulk as dual to such a conventional quantum field theory defined on its boundary, where a background space-time with multiple spatial dimensions is assumed for both. The right side depicts a prospective quantum gravity theory that does *not* presuppose any background space-time.

 None of these approaches has yet proved wholly successful, so the figure illustrates the fact that we still lack a satisfactory theory of quantum gravity (problem 1). While the fanciful figure on the right shows how hard it is even to imagine what a system described by such a theory could be like if it is in no sense spatio-temporal (problem 2).

 Half a century of work by many of our best physicists has not yielded an agreed solution to the first problem. I can merely encourage them in their continuing efforts! But my recent understanding of quantum theory has suggested a largely independent strategy for tackling the second problem. In the next section I’ll illustrate the strategy by applying it to an analogous case in which we do have a well-developed quantum theory from which classical behavior emerges: the quantum theory of the electro-magnetic field.

**3. How Light Emerges within a Quantum Field Theory** The **Q**uantum theory of free **E**lectro-**M**agnetism (QEM) is traditionally arrived at by canonical quantization of a classical field theory―Maxwell’s equations in a vacuum. This involves replacing magnitudes such as electric and magnetic fields by mathematical operators that act on a space of quantum state vectors (Fock space). Unlike classical electric or magnetic field magnitudes, these operators do not have the function of representing physical magnitudes. So one can ask what this quantum theory represents―in J.S. Bell’s terminology, ‘what are its beables?’ (i.e. “elements of physical reality”, if the theory were true). This is one case of the more general question “What are quantum field theories about?”, or in fancier language “What is the ontology of a quantum field theory?”.

 Two main candidates have been proposed for the ontology of a quantum field theory: particles, and (classical) fields. Unfortunately, philosophers have formulated strong objections to both proposals (Fraser, 2008: Baker, 2009). Physicists typically finesse such objections by regarding particles and fields as not among the theory’s beables, but rather as emergent entities. As one recent text (Lancaster & Blundell, 2014) puts it

“Every particle and every wave in the Universe is simply an excitation of a quantum field that is defined over all space and time.” p.1

The idea is that one kind of excitation may be treated as if it consisted of particles, while a different kind of excitation may be treated as if it consisted of classical waves. Here ‘being treated as’ does not mean ‘is composed of/identical to’ since the treatment is successful within limits, and only for certain purposes. But how is this ontological emergence supposed to work?

 Metaphysicians enamored with mereology may be uncomfortable with the idea of an emergent entity―something with no well-defined set of constituents. But our world is full of them. They include epidemics, hurricanes, water waves, Jupiter’s red spot, phonons and many other varieties of quasi-particles in condensed matter physics. The excitations from which photons and light waves emerge are quantum states of QEM. This suggests that quantum states may be the real beables of this theory, while more familiar entities like particles and waves emerge from particular kinds of excited states in certain circumstances.

 However, the ontological status of quantum states (“wave functions”) is currently a topic of intense controversy among physicists and philosophers working on conceptual foundations of quantum theory. In my view, quantum states are not beables of any quantum theory. In section 4 I’ll defend this view against objections based on some influential recent arguments. But for now I’ll treat it as an assumption to show how it can help us solve problem 2. For once granted, I think we can see how a theory of quantum gravity might be applied to a system without assuming that system is in some sense spatio-temporal. A solution to that problem would provide an additional argument for the assumption.

 It follows that quantum states are not beables of QEM: QEM *has no* beables! While ocean waves emerge from excited states of water, photons and (classical) light-waves do not emerge from anything described by QEM.

*Objection*: That’s crazy: *everyone* agrees that QEM describes the quantum/quantized electro-magnetic field!

*Reply*: Everyone agrees that mathematical objects (electro-magnetic field operators) appear in models of QEM that have been *successfully applied to* physical systems. But these models are not used to *represent or describe* the electro-magnetic field (classical or quantum). An application presupposes the existence of the system to which it is applied, and we can *call* this “the quantum/quantized electro-magnetic field”. But QEM is applied to it without in any way describing its features: successful application does not entail description. The quantum electro-magnetic field remains purely schematic in QEM.

