Scientific Realism and the Quantum

Steven French & Juha Saatsi
University of Leeds

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Contributors

VALIA ALLORI, *Northern Illinois University*

ALISA BOKULICH, *Boston University*

CRAIG CALLENDER, *University of California at San Diego*

DOREEN FRASER, *University of Waterloo*)

JAMES FRASER, *Durham University*

STEVEN FRENCH, *University of Leeds*

RICHARD HEALEY, *University of Arizona*

CARL HOEFER, *Universita Autonoma de Barcelona*

LINA JANSSON, *University of Nottingham*

PETER J. LEWIS, *Dartmouth College*

WAYNE MYRVOLD, *Western University*

LAURA RUETCHE, *University of Michigan*

JUHA SAATSI, *University of Leeds*

J. E. WOLFF, *University of Edinburgh*

DAVID WALLACE, *University of Southern California*

Contents

Introduction

Steven French and Juha Saatsi

Quantum physics represents our best and most fundamental physical science. Our understanding of numerous physical phenomena and our knowledge of the nature of light, electricity, solid matter, elementary particles, and even parts of chemistry, is rooted in quantum physics. But exactly what kind of knowledge does it provide us? This question gains significance from weighty epistemological issues that forcefully arise in this context — issues that are also at the heart of a more general debate on 'scientific realism' in the philosophy of science. This volume aims to advance both the realism debate as well as our understanding of the nature of quantum physics by bringing the two together in a productive dialogue.

Scientific realism was famously announced dead already back in 1984 by Arthur Fine, an American philosopher of science. He explained that its demise "was hastened by the debates over the interpretation of quantum theory, where Bohr's nonrealist philosophy was seen to win out over Einstein's passionate realism," and that its death "was certified, finally, as the last two generations of physical scientists turned their backs on realism and have managed, nevertheless, to do science successfully without." (1984, p. 261) Fine's diagnosis appears flawed, however, as more than thirty-five years later realism doesn't just linger on, but thrives in discussions about quantum physics! But debates over the interpretation of quantum theory have not become any calmer in the hundred or so years after its inception, even though Bohr's ideas have been debunked many times over (Becker 2018). If anything, it is currently even harder find a consensus about critical interpretive issues, as the range of seriously considered alternatives has steadily increased amongst broadly realist approaches to quantum physics. In this state of affairs there is considerable pressure to better articulate not just what "realism about the quantum" amounts to, but also what *justifies* a realist perspective over alternatives that rescind one or another realist theses. This volume collects together new work from the cutting edge of this active area of current research.

As indicated, the core realist intuitions about the physical sciences are resilient and hard to deny, but what exactly does "realism" stand for? As Richard

Healey explains in his contribution to this volume, this term of philosophical trade has many meanings. In the extensive philosophical and foundational literature on quantum theory, realism has most typically signified the notion that we can specify what the mind-independent physical world could be like so as to render quantum theory (approximately) true. Painting a picture of reality compatible with the truth of quantum theory is a business of *interpreting* the theory, its mathematical formalism and models. Realists like Einstein traditionally placed intuitive constraints on plausible pictures of reality compatible with quantum theory — in particular, that they should conform to a principle of locality according to which physical systems have determinate local properties not influenced by action at a distance.

Today's realist interpretations are a much more motley bunch, filling more of the space of logically coherent possible ways the world could be to make true one or another formal variant of quantum theory. These interpretations have emerged over decades of work by both philosophers and physicists engaged in foundational research. This work has largely aimed to tease out quantum theory's metaphysical and ontological implications, but hitherto much less attention has been paid to the concomitant epistemological issues. It is these latter issues that form the primary focal point of the present volume, which aims to engage more directly with the relevant epistemological questions that are also debated within general philosophy of science, concerning the status of our best scientific theories as a source of knowledge about unobservable reality or as furnishing representations of it.

The realist attitude towards well-established scientific theories is widely shared, seemingly common-sensical, and presupposed by the broadly accepted idea that such theories indeed do provide us genuine scientific understanding of natural phenomena through explanations in terms of how the unobservable world is structured and how it "works". Considerations in favour of realism tend to capitalise on the empirical success of science, variously manifested in triumphant theoretical predictions and the way science ever-increasingly supports our ability to manipulate the world to our liking through powerful interventions and applications that put to concrete use quantum theoretical notions such as 'spin'.

But while realists proclaim optimism about science's ability to tell us how things stand behind the veil of observable appearances, a very long tradition steadily opposes any such optimism on the basis of varied considerations regarding science at large. Two sources of scepticism have been particularly pervasive. First, there are historically driven concerns about the status of our current scientific theories' as "approximately true", based on the historical track-record of radical and unexpected (r)evolutions in foundational scientific theorising. Secondly, there are general "underdetermination" worries about the possibility of there being empirically indistinguishable — either in principle or for all practical purposes — theories that represent the world in radically different ways. These two broad sets of concerns have been raised time and again against scientific realism in various specific ways, sometimes individually, sometimes in unison.

