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REVIEW

ALYSSA NEY AND DAVID Z ALBERT
The Wave Function: Essays on the Metaphysics of Quantum Mechanics
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How many spatial dimensions does a quantum world have? In a little known and only posthumously published manuscript from 1926, Hans Reichenbach ([1991]) grappled with this question and came to a startling conclusion: space in a quantum world has a number of spatial dimensions that is, well, humongous.

To appreciate his reasoning, let's first ask why we think a classical world has three spatial dimensions. Consider a classical system of particles. Reichenbach notes that we can represent the positional aspects of the system as *n* particles evolving in 3-dimensional space, or as one representative 'particle' evolving in 3*n*-dimensional configuration space. Normally we treat the former as physical and the latter as abstract. Yet no information whatsoever is lost in moving between the two representations. So why do we distinguish the 3-dimensional as physical?

Reichenbach claims that we prefer 3-space to 3*n*-space because the former, but not the latter, preserves local causality. We want our theories to be locally causal, he says, and this preference distinguishes 3-space. How so? His argument is confusing because there aren't two entities in the 3*n* description to be in causal contact, local or not. But his thought is that if we add a wavepacket spreading out in the 3-dimensional case, it will create disturbances locally, whereas this same wavepacket represented in 3*n*-dimensions will create disturbances that are non-local. He adds that since there are no continuous one-to-one transformations between dimensions, it will be the same for any other choice of dimension too. Given a commitment to locality, Reichenbach concludes that 3-space is the most natural arena for physics.

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Whatever the merits of this argument, the funny thing about it now is that contemporary physics appears to turn this reasoning entirely on its head. As J. S. Bell famously proved, and experiments later confirmed, quantum phenomena display decidedly non-local correlations in 3-space. Meanwhile, up in Hilbert space or configuration space—two choices for the supposedly abstract space of quantum mechanics—the quantum state chugs merrily along locally since it is governed by the Schrödinger equation, a local differential equation. Hence, we have a reversal of the classical situation: the quantum world seems to be non-local in low dimensions but local in high dimensions. Following Reichenbach's reasoning, a quantum world therefore has $3n$-dimensions, vastly more than anything ever imagined even in superstring theory, as $n > 10^{82}$. Surprisingly, Reichenbach drew precisely this inference in 1926 by replacing the above 'disturbance' with a Schrödinger wavepacket; however, he decided against publishing it, perhaps because the interpretation of Schrödinger's waves was shifting at the time. Only the perplexing classical argument made it into his ([1957]) text. In his struggles, we see quite clearly how the fortunes of 3-space might be hostage to the metaphysics of quantum mechanics.

This observation brings me to this excellent book, *The Wave Function*, edited by Ney and Albert. This book dares go where Reichenbach didn't (in print, while alive), plunging into the metaphysics of the quantum state with the dimensionality of space hanging in the balance. The book's focal point is a modern and direct version of Reichenbach's argument due to Albert ([1996]): if we're realists about quantum mechanics, then we ought to be realists about the quantum state and treat it as a concrete physical entity. Since this entity 'lives' in a high-dimensional space, Albert concludes that a realist interpretation of quantum mechanics commits us to the claim that space has many more dimensions than three. The appearance of a low-dimensional world consequently emerges from this high-dimensional reality. With this argument as background, the book examines the pros and cons of such a position, as well as many different ontological stances one can take towards the quantum state.

The volume consists of ten articles by ten authors, plus an extensive introduction by Ney. Depending on how one classifies positions, four articles defend the idea that quantum mechanics is telling us that space is high-dimensional, and the rest either outline difficulties afflicting this position or suggest new metaphysics for the wavefunction that allow us to live safely in a low-dimensional space.

Let me briefly describe each chapter's contribution. Albert (Chapter 1) reprises and updates his ([1996]) argument. Allori (Chapter 2) and Goldstein and Zanghì (Chapter 4) posit primitive ontology that live in low dimensions and hold that the wavefunction's status is nomological, not ontological, and as such it doesn't dictate where the ontology lives any more than the Hamiltonian does.[1] French (Chapter 3) argues for a structuralist understanding of the wavefunction, one where the wavefunction is neither object nor artefact. Lewis (Chapter 5) holds that the sense in which the world is 3-dimensional is prior to that in which it is $3n$-dimensional because the former better fits what we mean by 'spatial' than the latter. Asking why we posit wavefunctions in the first place, Maudlin (Chapter 6) warns against taking the mathematics of quantum mechanics at face value, ontologically. Monton (Chapter 7) rehearses and amplifies some of his previous challenges to anyone wanting people, particles, and galaxies to 'emerge' from a $3n$-dimensional object. Responding to Monton and others, Ney (Chapter 8) sheds light on the issue by looking at it through the lens of reduction. North (Chapter 9) likewise responds to Monton, but here the argument is the quantum counterpart to her earlier case for realism about the structure of possibilities given by Hamiltonian mechanics. Finally, Wallace (Chapter 10) sketches how an Everettian might think about this question, urging a view—motivated by quantum field theory—wherein quantum states represent the states of space-time points.

Several features of this collection deserve special mention. First, there has been a strong effort made to reach out to an audience outside physics and the philosophical foundations of physics. Albert, Maudlin, Lewis, and others are well known for making philosophical progress on technical areas without overwhelming the reader with technicalia. What stands out is that everyone has done so in this volume.

Second, the long introduction by Ney is exemplary in this regard. She doesn't merely introduce the papers in the volume, she presents all the background material needed for the non-expert to come along and appreciate the subsequent chapters. The introduction is a real gem.

Third, given the first two points, I wish to encourage a philosophical readership that extends past the philosophical foundations of physics. If you are a metaphysician interested in space or quantum objects, or a philosopher of science interested in an exciting application of realism, I can without hesitation enthusiastically recommend this book. You won't have a problem reading it.

Fourth, as one can glimpse even in my brief summaries, the book is unusually focused on one particular philosophical problem in quantum mechanics: the whereabouts of the wavefunction. The virtue of this is that all the chapters are directed at the same problem. But that does lead to a warning: The physics literature is currently occupied with whether the wavefunction is a state of knowledge (psi-epistemicism) or part of reality (psi-ontology), and in

[1] This is also a position that I defend in (Callender [unpublished]).

particular, with discussion of the meaning of a recent theorem by Pusey *et al.* ([2012]). None of this literature makes the references here. This volume is very much a philosopher's take on the metaphysics of the wavefunction, so one looking for thoughts about what's going on in the corresponding physics debates needs to look elsewhere.

In sum, the editors did an admirable job of finding authors who would be seen as speaking to each other without also duplicating one another. Naturally, some chapters are better and more novel than others, but all are good or even excellent; no duds here. As a result, the book is an excellent and enjoyable piece of philosophy, as one gets to see a single problem attacked from many distinct and compelling perspectives. If interested in the metaphysics of the quantum wavefunction, then this collection is a great choice.

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