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S.I. THE METAPHYSICS OF ENTANGLEMENT

Lessons from realistic physics for the metaphysics of quantum theory

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Abstract Quantum mechanics, and classical mechanics, are framework theories that incorporate many different concrete theories which in general cannot be arranged in a neat hierarchy, but discussion of 'the ontology of quantum mechanics' tends to proceed as if quantum mechanics were a single concrete theory, specifically the physics of nonrelativistically moving point particles interacting by long-range forces. I survey the problems this causes and make some suggestions for how a more physically realistic perspective ought to influence the metaphysics of quantum mechanics.

Keywords Quantum mechanics · Quantum field theory · Classical mechanics

1 Introduction

Recent years have seen a sharp increase in interest by metaphysicians in the ontology of quantum mechanics, our current best theory of physics. But this welcome development has an unwelcome feature: the bulk of this work has taken a particular *example* of a quantum theory (the theory of finitely many nonrelativistic particles interacting by long-distance forces), in a particular formulation (the position representation) and treated it as if it were quantum mechanics *in general*.[1]

This leads to problems: first, because it confuses quantum mechanics, which is essentially a framework theory covering a huge number of particular theories, with one particular theory falling under that framework, and thus falls victim to a sort of

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[1] For examples, see Albert (1996), Esfeld et al. (2017), and most of the papers in Ney and Albert (2013).

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category error; second, because the discussions of the ontology of quantum theory mostly seem to aim at ‘fundamental’ ontology, while those quantum theories which are more plausible candidates for ‘fundamental’ physics (specifically, the quantum field theories underlying modern particle physics) differ radically from nonrelativistic particle mechanics.

In this paper, I try to provide a more realistic picture of what quantum theory looks like, in the hope of warding off these problems. I begin (Sects. 2–4) with classical mechanics as a sort of warm-up case, proceed to quantum mechanics (Sect. 5–6), and quantum field theory (Sect. 7). I also briefly consider modifications to quantum mechanics made to solve the quantum measurement problem (Sect. 8).

The physics I describe in this article is standard textbook material, and I don’t attempt to give original references; readers can consult, e.g., Arnol’d (1989) or Goldstein et al. (2013) for classical mechanics, Cohen-Tannoudji et al. (1977), Sakurai (1994), or Weinberg (2013) for quantum mechanics, and Banks (2008), Duncan (2012), Peskin and Schroeder (1995), or Zee (2003) for quantum field theory.

2 *N*-particle classical particle mechanics

One of the most important examples of classical mechanics is *classical N-particle mechanics*.[2] Mathematically, this theory describes the dynamics of N points in three-dimensional space, represented at each time t by vectors $\mathbf{x}_1(t), \ldots \mathbf{x}_N(t)$, and evolving under some differential equations

$$m_k \frac{\mathrm{d}^2}{\mathrm{d}t^2}\mathbf{x}_k(t) = \sum_{j=1, j\neq k}^{n=N} \mathbf{F}_{jk}(\mathbf{x}_j(t) - \mathbf{x}_k(t)), \tag{1}$$

where the m_k are positive real numbers and the $\mathbf{F}_{jk}$ are vector functions. And physically (at least at first sight) the ontology of the theory is tolerably clear: the objects are point particles—particles of zero extension—interacting with one another as they move through space deterministically; the m_j are the particle masses; the $\mathbf{F}_{jk}$ are the forces between particles. There remain substantive philosophical questions to ask: what is the nature of the force terms, and are they simply codifications of particle movement or somehow responsible for them? is the three-dimensional space of the theory representing an additional ontology of substantival space or simply a codification of distance relations between bodies? are the point particles, conversely, reducible

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[2] In this paper I use “mechanics” (as in ‘classical mechanics’ or ‘quantum mechanics’) to refer to the general framework of classical or quantum theories. This accords with current usage in theoretical physics (as seen in the titles of the references by Arnol’d, Cohen-Tannoudji et al., Goldstein et al. and Sakurai in the bibliography, each of which is concerned at least in large part with the framework theory) but conflicts with an older usage (still often seen in philosophy of physics) where the framework is called “classical/quantum theory” or “classical/quantum physics”, and “mechanics” is reserved for particle mechanics and to some degree for other more-or-less “mechanical” systems, like rigid bodies, springs and perhaps fluids. (The difficulty of saying exactly where “mechanics” leaves off is one reason I’ve adopted the more modern convention.) Where I have in mind the mechanics of point particles, I say “classical/quantum particle mechanics” explicitly.

to properties of the points of space?—but nonetheless we seem to have a clear grasp on what the theory is about.