Like much of general philosophy of science, the debates surrounding such concerns have been traditionally largely conducted in rather broad and abstract terms, quite independently of specific scientific detail. In a significant recent trend philosophers have become increasingly troubled about the potential limitations of sweeping, general arguments for or against realism, due to the variability of evidential, methodological and explanatory contexts and practices that seem relevant for the assessment and outcomes of these arguments. As a result, there has been increasing emphasis within the realism debate of the importance of discipline or domain specific scientific details. In this spirit more 'local' analyses of the key issues animating this debate have been undertaken in relation to disciplines such as, e.g. cosmology, economics, geology, molecular biology, paleontology (see, e.g., contributions to Saatsi 2018, Part IV).

Quantum physics of course also provides a very natural locus for such a 'local' analysis, as the contributions in this volume nicely demonstrate. On the one hand, realism towards quantum physics is very easy to motivate in the light of its truly outstanding empirical successes. On the other hand, the theory is well known for its exceptional interpretational challenges and the resulting bifurcation regarding what it is taken to tell us about reality. This bifurcation powerfully brings to life the kind of underdetermination that many anti-realists have tended to worry about in the abstract. Relatedly, many classic philosophical questions concerning the relationship between science and metaphysics — the latter being deeply problematic according to some prominent anti-realist philosophers — are also nicely brought into focus in this context. In addition to throwing new light on such well-known issues, there are also entirely new ideas to be considered that have recently emerged specifically in the context of the philosophy of quantum physics, such as quantum pragmatism (advocated by, e.g., Richard Healey), and quantum Bayesianism (advocated by, e.g., Christopher Fuchs). The fourteen chapters that follow engage with all these issues and many, many more.

Let's now turn to the contributions to this volume. A theme running through many of them is to respond to the above problems by changing the terms in which realism is articulated. **PART I** presents two proposals for accomplishing this by explicitly rethinking what scientific realism amounts to.

Carl Hoefer articulates and defends 'Tautological Scientific Realism' (TSR). It eschews standard ways of defending and delineating realist commitments with regard to Inference to the Best Explanation and considerations of what might be preserved across theory change. Nevertheless, TSR, much like standard realism, maintains that our current scientific picture of the world is to a significant extent correct and will be retained through future changes at the theoretical level. But such a realist stance is only appropriate, Hoefer argues, with respect to those areas of current science for which we simply cannot seriously imagine future developments that would show that we are seriously mistaken in our current ontological commitments — in the way that we were with regard to phlogiston, for example. These 'safe' areas of science embrace the core properties of atoms and the way they combine, as well as our knowledge of electronics, for example, but not, crucially, quantum physics. Hence, Hoefer argues — more contentiously — for a new way of delineating realist commitments, according to which our current *'fundamental'* theories, such as quantum mechanics and quantum field theory, are specifically excluded from the scope of TSR. The grounds for this are two-fold: first, quantum physics is subject to the kind of underdetermination indicated above (and as discussed in one way or another by most of the papers in this collection); and secondly, it is expected to be replaced by a theory capable of unifying quantum theory and general relativity. Thus, Hoefer argues that the appropriate attitude towards quantum physics is one of anti-realism: agnosticism about its ontology, coupled with instrumentalism about its theories.

Juha Saatsi also proposes an alternative articulation of realism, focusing his discussion on the exemplary quantum property of spin. As is well-known, spin has no classical analogue and, as Saatsi notes, it not only lies at the heart of many quantum theoretic explanations, but has come to be understood as increasingly manipulable in a way that allows it to feature in a number of exciting new technological developments (e.g. 'spintronics'). These features strongly motivate a realist stance towards spin in a way that is, Saatsi argues, analogous to the motivations behind Hoefer's TSR, thereby questioning the latter's exclusion of quantum physics from its scope. Yet spin also lies at the heart of the 'interpretational conundrums' of quantum theory and spelling out what spin *is* involves 'deep" metaphysical commitments that go beyond what is necessary to account for any theory's explanatory and predictive success. Here the underdetermination that bedevils realism raises its ugly head again: even the comparatively straightforward setup of silver atoms passing through a Stern-Gerlach apparatus arguably comes to be characterised in radically different ways depending on one's theoretical approach. Yet, these different ways seem to add nothing to the epistemic virtues of the theory — hence, Saatsi argues, they involve 'deep' metaphysics that remains unjustifiable by the realist's lights.

However, rather than abandoning a realist stance towards spin altogether, Saatsi argues that we should step away from such deep metaphysics and modify our realism accordingly. Thus he suggests we should give up the epistemic ambitions of what he calls 'truth-content' realism, grounded as it is in notions of reference and approximate truth. Instead we should accept and articulate a form of 'progress' realism which, in the case of spin, does not commit to claims about what spin is like, but nevertheless acknowledges that the relevant models function as representations of reality and to that extent can be considered to 'latch onto' the world in ways that ground the empirical success of the theory. This maintains a representational role for these models and, in naturalistic terms, allows for physics theorising itself to explain the success of spintronics, for example. It also constrains future theorising by pointing to those well-known exemplars of inter-theoretic relationships that motivate claims of theoretical progress and emphasising that this is how physics can make sense of its own empirical success.