 It is generally acknowledged that CEM (the **C**lassical theory of free **E**lectro-**M**agnetism) emerges from QEM in a suitable limit (“of coherent states with large mean photon number”).

But one can acknowledge such theoretical emergence while denying that QEM or its application describes any beables more fundamental than the (emergent) classical fields described by CEM. Here we have a example of two theories where the emergence of T2 from T1 does not require the ontology of T1 to be fundamental to that of T2.

**4. The Quantum State is not a Beable** Pusey, Barrett & Rudolph (2012) proved a result that might be taken to show that the quantum state is a beable. The proof is valid, but like all proofs its premises may be questioned. It does not show that quantum states are beables.

“The argument depends on few assumptions. One is that a system has a ‘real physical state’ not necessarily completely described by quantum theory, but objective and independent of the observer. This assumption only needs to hold for systems that are isolated, and not entangled with other systems. Nonetheless, this assumption, or some part of it, would be denied by instrumentalist approaches to quantum theory, wherein the quantum state is merely a calculational tool for making predictions concerning macroscopic measurement outcomes. The other main assumption is that systems that are prepared independently have independent physical states.” p.475.

As the argument proceeds, it becomes clear that the physical states referred to in the last sentence are taken to be real, so “the other main assumption” depends on the main premise stated in the second quoted sentence. But what is a ‘real physical state’?

 To clarify the notion of a physical state, the authors consider the classical mechanics of a point particle moving in one dimension. They take its (instantaneous) physical state to be completely specified by its phase space point with coordinates (*x*,*p*), functions of which constitute its physical properties. By taking these to include constant functions such as mass and charge, they apparently take the physical state of a classical particle to determine the values of all magnitudes pertaining to it at a time. So the physical state of a single classical particle moving in one dimension would be *real* if it correctly specified the particle’s instantaneous physical properties. By analogy, the physical state of a quantum system would be real only if it specified the system’s instantaneous physical properties, and complete if it specified all of these.

 PBR (2012) take the analogy with classical *statistical* mechanics to motivate imposition of a second necessary condition on the reality of a physical state *λ* of a system in quantum theory

“Now consider a quantum system. The hypothesis is that the quantum state is a state of knowledge, representing uncertainty about the real physical state of the system. Hence assume some theory or model, perhaps undiscovered, that associates a physical state *λ* with the system. If a measurement is made, the probabilities for different outcomes are determined by *λ*. If a quantum system is prepared in a particular way, then quantum theory associates a quantum state (assume for simplicity that it is a pure state) |*ψ*>, but the physical state need not be fixed uniquely by the preparation—rather, the preparation results in a physical state according to some probability distribution *μψ*(*λ*).” (*ibid*)

So PBR (2012) count a physical state *λ* as real only if *λ* *both* specifies a system’s instantaneous physical properties *and* determines the probabilities for different outcomes if a measurement is made on it. In Leifer’s (2014) terminology, such a state *λ* is an element of an ontological model. PBR clearly view their proof as directed against the *conjunctive* hypothesis that a quantum system has a real physical state *λ* and that this does not uniquely determine its quantum state.

 Given the second (independence) assumption, their proof shows that this conjunctive hypothesis is false. So if a quantum system has a real physical state, then this uniquely determines its quantum state. Now one thing that trivially uniquely determines that quantum state is the quantum state itself. So their result is consistent with the assumption that the quantum state is physically real. But it is equally consistent with the assumption that the quantum state is *not* real. A system’s quantum state does determine the probabilities for different outcomes if a measurement is made on it. But PBR count it as real only if it also specifies the system’s instantaneous physical properties. The result that the quantum state is real follows only if that is indeed a necessary condition for its reality and the condition is in fact satisfied.