N-particle mechanics does, however, have subtler mathematical representations that can also be useful, but which are further removed from this description of the ontology. A collection of N points in 3-dimensional space is mathematically equivalent to a single point in $3N$-dimensional *configuration space*: the first three coordinates of that point represent the spatial coordinates of the first particle, the fourth through sixth represent the coordinates of the second particle, and so forth. (The use of 'coordinate' language here can be replaced *to some degree* by a more coordinate-free geometric language, but it is important to realise that this $3N$-dimensional space must be taken as much more highly structured than Euclidean space, precisely so that each point in it can unambiguously code the separate features of each particle.)

The configuration-space way of thinking about classical particle mechanics is an example of a *state-space* formulation in physics, whereby a large number of properties of a complicated system are jointly represented by a single point in a high-dimensional space. For another example, note that the equations of motion (1) are *second order*, which means that to calculate the particles' future trajectory we need to know not only their instantaneous positions but also their velocities. The state of the system is then generally said to be specified by the $3N$ positions and the $3N$ velocities together, and so can be represented by a single point in a $6N$ dimensional space called *phase space*. The first three coordinates in this space represent the position of the first particle, the fourth through sixth represent the velocity of that particle, the seventh through twelth likewise represent the position and velocity of the second particle, and so forth. (For technical reasons the coordinates are better taken as representing the momentum of each particle—that is, its mass times its velocity—rather than the velocity, though the two are straightforwardly intertranslatable.)

Dynamics on configuration space, or on phase space, is known respectively as 'Lagrangian' or 'Hamiltonian' classical mechanics. Each permits the equations of motion to be put in a certain, elegant abstract form: in the case of Hamiltonian dynamics, for instance, we can define the Hamiltonian function $H(q^1, \ldots q^{3N}, p_1, \ldots p_{3N})$ of the $3N$ position coordinates q^i and the $3N$ momentum coordinates p_i, and write the equations of motion in the abstract form

$$\frac{\mathrm{d}q^i}{\mathrm{d}t} = \frac{\partial H}{\partial p_i}; \quad \frac{\mathrm{d}p_i}{\mathrm{d}t} = -\frac{\partial H}{\partial q^i}. \tag{2}$$

This is no more or less than a redescription of the equations (1), but it is a useful redescription in many technical situations. It's worth appreciating, though, that the possibility of a state-space description says virtually nothing about the theory's metaphysics. The coding of the properties of a complex composite entity (a collection of point particles standing in various distance relations to one another) in a low-dimensional space, in the position of a simple entity (a single point) in a very highly-structured high-dimensional space is just a mathematical move, available for pretty much any theory. Supposing (absent some further argument) that the mere existence of a state-space representation of the theory tells us that the *ontology* of the theory is that of a point in a high-dimensional space is thus fairly clearly unmotivated.

3 Other examples of classical mechanics

In much of modern metaphysics, ‘classical mechanics’ and ‘point-particle classical mechanics’ are treated as pretty much interchangeable. But in reality, the latter is just one example of the former. Other examples include:

- A spring (abstracting away dissipative effects), where the dynamics describes how the end of the spring moves as it contracts and expands;
- A rigid body, such as a spinning top, moving freely or on a hard surface;
- Vibrations in a solid body such as a crystal;
- The flow of a fluid (again, abstracting away dissipative effects);
- The behaviour of classical fields, notably the electromagnetic field;
- The dynamics of space itself, which is the way general relativity represents gravity.

What makes this plethora of theories ‘classical mechanical’? Here’s at least one natural answer—all can be characterised by:

1. A state space which has the formal structure of phase space, representing (in some abstract sense) the instantaneous configuration of the system and its associated momentum, and with a common mathematical structure (each phase space is a so-called ‘symplectic manifold’);
2. A dynamics given by a Hamiltonian function on phase space and a set of equations of motion of form (2).[3] (A more generous definition of ‘classical mechanics’ would allow a broader class of dynamics and would include systems with dissipation and friction.)
3. A composition rule for systems: the phase space of the combined system $A + B$ is the direct product of the phase spaces of A and B separately (and the Hamiltonian of the combined system is the sum of the individual Hamiltonians plus some interaction term). For instance, the phase space of a two-spring system decomposes into the product of the state spaces of two one-spring systems; given a partition of physical space into regions, the phase space of a field is the direct product of the phase spaces for the fields of each region. (The latter example can require a little mathematical care to make precise but the details will not be salient here.)