PART II contains three chapters that further explore the challenges faced by realism in the quantum context, focusing on the interconnected issues of underdetermination and interpretation. As already noted, there are well-known alternative realist approaches to quantum theory, such as Bohmian ('hidden variables'), Everettian ('many worlds'), and dynamical collapse formulations, as well as specific interpretations, such as Quantum Bayesianism, the 'transactional' approach, and myriad others. Which, if any, should a realist embrace, and on what grounds? Or does the problem of underdetermination completely undermine scientific realism in relation to quantum theory?

Craig Callender voices a degree of pessimism about realists' prospects for quarantining the blight of underdetermination. He helpfully characterises the different foundational/interpretational approaches in terms of Lakatosian 'research programmes', delineated by their hard cores and negative and positive heuristics. As he also points out, given the flexibility inherent in each programme, no crucial experimental test between them is likely in the near future. Furthermore, as Callender goes on to argue, the underdetermination here cannot be dismissed as artificial (with the various interpretations construed as philosophers' toys or mere notational variants); hence, the realist faces a genuine problem.

A natural move for the realist is to try to find some common ground between these different programmes in which she can plant her flag. Unfortunately, as Callender spells out, all we seem able to find are small disconnected 'islands of reprieve'. Following a suggestion by Alberto Cordero (2001), Callender looks at basic 'textbook level' cases of quantum models, to see what common ground can be found. He concludes that insofar as quantum models of, e.g., the water molecule underwrite incontestable claims, these claims are not distinctly quantum in nature. And much of the distinctly quantum theoretic content of models of, e.g., quantum tunnelling or the hydrogen atom, turns out to differ between different variants of quantum mechanics (e.g. the Bohmian theory vs. standard textbook presentations) — a point that chimes with Saatsi's claim about different accounts of the Stern-Gerlach apparatus. Even relaxing what one means by 'quantum' and shifting to the semi-classical level offers little hope for the realist, as Callender shows that most of what we say about the quantum realm is dependent on the chosen foundational perspective. And unless the realist substantially reins in her ambitions, along the lines suggested by Hoefer and Saatsi, for example, it seems she must make such a choice. But which? As Callender notes, it's not just a matter of balancing competing theoretical virtues, but of reconciling different attitudes towards such virtues and their relationship to empirical confirmation. In a sense, he concludes, we have a kind of philosophical gridlock.

David Wallace locates the disagreement between the different realist approaches to quantum theory at a more fundamental level: what is the theory that one is trying to interpret in the first place? In other words, when it comes to the issue of identifying the 'best interpretation of quantum theory', it is not just a matter of debating theoretical virtues, or what we mean by an 'interpretation', but how we identify quantum theory itself. Wallace argues that 'abstract' quantum mechanics, with its formalism of Hilbert space and self-adjoint operators representing observables and so on, should not be conceived of as a scientific theory at all, but as a theoretical 'framework' within which concrete quantum theories — e.g. quantum particle mechanics, quantum field theory, or quantum cosmology— can be expressed. The latter theories have limited applicability, depending on the type of system, the energy level involved, and so on. (This is analogous to classical mechanics, according to Wallace, where an overarching framework, provided by Hamiltonian or Lagrangian mechanics, encompasses a wide range of concrete theories.) These concrete theories are inter-related in various ways, and Wallace argues that in the quantum case these inter-relationships should be seen not as establishing a hierarchy, but something more akin to a patchwork (although not necessarily a disunified one). Given this understanding of quantum theory, he asks: what should we expect from an interpretation thereof?

The answer, Wallace argues, is an interpretive *recipe* that tells us how to understand any specific quantum theory, in a manner that is compatible with the relevant inter-theory relations. (Again, this is analogous to classical mechanics.) Such an interpretive recipe is arguably provided by the Everett interpretation. Other interpretational approaches, he claims, fail to similarly make sense of the relationships between specific, concrete quantum theories. Dynamical collapse and hidden variable approaches, for example, typically focus only on non-relativistic particle mechanics and, further, under the fiction that it is a fundamental and universal theory. The theoretical commitments of such approaches that in one way or another modify 'standard' quantum mechanics are disconnected from the actual practice of physics, and incapable of accounting for the successes of quantum theories as *non-fundamental*, effective theories applicable in a given domain or energy regime. In the same spirit Wallace argues that interpretational strategies that take the quantum state to be a non-representational (e.g., Richard Healey's quantum pragmatism, see Ch. 6) fail to make sense of how quantum physics captures a quark-gluon plasma, for example, involving an interplay of many concrete quantum theories and their relationships.