 PBR maintain that this result indeed does follow. They take the fact that the quantum state can be inferred uniquely from *λ* to show that the quantum state is *itself* a physical property of the system (p.476). But this follows only if *λ* *does* specify a system’s instantaneous physical properties. However, that is a consequence of its reality only given what they take to be required for a physical state to be objectively real and independent of the observer. This is essentially the requirement that such an objectively real state be what Bell called a beable—a physical magnitude or property, at least as represented by some physical theory.[[1]](#footnote-2)

 In the pragmatist view of quantum theory I am assuming here, the quantum state of a system is *not* a beable. But it is still objectively real, no matter what any observer may take it to be. Indeed, anyone who accepts quantum theory should believe that systems would have had quantum states even if there had been no observers. The quantum state is not merely a calculational tool for making predictions concerning macroscopic measurement outcomes.

 A state vector |*ψ*> (or other mathematical representative of a quantum state) does have a distinctive non-representational role within quantum theory. A statement in which |*ψ*> is used to assign a quantum state to a particular system at a time is objectively true or false, from which it trivially follows that |*ψ*> represents something objectively real. According to Healey (2017), this is not a (monadic) property of the system, since a quantum state is assigned relative to the physical situation of an actual or hypothetical agent. So the objective reality represented by |*ψ*> involves a relation to a physical situation, relative to which it is assigned. But the *function* of that statement within the theory is not to describe physical properties of the system at that time. Instead, a quantum state functions as a source of advice on the significance of statements about the values of magnitudes and on how credible are those that are meaningful enough to be entertained.

 The Born rule is key to both these functions of the quantum state. Applied to a system’s quantum state, it directly assigns a probability to each significant statement about the value of a magnitude on that system, *not* about the outcome of its measurement. But not every statement about the value of a magnitude is significant in a given physical situation, and the Born rule may never be legitimately applied to all such statements at once. The relevant feature of the physical situation is the system’s environment. So assessing the legitimacy of an application of the Born rule to a particular statement assigning a value to magnitude on the system requires information about the environment and its interaction with the system. Such information may be provided independently of quantum theory. But it does not have to be, since quantum theory itself may be used to model the system’s interaction with its environment.

 This is the role of models of environmental decoherence. In a model a quantum state may be assigned to a larger system that includes both the original system and its environment, and their interaction modeled by an interaction Hamiltonian. If the reduced quantum state of the system would evolve into a form that is robustly diagonal in some orthonormal basis, then each statement assigning a value to a magnitude equal to an eigenvalue of the corresponding operator is certainly significant enough to be assigned a probability by the Born rule applied to the quantum state originally assigned to the system alone. But the Born rule is not legitimately applied to a statement assigning a value to a different magnitude corresponding to an operator none of whose eigenvectors is even close to an element of that orthonormal basis. It is by restricting legitimate applications of the Born rule in this way that one secures consistency with so-called no-go theorems such as those of Kochen & Specker (1967) and Bell (1964, 1966).[[2]](#footnote-3)

 The Born probability assigned to a significant statement about the value of a magnitude on a system has the same status as the quantum state used to assign it. It, too, is objective and relative to the same physical situation as the quantum state, though it is not a beable. But it is not objective in Maudlin’s (2011) sense.

“...there could be probabilities that arise from fundamental physics, probabilities that attach to actual or possible events in virtue solely of their physical description and independent of the existence of cognizers. These are what I mean by objective probabilities.” p.294.

It is important to note that the reason Born probabilities aren’t objective in Maudlin’s sense is not that they are dependent on the existence of cognizers. Born probabilities, like quantum states, would exist in a world without cognizers. Maudlin’s reason for not counting them as objective would be that they are relational: they do not attach to actual or possible events in virtue solely of the physical description *of those events*.