So: what is the ontology of classical mechanics *in general*? I hope it’s clear from the range of examples that this is a bad question, indeed a category error. Radically different theories, with radically different ontologies, coexist in the framework of classical mechanics. We can coherently ask what the general ontological features of classical-mechanical theories, plural, are, but so far as I can see that list is short:

Phase-space point representationalism: The distinct points in phase space represent different physical possibilities (rather than, say, representing an agent’s partial knowledge of a system).

Separability: Because of the direct-product rule for composing systems, the properties of a composite system are exhausted by the properties of the component systems.

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[3] Albeit with some subtleties in the last two cases, due to various aspects of gauge invariance (see, e.g., Matschull 1996).

Beyond that, while we can coherently ask questions about the ontology of a *particular* classical-mechanical theory—and while, mathematically speaking, any particular (non-trivial) classical-mechanical theory has a state space that is richly structured, well beyond the basic structure required by classical mechanics in the abstract—there is little or nothing to say about the ontology of classical mechanics as a whole.

4 The failure of classical-mechanical fundamentalism

The would-be metaphysician of classical mechanics might respond thus:

> What I care about is *fundamental* ontology. And most of these examples of classical-mechanical theories are clearly non-fundamental: springs, fluids and the like are complicated composites. Set them aside and look at the fundamental classical theory: presumably particle mechanics, or maybe field theory, or some combination of the two. When I say 'the ontology of classical mechanics', I mean the ontology of fundamental classical mechanics.

But this response assumes that we can identify some classical microphysics such that all (or at least: a reasonable-sized chunk) of the rest of classical physics can be seen as emergent from it. And there is no such classical microphysics. To be sure, since Newton—indeed, since Democritus—natural philosophers have *hoped for* an account of macroscopic matter (springs, fluids and the like) in terms of the movements of point particles. But that hope has never been fulfilled, and we now know it never will be, because *quantum* mechanics turns out to play an indispensible role in our understanding of atomic and molecular physics. Indeed, it was the realisation, in the late nineteenth and early twentieth centuries, of the widespread failure of classical microphysics to underpin bulk matter—in the instability of the atom, or the anomalous heat capacity of low-temperature bodies, or the paradoxical predictions of statistical mechanics when applied to classical black-body radiation—that led to the development of quantum mechanics in the first place.

This is not to say that classical models of microphysics are not often deployed—but they are deployed in a piecemeal, opportunistic fashion that belies any attempt to look for a unified classical micro-ontology. Mark Wilson (in his extensive analysis of ths topic) puts it thus:

> [A] survey of successful exemplars of classical "molecular modeling" shows that …sometimes the "molecules" selected can be modelled as point masses, sometimes as rigid bodies and sometimes as some simple flavor of flexible body (in other words, modeling practice picks no favorite among the standard competitors for serving as the "basic objects" of classical physics). Quite commonly, sundry gaps arising within the classical narratives get patched over with straightforward appeals to quantum considerations, without any attempt to construct a "classical story" for these splices …The net effect of this bumpy support makes classical doctrine look like a suit of armor welded together from a diverse set of stiff plates. Considered solely in its own terms, its organizational rationale will seem elusive, but, regarded as outer fitting suitable for a quantum mechanical knight, the entire affair makes complete strategic sense as an efficient asymp-

> totic covering. To dogmatically assume that this jumble of hinged doctrine can be regularized into an axiomatised format that employs only Newtonian terminology misdiagnoses the true nature of its descriptive successes…[I]f we purify the contents of the predicates that repose upon our facade into complete internal coherence, we will find ourselves sitting within the land of quantum mechanics, and no longer in classical mechanics at all. (Wilson 2006, pp. 196–197)

Of course, nothing prevents the metaphysician from speculating about the metaphysics of a possible world in which Newtonian particle mechanics is exactly correct; but then, nothing prevents them from speculating about the metaphysics of a possible world in which springs or fluids are fundamental. What needs to be recognised in any such speculation is that there is no reason whatever to think that these possible worlds are phenomenologically remotely like ours. (And then it becomes a somewhat pressing question what the point of such speculation is, absent any reason to think that it gives a rough version, or first draft, of the ontology of a world like ours.)