J.E. Wolff adopts a broader perspective on the question of what it is to interpret quantum theory. She contrasts a 'naturalistic', science-driven philosophical stance towards theories with that of the more principled, 'empiricist' stance, as represented by van Fraassen. Regarding the former, the Everettian interpretation favoured by Wallace is a clear example of an attempt to naturalistically 'read off' ontology from the theory. However, van Fraassen raises a challenge for the naturalistic stance. Following Maddy (2007), a 'naturalistic native' is someone so deeply immersed in scientific practice that she approaches *all* questions, including interpretive ones, from within that practice. Van Fraassen questions the idea that a naturalistic philosopher can consistently regard a paradigmatic participant of current science as such a naturalistic native. If such a native is incapable of adopting a distinctly philosophical interpretation of her own scientific practice, how will she cope with situations where scientists are more or less forced to step back and reflect on their aims and methodologies? Paradigmatic cases of such a situation were involved in the development of quantum mechanics, and hence a naturalist philosopher must here face van Fraassen's challenge: on the one hand, if the naturalistic native cannot engage in such reflection, then she cannot function as the paradigmatic participant in science, as she will be unable to handle crisis situations; on the other hand, if she is allowed to step back and reflect, then she cannot be really characterised as a 'naturalistic native'. Thus, van Fraassen insists (from within his empiricist stance) that interpreting theories necessarily requires stepping outside of science itself, since interpreting a theory like quantum mechanics involves considering how the world could possibly be the way the theory says it is and that involves investigating alternatives.

As Wolff suggests, the naturalist, in response, might question whether interpretation necessarily involves stepping outside of science in this way. To this end she identifies three different 'moments of interpretation' that arose in the development of quantum mechanics: interpretive questions that featured in that very development; the presentation of alternative views in competition with the 'orthodox' interpretation; and articulating what the world would be like were the theory to be true. With regard to the first, Wolff argues that this did not require scientists at the time to step back from their scientific practice or engage in particularly philosophical reflection, so there is no issue for naturalism here. When it comes to the second 'moment', the naturalist could maintain that the hidden-variables and the dynamical collapse approaches are actually different theories rather than different interpretations per se. As for the third project of interpretation, which is the one van Fraassen primarily has in mind, this does seem to present a problem for the naturalist, insofar as it invites metaphysical speculation. One option for the naturalistic philosopher identified by Wolff is to deny that there is a plurality of such speculative interpretations worth engaging with. Thus she could follow Wallace, for example, in adopting a 'literalist' line and arguing that the Everett interpretation is the only one that takes the theory literally, thereby rejecting the basis of van Fraassen's challenge.

However, Wolff continues, the risk then is that the naturalist might be unable to accommodate the way that such interpretive projects aid our *understanding* of the theory. After drawing a distinction between 'symbolic', 'objectual' and 'explanatory' forms of understanding, she argues that the last, in particular, is not closed off to the naturalist. Focussing on de Regt and Dieks' contextualist approach to this form of understanding, Wolff notes that by characterising it as an epistemic aim of science — something the empiricist would reject, of course — this approach would surely look attractive to the naturalist. And in the quantum context, both the hidden-variables and dynamical collapse approaches, for example, can be viewed as offering such explanatory understanding. This underwrites them as appropriate for the naturalist's consideration, and thus the naturalistic native is ultimately not precluded from engaging in various forms of interpretive endeavour.

PART III comprises three chapters that focus on pragmatism about quantum theory, representing a step further beyond traditional conceptions of scientific realism, but without embracing traditional anti-realism either.

Richard Healey is a key advocate of such a pragmatist interpretation, at the heart of which lies the rejection of the 'representationalist' assumption that a scientific theory can give us a literally true account of what the world is like only by faithfully representing the world. As Healey notes, those parts of quantum physics that are actually used in incredibly successful technological developments such as spintronics, for instance, are independent of foundational and interpretational issues. If we think carefully about how quantum mechanics is actually applied to physical systems, Healey argues, we should see that the name of the game is not the representation of quantum reality but rather to give us, the users of the theory, appropriate information about the significance and credibility of claims regarding non-quantum physical features associated with those systems. Thus, for example, according to Healey the primary role of the notion of the interpretationally troublesome 'quantum state' is not to represent, or describe, some system, but to rather prescribe how we should determine the probabilities associated with various measurable eventualities (by applying the Born rule).

However, Healey insists, this is not a form of instrumentalism or empiricism (of the sort advocated by van Fraassen, for instance), since it does not rely on any distinction between 'observable' and 'unobservable' features of the world; rather, various claims about unobservable physical magnitudes are significant and true or false, depending on how the world is. It is the function of (non-quantum) magnitude claims to represent the relevant features of reality and ultimately it is the truth or falsity of such claims that we care about. This is still compatible with a 'thin' version of the correspondence theory of truth, in the sense of one that eschews some form of causal account of reference, so that we're not misled into thinking that terms appearing in magnitude claims refer to their subject matter via some form of causal connection. Indeed, Healey maintains, recent arguments regarding a form of the Bell inequalities put paid to such thinking. Nevertheless, we can still accept the existence of a physical world that is independent of our thinking about it. What the pragmatist adds to this conception is a broader perspective on how we gain knowledge of that world: this is achieved not via representation per se but, in effect, by taking the theory's advice on how the world might be meaningfully represented and what the likelihood is of such meaningful representations being true. Furthermore, from this pragmatist perspective quantum theory still helps us to explain a range of otherwise puzzling phenomena by showing that they were to be expected and also what they depend on.