 Since a quantum state is not a beable, it is not even a candidate for the job of real physical state *λ* as this appears in an ontological model. As Leifer (2014) puts it in his comprehensive review article

“The idea of an ontological model ... is that there is some set of ontic states that give a complete specification of the properties of the physical system as they exist in reality.” p.82.

PBR prove that in any ontological model of (a certain fragment of) quantum theory, the quantum state is uniquely determined by the state *λ* of the model. But while the quantum state is objectively real, it is not a beable, and so is not determined by the ‘real physical state’ of any ontological model. Quantum theory has no ontological model even though the quantum state is objectively real. Leifer (2014) analyzes similar proofs by Colbeck & Renner (2012) and by Hardy (2013). Since these all assume the ontological models framework it is not necessary to consider them further here. No so-called *ψ*-ontology theorem can show that a quantum state is a beable.

**5. How Space-time might Emerge in Quantum Gravity** The emergence of the classical electro-magnetic field from QEM may provide us with a good conceptual model for the emergence of space-time in a quantum theory of gravity. The first step toward understanding the emergence of space-time would be to follow Einstein in identifying space-time with the classical field *gμν* of the general theory of relativity (GR). We seek a quantum theory of gravity (QG) from which GR will emerge as a suitable limiting case, much as CEM emerges from QEM in the limit of coherent states with large mean photon number. As a quantum theory, QG need have no beables of its own.

 Suppose we had a satisfactory quantum field theory of the gravitational field QG. Such a theory would be clearly formulated and mathematically consistent. It would be predictively successful and explanatorily powerful: it might even permit us to control natural phenomena we cannot now control. But, as a quantum theory, it would not describe or represent the properties of a quantum gravitational field. Instead, it would contain mathematical models for application through the assignment of quantum states to a quantum gravitational field. But that field would not be a beable of the theory, and it would figure in no ontological model within or underlying that theory.

 The emergence of GR (and hence space-time) need require no ontological dependence of *gμν* on anything more fundamental described or represented by QG. We could *say* that the quantum gravitational field is fundamental to space-time. But a successful QG need not describe this field at all, and so neither as spatiotemporal nor as spatio-temporal in some extended sense (cf. string theory). Scientists could justifiably celebrate such an extraordinary extension of human knowledge. But metaphysicians might feel dissatisfied by such an ineffable fundamental ontology.

**6. What Makes such Emergence Independent** If space-time were to emerge within a quantum theory of a gravitational field whose properties and behavior it does not represent, then its emergence would undermine the claim that general relativity (or some other classical space-time theory) can be reduced to that quantum theory. This is a consequence of Butterfield’s (2011a,b) understanding of reduction as a relation of deduction or determination between theories. While seeking to distance the concept of emergence from that of reduction, Crowther (2016) still requires emergent phenomena to be dependent on, constituted by, or generated by underlying processes. That requirement could not hold either, if space-time were to emerge in the way suggested in the previous section. The emergence of space-time within a quantum theory of gravity would count as independent, whether dependence is understood as a relation between theories or a relation between processes described by them. But the relational nature of quantum states provides an additional reason for taking the emergence of classical space-time within a quantum theory of gravity to be independent.

 In my (2017) pragmatist view, any assignment of a quantum state is relative to the physical situation of a hypothetical agent. So to apply any quantum theory (including a hypothetical, successful QG) it must be possible to contemplate an agent’s occupying such a situation—to place oneself in that agent’s position, if only in thought. A key aspect of a hypothetical agent’s physical situation is its space-time location, as becomes clear from a consideration of the different quantum states correctly assigned to the same quantum system by spatially separated agents Alice and Bob in Bell tests on entangled pairs (see Healey, 2016). If this is right, then any application of any quantum theory implicitly assumes the existence of space-time sufficient to permit contemplation of a hypothetical agent’s space-time location.