Furthermore, it's worth recalling that Newtonian particle mechanics itself has quite rarely been used to describe or model 'fundamental' point particles (unsurprisingly, I suppose, since there are no such things). The original applications of the theory were to celestial mechanics, where the 'points' are entire planets, or more precisely the centres of mass of those planets. Other applications are to the centres of masses of other rigid bodies, such as cannonballs or the hard spheres used in models of dilute gases. As usual in physics (I'm tempted to say: 'as always in physics'), we are engaged in modelling the dynamics of *salient degrees of freedom* of a system, rather than modelling the system in its entirety.

This is not to say that there is no value in considering the ontology of a given classical theory. It *is* to say that the value must consist in understanding the emergent ontology applicable to systems described by that theory, in the regimes where that description is valid. A detailed account of what it is to consider emergent ontology in this sense lies beyond the scope of this paper: I sketch my own approach to the question in Wallace (2012, ch. 2) (the concept of 'scale-relative ontology' introduced in Ladyman and Ross (2007) is also salient here).

In sum, classical mechanics has these lessons for ontology:

1. Don't blindly reify state spaces: phase-space-point *representationalism*, the view that each point in state space represents a distinct physical possibility, should be distinguished from phase-space-point *realism*, the radical (and unmotivated) view that the world according to classical mechanics is a single point in a high-dimensional space.
2. Remember that ontologically very heterogeneous theories fit under the general dynamical framework of classical mechanics, and that only very limited things can be said about the ontology of these theories in general.
3. Don't automatically assume that these theories lie in a neat ontological hierarchy.
4. Insofar as there is value in studying the ontology of a given classical theory, recognise that this ontology is not a candidate for *fundamental* ontology.

We will see that to a large extent the same lessons apply in quantum mechanics.

5 Quantum theory in the abstract

In classical physics, normally the state-space formalism is derivative: we are given the theory directly, in terms of (say) a collection of functions on spacetime, or trajectories through spacetime, and the dynamics for that collection, and then define the configuration-space or phase-space description of the theory in terms of those more basic entities. Quantum theory, however, is conceived in sin: in general the theory is given directly in a state-space formalism.[4]

That formalism, in the abstract (that is, at the level of abstraction analogous to abstract Hamiltonian classical mechanics), consists of the following:

1. A state space (the space of density operators, i. e. positive trace-one self-adjoint operators, on some Hilbert space);
2. A dynamics given by a Hamiltonian $\widehat{H}$ (a self-adjoint operator on the Hilbert space) and an equation of motion of the form

$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\rho} = \frac{i}{\hbar}\left[\widehat{H}, \widehat{\rho}\right]. \tag{3}$$

3. A composition rule for systems: given systems A and B, the state space for the combined system $A + B$ is the space of density operators on the tensor product of the Hilbert spaces of A and B.

A particular subset of quantum states (so-called 'pure states') can also be represented by normalised vectors in the Hilbert space.

Any particular quantum theory will have much more structure than this (normally given via some preferred algebra of observables); as in the classical case, there is relatively little to say about the ontology of such theories in general, without looking at these theory-specific details. Indeed, the list begins by paralleling the classical one:

Quantum state representationalism: The distinct states in quantum state space represent different physical possibilities.

Unlike in the classical case, this should not be taken as trivial. There is a strong *prima facie* similarity between the formal structure of quantum theory and that of classical *probability theory*: in particular, the latter also has a tensor-product composition rule, reflecting the possibility of probabilistic correlation between systems. These similarities become more marked when we consider that the empirical content of quantum mechanics is contained entirely within the Born rule, whose predictions are generically[5] probabilistic, and are also reflected in various structural similarities between classical probabilistic dynamics and quantum dynamics (Bartlett et al. 2012), and so authors both old (Einstein et al. 1935) and new (Spekkens 2007; Harrigan and Spekkens 2010) have sought to interpret quantum mechanics this way. (The contemporary term for such an approach is ψ*-epistemic*.)