The following two chapters focus on critical issues about the pragmatist attempt to construct a 'middle road' between realism and instrumentalism.

Lina Jansson focuses on the issue of explanation and the close ties that it has with scientific realism and argues that from this perspective, Healey's pragmatist interpretation comes with significant costs. She begins by inviting us to consider the putative truism that genuine explanations posit true explanans. This intuitive idea has to be immediately qualified, however, due to well-known challenges arising from the roles of idealisations, distortions and fictions within scientific explanations. A realist can try to hang onto the gist of the putative truism by appropriately distinguishing the explanatory from the non-explanatory roles played by different aspects of scientific explanations, in such a way that the latter's ontological commitments are tracked. However, such moves are not open to Healey who rejects, as we have seen, the claim that quantum models explain by virtue of representing quantum reality, arguing instead that they explain by virtue of telling us what to expect regarding non-quantum magnitudes, together with what such magnitudes depend upon. A crucial issue is how to make sense of this explanatory dependence by the pragmatist's own lights.

As Jansson suggests, one possibility is to adopt a popular counterfactual approach based on 'what-if-things-had-been-different' questions (in the spirit of James Woodward), while also allowing for non-causal dependencies. However, without causation to rely on, there is no straightforward way of distinguishing the explanatory theoretical posits from the non-explanatory roles played by idealisations and the like. The way to proceed, she averts, is to carefully distinguish different kinds of dependence within the epistemic dependence approach to explanation and, in particular, to look to what it is that allows us to make the relevant inferences about the counterfactually robust connections between the initial input of the explanans and the explanandum. Idealisations, distortions and fictions can serve to do that, without acting as the relevant input into the explanans. In Healey's account, since the quantum state is not taken to represent the system in question, it cannot serve as such an initial input but it may nevertheless be indispensable to us in offering the appropriate explanations. As a result, Jansson argues, crucial information about the physical grounds for the appropriate assignment of such states has to be effectively 'black-boxed', a feature that she highlights as one of the costs of adopting this form of pragmatist stance.

Peter Lewis also examines the costs of pragmatist approaches — here taken to embrace also Simon Friederich's (2015) account — not only with regard to explanation but also when it comes to our understanding of the content of propositions. In articulating their position the pragmatists appeal to an inferentialist account of meaning according to which the meaning of a proposition lies with the material inferences that it supports, rather than in its representational content. It arguably follows from such an account that claims concerning, e.g., quantum states, spin, etc., are best viewed not as describing physical systems, but rather as *prescribing* degrees of belief in non-quantum magnitude claims that do have descriptive content. Lewis illustrates this by reference to a quantum state associated with a particular molecule. This quantum state can license appropriate probabilistic inferences regarding, e.g., the molecule's location upon encountering a silicon surface through the application of the Born rule (underwritten by decoherence). A claim concerning the molecule's location on the surface is an example of a non-quantum magnitude claim that has descriptive, empirical content that is worth asserting, since it supports material inferences about, e.g., image formation in an electron microscope. The quantum state itself allegedly does not have such content; any claim about the molecule's location at a diffraction grating, for example, would lead to erroneous inferences concerning which slit the particle is going to go through, for instance. Hence, apart from prescribing probabilistic inferences supported by the Born rule in situations where the quantum state decoheres, arguably the state ascription has no content, especially when the Born rule is inapplicable.

As Lewis notes, one might worry that the distinction between prescriptive and descriptive content is not supported by the inferentialist account itself and here perhaps appeals to further elements of the pragmatist toolbox must be made. More acutely perhaps, Lewis raises the issue that it is not clear how counterfactual inferences are to be treated on the pragmatist approach: if a diffraction grating were to be replaced by a silicon surface, we would shift from a situation in which no credences regarding location can be assigned, the relevant claims being taken to be devoid of content, to one where definite probabilistic prescriptions can be made, the relevant claims being contentful. But given that latter point, if counterfactuals contribute to the content of quantum state attributions, then, Lewis argues, the former claims should also be understood as having at least some content, contrary to what the pragmatists assert. One possible response to this worry would be to reconsider the role of decoherence with regard to this shift in context — rather than delimiting the range over which claims have content it should be understood as delimiting the range over which our material inferences can unproblematically draw on our classical intuitions. Resolving these sorts of worries, together with those concerning explanation, Lewis concludes, will crucially determine whether this sort of pragmatist approach has enduring advantages over its realist rivals.

PART IV includes three chapters that focus on various issues concerning the nature of the quantum state, standardly taken to be — in contrast to the pragmatist approach — represented by the wave function. Indeed, advocates of so-called wave function realism argue that this representational role should place the wave function at the centre of the scientific realist endeavour.