 A successful QG need not itself *describe* an agent, its physical situation or space-time location. But the theory could not be successful if it were impossible to apply it, and so the success of a QG theory implicitly assumes the existence of space-time enough to permit its application. If a classical space-time does indeed emerge from a successful QG, then that assumption is justified, at least for any conceivable application. So we can certainly contemplate applying such a QG to extreme situations including events we typically describe as occurring within the event horizon of a black hole, or in what we think of as the extremely early universe. We can do this because the “Archimedean platform” from which we contemplate applying the theory is our own, relatively benign, physical situation: it is not that of the target of the application, and it is an adequacy condition on any successful QG that a classical space-time should emerge in such benign situations.

**7. Fundamentality: Physical and Metaphysical** Metaphysicians sometimes talk of ultimate reality: this would presumably be something more fundamental than space and time, if anything is. The obscure metaphysical formulations:

*x is fundamental to y ≡ y is grounded in x*

 *x is an element of ultimate reality ≡ nothing (else) is fundamental to x*

suggest an obscure metaphysical criterion of reality

 *y is real ≡ y is grounded in ultimate reality*

and a (slightly less?) obscure suggestion

*y is real ≡ y is grounded in ultimate physical reality*

These formulations inherit their obscurity from that of the grounding relation, a currently fashionable item in the metaphysician’s toolkit. But their obscurity is not the only thing wrong with them, as we can see by reflecting on this examination of the status of space, time and the quantum state in fundamental physics.

Is the quantum state real? Quantum states play a key role in our best fundamental physics, according to which a statement (correctly) assigning a quantum state to a system is objectively true. So we should believe that the quantum state is real. To note that the quantum state plays this role in physics rather than some other discipline one might choose to say that quantum states are *physically* real. But a quantum state is not a beable. So accepting quantum theory involves accepting quantum states as real even though they are neither elements of nor grounded in an ultimate (physical) reality to which that theory is applied.

 So quantum states provide counter-examples to the obscure metaphysical criterion of reality, and to the (slightly less?) obscure suggestion. Since their primary role is to serve as a source of the Born probabilities we derive from them, those quantum probabilities are also real but not grounded in ultimate (physical) reality. I think that probability is a source of counter-examples to the obscure metaphysical suggestion even outside of its application in quantum theory, as also are color, causation, laws, modality, etc. But I won’t try to argue that here!

 Are space and time real? Each remains fundamental to us in our daily lives, and to most of science. Scientific theories involving these concepts emerge from more fundamental theories of (classical) space-time, especially general relativity. In classical physics, the relation between pre-relativistic and relativistic theories and what they represent can be made to fit conventional models of reduction (Butterfield), and emergence (Crowther). Here space and time emerge from something more fundamental on which they depend. I leave it to metaphysicians to decide whether this means that space and time are grounded in space-time.

 We currently have no completely successful quantum theory of gravity. This makes it premature to render a final verdict on the status of space-time. I have argued that space-time may emerge from a successful quantum theory of the gravitational field that represents nothing more fundamental. If that turns out to be right, then space-time emerges independently within that theory. The only sense I can make of the suggestion that space-time would then turn out not to be fundamental is that it would depend for its existence on *something*, we know not what. That might satisfy a Kantian, but I think it would greatly disappoint a contemporary, naturalistically- inclined metaphysician.

**Acknowledgment** The figure 1.3 is reproduced with permission from Cambridge University Press, the publishers of the work (*Covariant Loop Quantum Gravity* by Carlo Rovelli and Francesca Vidotto) in which it first appeared.

**References**

Baker, D. (2009) Against field interpretations of quantum field theory, *British Journal for the Philosophy of Science*.60, 585‒609.

Bedau, M. (1997) Weak emergence, in J. Tomberlin (ed.) *Philosophical Perspectives: Mind, Causation and World* 11, 375‒399.

Bell, J.S. (1964) On the Einstein-Podolsky-Rosen paradox. *Physics* 1, 195‒200: reprinted in Bell (2004), 14‒21.