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[4] This disanalogy is largely absent if we formulate quantum mechanics in path-integral form, but in this paper I confine my attention to the more familiar Hilbert-space formalism.

[5] That is: whenever the state is not an eigenstate of the observable being measured.

However, quantum entanglement makes ψ-epistemic approaches to the quantum state very difficult to sustain, as underlined by various formal no-go results, notably Gleason's theorem (Gleason 1957), the Kochen–Specker theorem (Kochen and Specker 1967) and the more recent PBR theorem (Pusey et al. 2011). See Maroney (2012) and Leifer (2014) for detailed reviews, but in short: it looks reasonably clear (without being *universally* accepted) that any plausible non-representational reading of the quantum state will have to presume instrumentalism (Fuchs and Peres 2000) or some other radical departure from the usual scientific-realist conception of physical theories as giving a third-party, agent-independent account of the world [cf, e.g., Fuchs et al. (2014) or Healey (2012); cf also my discussion in Wallace (2018c)].

Non-separability: In sharp contrast to the classical case, the state of a composite system is *not* fully given by the states of the component systems: in general, the quantum state of a composite is *entangled*, and cannot be written as the product of the states of the components.

Physicists distinguish between 'true' entanglement (which could not even be simulated by a local-hidden-variable model and classical probabilistic correlations) and 'mere correlation' (which could be) but the distinction, though of great significance to quantum information, does not seem to be metaphysically salient.

To this could *perhaps* be added:

Superposition: The linear structure of Hilbert space, and derivatively of the quantum state space, means that quantum theory always comes with a well-defined way to add states of a system together to form other states of the same system, and it is an important question what, in general, can be said about the conceptual and metaphysical status of this superposition principle.[6]

If there is more than this to say about the ontology of quantum theories *in general*, it eludes this author.

6 The focus on nonrelativistic particle mechanics

What are some concrete examples of quantum theories? They include:

- Systems of finitely many systems with two-dimensional Hilbert spaces. In abstract quantum-information settings, these systems are called qubits; more concretely, they can represent the spin degrees of freedom of spin-half particles like electrons or protons.
- Harmonic oscillators or coupled collections of such.
- Systems of finitely many distinguishable, spinless, non-relativistic point particles interacting under some multi-particle potential. ('Nonrelativistic quantum particle mechanics'.)

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[6] Readers familiar with the mathematics of quantum theory will recognise that linear sums of *mixed* states are not the same sort of thing as superpositions of pure states; further consideration of these subtleties lies outside the scope of this paper.

- Vibrations in solids, such as crystals (including in situations, like low-temperature phenomenology, where classical models fail).
- Fluids (including systems like superfluids where classical models fail).
- Quantum fields.

The list is as heterogeneous as in the classical case, and indeed includes quantum versions of most of the same systems. (The main exception is gravity, where we have no fully satisfactory quantum theory as yet.) But the overwhelming majority of recent work[7] on the metaphysics of quantum mechanics is concerned with a single example from this list: nonrelativistic quantum particle mechanics (NRQPM), the quantum-mechanical version of the theory of non-relativistic point particles discussed in Sect. 2. Indeed, a student of the recent literature could be forgiven for conflating quantum theory in general with this particular example of quantum theory.

In fact, that recent literature is for the most part not concerned simply with NRQPM in the abstract, but with a particular way of formulating NRQPM. In that formulation, the Hilbert space for a one-particle system is identified with a certain space of complex functions on three-dimensional Euclidean space, so that a pure state of an N-particle system is a complex function on a $3N$-dimensional space. This starting point has led to a popular move in recent discussions of quantum-mechanical metaphysics: *wavefunction realism*, where the theory is interpreted as implying that physical space is high-dimensional and that the physical world consists of a field on that very high-dimensional space. (Wavefunction realism was introduced by Albert (1996) and is discussed extensively in Ney and Albert (2013) and Ney (2018).)

Wavefunction realism can be usefully compared with a position that (so far as I know) is never seriously advocated[8]: *state-space point realism* (in a quantum or a classical guise), in which the state space of a theory is identified with its physical space and the ontology of the theory is a single point in that high-dimensional physical space. In classical state-space point realism, space is $3N$-dimensional, with N the number of particles; in quantum state-space point realism, space is typically infinite-dimensional.