Alisa Bokulich challenges this view and the 'hegemony of the wave function' in general by presenting a formulation of quantum mechanics that doesn't make use of it. This is 'Lagrangian quantum hydrodynamics' according to which the state is represented via the displacement function of a continuum of interacting 'particles' following trajectories in spacetime. Schrödinger's equation is then recast as a second order Newtonian law governing such trajectories. Although this formulation is helpfully motivated by classical hydrodynamics, Bokulich is at pains to emphasise that it does not require commitment to some notion of a 'quantum fluid'. Instead the fundamental state entity via which one can understand the time evolution of the system is given by the congruence of the trajectories.

As she goes on to note, the centrality of these trajectories in this formulation suggests an obvious comparison with Bohmian mechanics. However, there are crucial differences, most notably with regard to the role played by the wave function in the latter. Furthermore, Bokulich insists, Bohmian mechanics is an *interpretation*, whereas Lagrangian quantum hydrodynamics is a *formulation*, and as such has entirely different interpretive ambitions (with regard to the measurement problem, for example). Interestingly, as Bokulich outlines, this alternative formulation reveals a previously obscured symmetry of quantum mechanics, associated with the infinite-parameter particle relabeling group, which implies the conservation of quantum forms of circulation, density and current. Controversially, perhaps, when transposed to the relativistic context, the conservation law allows for the definition of global simultaneity manifolds. More significantly, it is partly because it allows the articulation of this relabeling symmetry that the Lagrangian formulation should be regarded as more fundamental than the apparently equivalent Eulerian formulation of quantum hydrodynamics (associated with Erwin Madelung), which retains the wave function representation of the quantum state.

What does this imply for the various realist projects adopted and pursued in the context of quantum theory? As Bokulich notes, the formulation not only challenges the hegemony of the wave function, but also offers a new perspective on experiments — such as those involving protective measurements — that are invoked as evidence for its reality. More generally, the existence of the Lagrangian formulation encourages us to be cautious in reading off our realist commitments from features of the standard mathematical presentation of quantum mechanics. Finally, one could also adopt a realist stance towards this formulation itself. Here Bokulich identifies three possible ways forward. One is to render it an interpretation of the theory, as in the 'Many Interacting Worlds' or 'Newtonian QM' views. Another is to adopt a 'duality' line towards the quantum state, with the wave functional and trajectory based aspects regarded as a new take on the (in)famous wave-particle duality. The third approach is what Bokulich calls 'inferential realism' which urges a shift in realist focus from asking 'what is the world like?' to 'what true things can we learn?' instead. Drawing on Ernan McMullin's emphasis on the role of metaphors in the realist enterprise, Bokulich insists that inferential realism is more about developing a plurality of fertile interpretations than finding the one true picture of the world, and both the trajectory-based and wave function conceptions of state feature in this plurality.

Valia Allori similarly seeks to decentre the wave function in realist approaches to the theory. Like Bokulich she argues that we should not simply read off our realist commitments from a given formulation, but instead start the interpretive project with a 'primitive ontology' and construct our interpretation around that. In Newtonian mechanics the primitive ontology is that of particles, for example, represented by points in three-dimensional space and our understanding of the theory is grounded in this. Shifting to the quantum domain, Allori argues that we should retain the same approach, dropping the representational role of the wave function, not least because of the issue of how to understand superpositions. Instead, she maintains, we should begin with a primitive ontology located in space-time, and select an appropriate law of evolution for the relevant entities and aim to understand the theory on that basis. Different such primitive ontologies can then be combined with different laws of evolution, and Allori considers three kinds of the former: particles, matter fields and 'flashes'. This array of alternatives can accommodate a whole slew of theories, as she sets out. Within this interpretive framework the role of the wave function is to help implement the law that governs the spatio-temporal evolution of whatever primitive ontology has been chosen. Thus the wave function can be regarded as having a nomological character, a suggestion that appear more palatable to many if understood from a Humean perspective, according to which law statements are simply the axioms and theorems of our best theoretical system, representing regularities found in the world. Given the choice of modifying our conception of what counts as ontology or that of what counts as a law in the quantum context, Allori prefers the latter.

This general approach meshes well, she argues, with selective realism about the 'working' posits of the theory that are responsible for its explanations and predictions. Here the primitive ontology would supply the working posits, the wave function counting as a merely 'presuppositional' auxiliary that is necessary for the theory's mathematical formulation (however see Bokulich above) but not to be understood realistically. Nevertheless, in some of the theories canvassed here, there remains a kind of dependence of the primitive ontology on the wave function and Allori suggests that this yields a useful way of categorising solutions to the measurement problem: in theories of type 1 the primitive ontology and the wave function are independent, as in particle theories; in theories of type 2 the two are co-dependent and these include flash and matter density theories. Armed with this distinction Allori goes on to explore how such theories differ with respect to their super-empirical virtues (e.g. empirical coherence, simplicity and relativistic invariance), arguing that Bohmian interpretations with particles as their primitive ontology and GRW approaches with a flash ontology should be viewed as the leading contenders, with the former, according to Allori, just nosing ahead. More importantly and generally, she concludes that once we get the wave function off centre stage we can more easily explore the different ways quantum mechanics can be made compatible with realism.