Bell, J.S. (1966) On the problem of hidden variables in quantum theory. *Reviews of Modern Physics*.38, 447‒52: reprinted in Bell (2004),1‒13.

Bell, J.S. (2004) *Speakable and Unspeakable in Quantum Mechanics*, 2nd edition. Cambridge, Cambridge University Press.

Butterfield, J. (2011a) Emergence, reduction and supervenience: a varied landscape. *Foundations of Physics*. 41, 920‒959.

Butterfield, J. (2011b) Less is different: emergence and reduction reconciled. *Foundations of Physics*. 41, 1065‒1135.

Colbeck R. & Renner R. (2012) Is a system’s wave function in one-to-one correspondence with its elements of reality? *Physical Review Letters*. 108, 150402.

Crowther, K. (2016) *Effective Spacetime: Understanding Emergence in Effective Field Theory and Quantum Gravity*. Switzerland, Springer International Publishing AG.

Einstein, A. (1905) Zur Elektrodynamik bewegter Körper. *Annalen der Physik*

17, 891‒921. English translation in (Jeffery & Perrett (eds.), 1923).

Einstein, A. (1961) *Relativity: the Special and the General Theory*. New York, Bonanza Books.

Fraser, D. (2008) The fate of “particles” in quantum field theories with interactions. *Studies in History and Philosophy of Modern Physics* 39, 841‒5.

Hardy, L. (2013) Are quantum states real? *International Journal of Modern Physics* B. 27, 1345012.

Healey, R. (2012) Quantum theory: a pragmatist approach.  *British Journal for the Philosophy of Science*.63 (2012), 729‒771.

Healey, R. (2016) Local Causality, Probability and Explanation, in Mary Bell & Shan Gao, editors *Quantum Nonlocality and Reality*. Cambridge, Cambridge University Press, 172‒194.

Healey, R. (2017) *The Quantum Revolution in Philosophy*. Oxford, Oxford University Press.

Healey, R. (forthcoming) The measurement problem for emergent space-time in loop quantum gravity, in Wüthrich, C., Le Bihan, B. and Huggett, N. (eds.) *Beyond Spacetime: the Philosophical Foundations of Quantum Gravity*. Oxford, Oxford University Press.

Jeffery, G.B. & Perrett, W. (1923) *The Principle of Relativity.* London, Methuen & Company, Ltd.

Kochen, S. & Specker, E. (1967) The problem of hidden variables in quantum mechanics.  *Journal of Mathematics and Mechanics*. 17, 59‒81.

Lancaster, T. & Blundell, S.J. (2014) *Quantum Field Theory for the Gifted Amateur.* Oxford, Oxford University Press.

Leifer, M. (2014) Is the quantum state real? An extended review of *Ψ*-ontology theorems.  *Quanta*. 3, 67‒155.

Maudlin, T. (2011) Three roads to objective probability, in Claus Beisbart & Stephan Hartmann, editors *Probabilities in Physics*. Oxford, Oxford University Press, 293‒319.

Minkowski, H. (1908) Space and time. English translation in Jeffery & Perrett (eds.), 1923.

Pusey, M., Barrett, J., & Rudolph, T. (2012) On the reality of the quantum state. *Nature Physics* 8, 475‒478.

Rovelli, C. (1996) Relational quantum mechanics. *International Journal of Theoretical Physics* 35, 1637‒78.

Rovelli, C. & Vidotto, F. (2015) *Covariant Loop Quantum Gravity*. Cambridge, Cambridge University Press.

1. Here is a more precise statement of their requirement. A theory represents a real physical state only if that state uniquely determines the value(s) of one or more magnitudes within the theory. [↑](#footnote-ref-2)
2. The use of models of decoherence for magnitudes represented by operators with continuous spectrum is analogous but involves additional complexities though no essentially new concepts. In no case does this use of a model depend on perfect decoherence in a fixed orthonormal basis. [↑](#footnote-ref-3)