The error in state-space point realism is hopefully clear: the position conflates *representationalism*, the view that distinct points in state space represent distinct physical possibilities, with full-on *literalism* about the state, the view that since a state is a single point, the physical universe consists of a single pointlike object. Representationalism is more or less built into classical mechanics, and we have seen that there are powerful arguments for it in the quantum case. But literalism is unmotivated: the whole point of a state-space description is to represent all the physical complexities of a system in the geometry of the space, so that a single point in that space can uniquely represent all the various complex properties the system has. The very generality of the state-space move (pretty much any dynamical theory can be given a state-space formalism) shows the emptiness of trying to read ontology from it.

Wavefunction realism is not quite as manifestly absurd as state-space point realism, but it shares some of the same flaws. In particular, it is an awkward half-way house between something like a particle description of a theory (where the state of the sys-

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[7] See, for instance, pretty much all the papers in Ney and Albert (2013).

[8] Albert (1996), in his discussion of the 'marvellous point', flirts with but does not commit to the position.

tem is represented by a complicated object—a collection of N points in certain spatial relations—in a relatively structureless space) and a state-space description (where all the structure of the system is represented by its location in a very nonhomogeneous space, and the state itself is structureless). In particular, while a wavefunction is a fairly highly structured object, the space on which it lives is also highly structured: formally, it is classical N-particle configuration space, which is much more structured than $3N$-dimensional Euclidean space. (It has to be, since any point in that space uniquely picks out the spatial configuration of a collection of N points in three-dimensional Euclidean space.) Indeed, the structure of the wavefunction serves entirely to represent quantum-mechanical features of a system (the fact, for instance, that it is in a superposition of two macroscopically different positions). Any quantum state intended to represent an approximately classical state of affairs can be expected to have a pretty-much-structureless wavefunction, with all the structural information encoded by that wavefunction's location in configuration space.

So I think we have strong reasons to be sceptical of wavefunction realism, or at least to recognise that it is not an automatic consequence of state representationalism. At the very least, we should keep in mind that it follows from applying a rather literal-minded approach to what is ultimately only one of many possible formulations of NRQPM.

However, the flaws of wavefunction realism are not my main focus here. (For more on them, see Wallace (2018a) or Wallace and Timpson (2010).) Instead, I want to ask the parallel question as for classical mechanics: why focus on NRQPM at all, when it is just one example of a quantum-mechanical theory?

I'm not aware of any real engagement with this question in the recent literature on the metaphysics of quantum mechanics. (Indeed, very little of it so much as mentions that there are other quantum theories.) But some natural thoughts[9] might include:

1. *Because it's simplest?* But it isn't. Finite-dimensional systems like the spin degrees of freedom of electrons are much simpler.
2. *Because it's empirically adequate, at least outside the exotic regimes of high-energy physics?* The name 'nonrelativistic quantum particle mechanics' might suggest this. But again, it isn't. To be sure, it has a rather wider scope than classical particle mechanics, and a few relatively simple modifications—intrinsic spin, particle indistinguishability—widen that scope further. But it's still a theory that is deployed piecemeal, with the forces between particles set on semi-phenomenological grounds, and with electromagnetic effects handled semiclassically and in a rather *ad hoc* manner. And many important phenomena—notably, those involving light—cannot be handled at all within NRQPM. The two-slit experiment, or the photoelectric effect—paradigm historical experiments on the road to quantum theory—are outside the scope of NRQPM. So is the emission of spectral lines by hot atoms. So is the laser.

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[9] An anonymous referee makes another suggestion: that given that the ontology of particular classical theories is often relatively transparent, while the ontology of particular quantum theories is invariably obscure, one virtue of studying a quantum theory of (say) particles is to clarify the relation it holds to a classical theory of particles—and this can be pursued whether or not we are treating the theory as fundamental. Extant metaphysics of quantum theory mostly has not taken this route, but it seems worth exploring further.

3. *Because salient ontological lessons can be expected to carry over to other quantum theories?* The popular accounts of 'particle physics' might give the impression that the point-particle paradigm will extend just fine beyond the restricted domains of NRQPM, so that if we understand the ontology of a world in which NRQPM is exactly true, we'll understand at least the general features of the ontology of a world governed by our more fundamental quantum theories. But as we will see, this too is radically false.