Wayne Myrvold considers a broader set of reasons for denying that quantum states represent something physically real and argues that at best these provide grounds for pursuing theories in whose ontologies quantum states don't appear. Such reasons may draw on certain classical 'toy' models in the context of which apparently quantum phenomena can be reproduced, such as the existence of pure states that cannot reliably be distinguished. However, Myrvold notes, these phenomena are at best only 'weakly' non-classical and such models cannot capture the Bell inequalities, for example, which are regarded as exemplars of quantum behaviour. Likewise, he argues, the fact that quantum mechanics exhibits classical behaviour under certain restrictions is better regarded as a prerequisite for taking the theory as comprehensive in the first place, rather than as evidence that quantum states are not real.

Myrvold then goes on to give positive reasons for an ontic construal of quantum states, within the context of the information theoretic 'ontological models framework'. From this perspective, he explores the importance of two theorems that constrain the set of possible theories that could account for quantum phenomena. The first is due to Barrett, Cavalcanti, Lal, and Maroney and shows that quantum states cannot be construed as probability distributions over an underlying state space in such a way that the operational indistinguishability of such states can be accounted for in terms of overlap of the corresponding probability distributions. The motivation for constructing an interpretation under which the quantum states are not ontic is thus stymied. The second theorem, due to Pusey, Barrett and Rudolph, demonstrates that distinct pure quantum states are ontologically distinct. Crucially this assumes the so-called Preparation Independence Postulate (PIP), which has to do with independent preparations performed on distinct systems. Myrvold problematises PIP in relation to quantum field theory, and proposes that it be replaced with what he calls the Preparation Uninformativeness Condition (PUC), which, he argues, suffices to show that distinct quantum states must be ontologically distinct.

Given these results, he concludes, the project — which goes back to Einstein, of course — of understanding the quantum state in epistemic terms must be abandoned. Myrvold's argument hinges on the requirement that the ontological lessons we draw from a theory should rely only on premises that could reasonably be expected to be preserved when we shift to the successor theory, in this case quantum field theory. This raises the further question: How does realism fare when we move to consider quantum physics beyond the realm of non-relativistic quantum mechanics?

PART V examines various responses to this question, specifically in the context of quantum field theory.

Doreen Fraser focusses on the example of the Higgs boson as exemplifying the use of certain formal analogies holding between mathematical structures in the absence of any physical similarity between the relevant models. This, she suggests, represents a major challenge to the support that is typically adduced in favour of scientific realism. The construction of the Higgs model proceeded by drawing formal analogies with the relevant order parameters in certain models of superconductivity: with regard to the latter, it is the effective collective wave function of the superconducting electrons, which distinguishes the normal state of the metal from the superconducting state, and in the case of the Higgs model, this is the complex scalar quantum field associated with the Higgs boson.

Fraser argues that the physical dissimilarities of the various elements means that these analogies must be regarded as purely formal. Thus, for example, the internal relationships these elements enter into in each model are quite different: the transition to a superconducting state, involving spontaneous symmetry breaking, is a temporal process, but there is no analogue of this in the Higgs model.

What then is the explanation for the successful application of such analogies? Fraser argues that they opened up the space of mathematically conceivable models by showing that it was possible to incorporate spontaneous symmetry breaking into one's model accompanied by massive bosons. Furthermore, because of the physical disanalogies, crucial features of the superconductivity model were open to experimental investigation, allowing the formal analogies to play a heuristically useful role.

This then presents a fundamental challenge to realism, as the purely formal reasoning used to construct the Higgs model was instrumentally successful, yet, Fraser insists, the truth or falsity of the theoretical statements asserting the appropriate causal connections cannot be relevant to explaining its success because there is no plausible physical analogy underpinning them. Thus we seem to have an example of scientific success that cannot be accommodated in realist terms.

Fraser concludes by noting that realists and anti-realists alike tend to draw on diachronic sequences of theories in defence of their opposing claims. However, she argues, what the Higgs case study demonstrates is that when it comes to the development of specific quantum theories (and here we might recall Wallace's point above), it is also *synchronic* relationships that need to be considered, involving new sets of challenges.

James Fraser is more sanguine, insisting that despite the challenges, we can give a realist reading of quantum field theory. However, he argues, restricting our attention to perturbative or axiomatic treatments is unhelpful in that regard. It is the former approach that lies behind the striking empirical predictions of the theory, including many of those tested at the Large Hadron Collider, for example. Yet the underlying strategy is famously problematic and has been widely regarded as lacking in mathematical rigour, depending as it does on the removal of certain infinities in a suspiciously ad hoc manner. Indeed, it leaves the realist unable to specify what the theory says about the world. In desperation, perhaps, one might turn to the so-called axiomatic approach that at least gives a clear set of theoretical principles for the realist to work with. Unfortunately, as is well-known, these principles can only be used as the framework for certain physically unrealistic 'toy' models.