7 Quantum field theory

I identified 'quantum fields' on my list of quantum theories, but in one respect this is misleading. There are a great many quantum field theories, applicable to a great many physical systems, and in fact it would be more accurate to regard "quantum field theory" as a framework for theories: all quantum field theories fall under the general description given by quantum theory, but they share various structural features beyond those given simply by the axioms of quantum mechanics.

Why pay attention to this particular class of quantum theories? Because pretty much all of modern quantum theory either *is* quantum field theory, or can be understood as *derived from* quantum field theory:

- Quantum field theory, not N-particle mechanics, is the general framework in which high-energy 'particle' physics is expressed;
- It is also the standard framework for modern condensed matter physics;
- Anything involving interactions with light requires quantum field theory;
- Nonrelativistic particle mechanics is now understood as a certain emergent theory underwritten by the quantum field theories of relativistic 'particle' physics.

So insofar as 'metaphysics of quantum mechanics' ought to be focussed on a particular quantum theory (or class of theories), quantum field theory, rather than NRQPM, looks like the right theory to study. Furthermore, quantum field theory (or, more precisely, one particular quantum field theory, the Standard Model of Particle Physics plus perturbative spin-2 gravity), *unlike any previous theory in physics*, appears to be basically empirically adequate for pretty much all phenomenology outside some very extreme (mostly cosmological) regimes. Much of the metaphysics of science discusses 'physics' as if it is a unified whole that can model all physical phenomena (or at least, say, all physical phenomena on the surface of the Earth) in one go, in one model. But classical particle mechanics never had a hope of doing that. Nor did quantum particle mechanics. The standard model is the first, and so far the only, physical theory that gets anywhere near doing it.[10]

So much for the advert; what are the distinctive features of quantum field theory from a metaphysical point of view? The details of the theory are well beyond the scope of this article, but in outline: *unlike* NRQPM, in quantum field theory

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[10] This is not to say that the standard model in any way rules out more disunified approaches to physics, like Nancy Cartwright's (1983,1999)—only that prior to the standard model, there was no single physical theory that was even a plausible candidate for unifying the physics of the observed world.

- There is an intimate, fundamentally-specified link between spacetime and the dynamical variables;
- There is a very indirect, emergent, dynamically driven relation between the microphysically fundamental variables and the phenomenologically accessible variables;
- In particular, ‘particles’ are just excitations of the quantum field (and the particular excitations we get are regime-dependent: a more accurate gloss of the popular-science idea that protons are ‘composed’ of quarks is that ‘quarks’ are the appropriate excitations in a high-energy regime but ‘protons’ and ‘neutrons’ are the appropriate excitations in a lower-energy regime);
- The process of ‘renormalisation’ scrambles up the degrees of freedom, so that particle states (and other phenomenologically relevant states, like the coherent states that describe quasi-classical states of the electromagnetic field) are very complicated, highly-entangled states when described in terms of the fundamental (i. e., bare, unrenormalised) degrees of freedom;
- The whole point of renormalisation theory is that the form of the microphysical degrees of freedom is largely (albeit not completely) underdetermined by the phenomenology, so that the phenomenological success of quantum field theory gives very little information about what the world is ‘fundamentally’ like.

So quantum field theory leaves the would-be student of ‘fundamental’ ontology with a paradox. On the one hand, it’s comfortably the most fundamental physical theory we have; on the other hand, its own central features inform us that it does not give reliable information about the fundamental level.[11] We have good reason to believe that some still-more-fundamental theory replaces the Standard Model beyond the energy levels at which it breaks down, but at present we have only the most tentative idea of what that theory is like.

8 Modifications of quantum mechanics

All of my discussion of quantum theory so far has concerned varieties of orthodox, textbook quantum mechanics. But quantum mechanics faces the measurement problem, and in philosophy (though not in physics) it is widely thought that orthodox quantum mechanics must be modified and/or supplemented to solve the measurement problem. And so, much of the metaphysics of quantum mechanics is the metaphysics of these modifications/supplementations—notably, the metaphysics of the de Broglie–Bohm pilot-wave theory (aka Bohmian mechanics) (Bohm 1952) and of the Ghirardi-Rimini-Weber (GRW) dynamical-collapse theory (Ghirardi et al. 1986).

A distinctive feature of these modifications is that they are defined not for quantum theory in the abstract, but for specific instances of quantum theory—nearly always for NRQPM. My discussion so far would suggest that it would make more sense to study appropriate modications of quantum field theories, in particular the Standard Model,

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[11] I should acknowledge that this position on quantum field theory, though standard in theoretical physics, is contested in philosophy of physics; see Wallace (2011, 2018b) and, for the opposing view, Fraser (2009, 2011).

but at present there *is no* fully satisfactory extension of either hidden-variable theories like Bohmian mechanics, or dynamical collapse theories like GRW, to the Standard Model, or indeed very far beyond NRQPM.[12]

In my view, the absence of such extensions, and the resultant failure of modificatory accounts of quantum theory to satisfactorily account for a huge fraction of observed quantum phenomena, is itself a case for rejecting these accounts, and looking for a realist understanding of unmodified quantum mechanics—a search which (I argue in Wallace 2012) leads to Everett's 'many-worlds' interpretation. But put that aside: the metaphysician who rejects Everett has a potential fourth rationale to study NRQPM.

But this rationale is ultimately no more defensible than those I considered in Sect. 6. GRW and Bohmian mechanics may be the best we've done so far in pursuing modifications to quantum theory to solve the measurement problem, but they are not *true*, nor is there any very good reason to expect their central features to be preserved by future modifications of more empirically adequate theories like the Standard Model. Indeed, the radical changes in the structure of the quantum theories that are to be modified gives strong *prima facie* grounds to suspect that those features will *not* be preserved. In particular, both GRW and Bohmian mechanics give a special role to the particle position observable, which has no correlate in the fundamental dynamical variables of quantum field theory; more generally, the gulf that renormalisation opens up between fundamental and phenomenological dynamical variables makes it difficult at best to guess the structure of a hypothetical empirically-adequate modification to quantum theory.

That is not to say that these theories are not of philosophical (or indeed metaphysical) interest *tout court*. They are rightly celebrated as proofs of principle: demonstrations that it is *possible* to solve the measurement problem by modifying dynamics or adding ontology, possible route markers on the path to new physics that would solve the measurement problem in deeper-level physical theories, and thought-experiment laboratories to consider the general conceptual, epistemic and metaphysical implications of theories of this kind.

But the metaphysician who wishes to go beyond that sort of tentative exploration and actually treat the ontological specifics of either theory as a candidate for fundamental metaphysics—who wishes, for instance, to speculate about a world consisting only of point particles on the basis that Bohmian mechanics seems to describe such a world—owes us, at the very least, a proper story as to why their approach should be expected to tell us anything much about the real world. Absent such a story—and I do not really see how to tell it—the right course of action for a metaphysician who believes we need to modify quantum mechanics and who wants to say specific things about fundamental metaphysics would seem to be silence, until such time as physically realistic modifications are actually available.

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[12] There are a variety of proposals both for relativistic hidden-variable theories (Colin 2003; Dürr et al. 2005; Colin and Struyve 2007) and for relativistic collapse theories (Tumulka 2006; Bedingham 2010) but to my knowledge no full working through of any such theories to cover realistic interacting, renormalised theories.

9 Conclusions

The main point of this paper is just to give a realistic account of the complexity and variety of quantum (and to a lesser extent, classical) physical theories, as an antidote to overly simplified, unified and reductive accounts that seem to be predominant in the contemporary metaphysics of physics. However, some general conclusions can be drawn:

1. State spaces, ubiquitous in physics, should not be (blindly) reified.
2. Only very general, abstract conclusions about the ontology of quantum (or classical) mechanics as a whole are likely to be possible.
3. There is no 'fundamental' classical mechanics: no single classical-mechanical theory from which all other empirically-relevant classical theories can be derived.
4. There might be a 'fundamental' quantum mechanics in this sense, but if so, it is not nonrelativistic particle mechanics; rather, it is a quantum field theory, the standard model of particle physics.
5. In principle, metaphysicians of quantum theory ought then to be looking at quantum field theory—but they should do so with a clear appreciation that the theory (at least as understood by working physicists) is, by design, largely silent about 'fundamental' ontology. If there is a physical theory which does tell us about fundamental ontology, we don't as yet have it.
6. Metaphysicians interested in the ontology of various modifications or supplements to nonrelativistic quantum particle mechanics need to have a methodological story to tell as to what they are doing and why it is worthwhile.

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