All is not lost, however. As Fraser notes, developments in renormalisation theory offer a way forward and here he sketches the core features of the momentum space approach — in particular the way in which certain coarse-grained transformations induce a 'flow' on the space of possible theories which offers information on the behaviour of systems at different scales. These systems, modelled by QFT, display a feature known as 'universality', whereby models that display very different behaviour at high energies manifest very similar physics at lower energy levels. What this means is that if the high energy degrees of freedom are removed, as in a 'cut-off', this will leave the lower energy behaviour more or less unaffected. This in turn allows the realist to 'bracket off' what the world is like at the fundamental level, while still accurately modelling its lower energy properties.

This then helps to justify the various steps of the perturbative renormalisation procedure. Thus, for example, it justifies the absorption of the physics beyond a certain ‘cut-off’ point into an effective action and reveals that what this procedure is really about is ensuring the right kind of scaling behaviour exhibited by the system in question. Finally it pragmatically justifies taking the cut-off to infinity, which yields significant computational benefits.

Given this procedure, Fraser argues that the renormalisation group offers a way of developing a selective realist reading of QFT, according to which we should be realist about those constituents that underwrite a theory’s predictive success. In particular, it reveals that certain features play no role in that success and can be set aside as far as the realist is concerned. However, it also helps the realist articulate the relevant positive theoretical commitments, with regard to relatively large-scale, non-fundamental aspects of the world. It shows, for example, that they are largely insensitive to the details that obtain at high energies and hence can be considered ‘robust’ and thereby worthy of realist commitment.

Nevertheless there remain challenges. Thus, for example, even granted the robustness of low-energy features of the relevant models, it remains unclear what aspects of the world they are latching onto. Here, Fraser argues, the realist needs to pay further attention to such claims about the non-fundamental and consider more carefully the terms in which they are characterised. This is in addition to the more well known concerns regarding what the world is like according to quantum theory, as canvassed in this volume, as well as the additional puzzle posed in the context of QFT by the existence of unitarily inequivalent Hilbert space representations. As Fraser concludes, such puzzles and concerns highlight the need for a comprehensive re-examination of realist strategies in general.

Laura Ruetsche agrees that the development of the Standard Model and the quantum field theory that underpins it present a range of new challenges to realism. She focuses on one of the strategies indicated by James Fraser, namely adopting a selective attitude as embodied in what she calls ‘effective realism’. As she notes, this takes seriously the point that our best current theories are merely ‘effective’ in the sense that they’re not true across all energy regimes and uses the renormalisation group as a means of motivating the core ‘divide et impere’ move of such an attitude. Unfortunately, she points out, the action of the renormalisation group is defined on a specific space of theories and whatever the virtues are of our best current models, if the true, final theory lies outwith that space, then, as she puts it, all bets are off.

Even more worryingly, Ruetsche notes that it is not clear how realist ‘effective realism’ is! Through an examination of various features of effective theories, she concludes that in order to distance herself from the empiricist, the effective realist must approach such features in the light of certain interpretive projects. So, for example, the effective realist might endorse particles corresponding to fields that are robustly present in the relevant Lagrangian at a certain length scale, but to do so she must engage in interpretive manoeuvres that are typically articulated in terms of a theory's truth conditions and which she supposedly repudiates.

However, Ruetsche suggests, the effective realist needn't disavow such interpretive work per se, as long as she is mindful of the distinction between asking what the world is like according to a given theory, and asking why that theory is so successful. According to the view Ruetsche labels 'fundamentalism', the answer to the second question is given in terms of the answer to the first: the theory is so successful because it accurately describes how the world is. When it comes to effective theories, however, she argues that this intertwining of the answers is a mistake because what explains the success of an effective theory is something exogenous to it. Recognising that and rejecting fundamentalism then brings effective realism closer to what she calls a 'humble' form of empiricism that explains a theory's success in terms of its approximation to the predictions of some final theory within experimentally accessible regimes. The humble empiricist accepts that we can give an explanation of a given theory's success, just not in terms of its truth and that we can entertain the possibility of some true, final theory but that we should adopt an agnostic stance towards a given effective theory's set of unobservables.

To conclude, Ruetsche suggests that whether the commitments of effective realism actually count as realist or not depends on how they're understood. It is better, she maintains, to embrace a stance of humble empiricism that has the resources to accommodate the myriad ontological subtleties of quantum physics.

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This collection of papers is thus 'book-ended' by attempts to shift realism away from the traditional conception in the face of the multiple problems posed by quantum physics. The nature and extent of that shift varies from author to author — in some cases it involves a move away from the foundational, in others dropping the emphasis on the truth-content of theories, and in yet others it requires some form of non-literal 'reading' of quantum theory. There are a variety of options 'on the table' and what realists in general need to do now is not just take quantum physics seriously but to continue articulating, defending and contrasting these epistemic alternatives along the lines presented in this volume, which we hope will come to be seen as a significant step in the right direction.

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