Mereological Atomism's Quantum Problems

0. Abstract
The popular metaphysical view that concrete objects are grounded in their ultimate parts is often motivated by appeals to realist interpretations of contemporary physics. This paper argues that an examination of mainstream interpretations of quantum mechanics undercuts such atomist claims. First, mereological atomism is only plausible in conjunction with Bohmian mechanics. Second, on either an endurantist or perdurantist theory of time, atomism exacerbates Bohmianism's existing tensions with serious Lorentz invariance in a way that undermines the realist appeal of both views. Bohmians should therefore resist atomism, leaving atomists somewhat physically homeless.

1. Introduction to Atomism
Feynman (2015) has suggested that atomism is the most important and fundamental deliverance of physical science. While Feynman is not explicit about what he means, one natural way of cashing out the thesis is as mereological atomism: everything is ultimately composed of atoms—simple parts which lack proper parts of their own (Simons 1987; Varzi 2017). This view was also held by metaphysicians like David Lewis (1991). In Lewis's view, simple parts are supposed to be fundamental, and composed objects are merely derivative fusions which add nothing substantive to our ontology, whose existence is secured by the universal fusion axiom of classical mereology. Because wholes are nothing more than fusions of their parts on this view, and fusions are rigid, mereology must also be extensional: fusions are identical if and only if they have all the same parts.

Even metaphysicians whose overall projects are quite at odds with Lewis often endorse similar views, motivated by scientific reports like Feynman's. For example, Fine (1992) suggests that:

> With the advance of science, we know that there is no special force or principle which binds together the different parts of the body and yet is not operative in the universe as a whole; and in the absence of any such force or principle, it is rather hard to see what ontological basis there could be for distinguishing between the constituency of substances and of mere heaps.[1]

To say that some macro-object is a "mere heap" is to say that it is nothing more than its fundamental ultimate parts taken collectively, including their relations—a fusion in an extensional mereology. Post (1975) takes this as the central meaning of atomism in the metaphysics of science. As Kim (2002) argues, the real historical contrast with this position that makes ultimate parts fundamental and freely builds fusions using the tools of classical mereology is emergentist views like van Inwagen (1995), where composition must be restricted precisely because wholes are not mere heaps.

Feynman, Lewis, Fine, Post, and Kim were all led to atomism as the metaphysical view they found most compatible with modern science. More recently, however, Schaffer (2010; Ismael and Schaffer 2020)

[1] This is only Fine's view of synchronic cases; Fine (1994) rejects it in diachronic cases.

has argued that quantum physics supports atomism's direct opposite, priority monism, where the ultimate whole is fundamental and the parts mere derivative dependencies. Metaphysical atomists should thus take a keen interest in which realist interpretations of quantum mechanics, if any, support their view. Conversely, philosophers of quantum mechanics should take some interest in mereology, since it is the most direct route for relating the direct ontology of the theories they study to the manifest image of reality necessary for describing the experiments which suggest and confirm those theories (Maudlin 2011).

2. The Atomist's Need for Bohmian Mechanics

What currently viable interpretation of quantum mechanics, then, might make atomism plausible? Since we are inquiring after a mind-independent metaphysics (the fundamentality and parthood relations of the world), only realist interpretations of quantum mechanics are relevant. Maudlin (1995) lays out the measurement problem as a trilemma, in which denying each of three (collectively unstable) premises yields a realist interpretation of quantum mechanics:

1. Deny that measurements of systems described by identical initial wave-functions have determinate stochastic outcomes (Everettian Many-Worlds Theory)
2. Deny that the wave-function of a system always evolves according to the deterministic Schrodinger equation (Ghirardi-Rimini-Weber [GRW] Objective Collapse Theory)
3. Deny that the wave-function of a system specifies all of its physical properties (De Broglie-Bohm Pilot Wave Theory)

In a narrow, logical sense these claims are each about dynamics, not ontology. The Schrodinger equation alone, the stochastic GRW equation, and the Schrodinger equation supplemented with the De Broglie-Bohm guidance equation have all been proposed with various ontologies. Nonetheless, there is a close relationship between dynamics and ontology here: not all ontologies are equally suitable for all dynamic theories, especially when those theories are considered as ongoing research programs and not merely non-relativistic toy models. This motivational compatibility with ongoing research is important, both because relativistic quantum mechanics with interactions is the current stable working theory most suitable for ontologizing (Wallace 2020) and because atomism is supposed to be broadly motivated by science, not merely compatible with some vaguely nomologically possible toy model. Here atomism's prospects are rather narrower.

2.1 Everettianism's Challenge to Fundamental Ultimate Parts

The many worlds interpretation is compatible with a couple of different ontologies, but none bode well for atomism. Ney (2021)'s wave-function realism is explicitly priority monist, with the wave-function—which is separable in configuration space—prior to its concrete parts—which are inseparable in four-dimensional spacetime. Wallace and Timpson's (2010)'s spacetime state realism, meanwhile, is a completely inseparable four-dimensional ontology which explicitly disclaims the possibility of any mereological relations between the overall state and micro-physical particles or macro-scale entities. In neither view are we led to suspect the existence of any atomic parts, and in any case those parts will be derivative from the whole rather than fundamental. There may be some mereological relationship between particles and macro-objects, but this cannot be the strict relationship of classical mereology since particles only exist in the first place "to a degree" (Ney 2021) or as "patterns" (Wallace and

Timpson 2010). Ismael and Schaffer (2020) are right to list these ontologies as supportive of priority monism. As Crull (2013) argues persuasively, unaugmented quantum mechanics—the essence of the Everettian approach—suggests extremely strong holism.

Moreover, Everettianism is the natural home for Schaffer's master argument for priority monism. The many worlds research program is deeply committed to Schaffer's recombinability principle that entanglement among actual concrete objects would imply local causal connections. Wallace and Timpson (2010)'s ontology is inseparable precisely because locality is preserved, and Ney (2021) identifies the wave-function as fundamental precisely because it is separable and local in a way her three-dimensional ontology is not. If atomists *could* somehow identify a plurality of fundamental actual concrete objects (atoms) in an ontology compatible with Everettianism, those atoms would be fully entangled in the absence of any mechanism for wave-function collapse. And if atomists *could* somehow arrange the axioms of classical mereology to hold in such an ontology, those atoms would be parts of the cosmos by universal fusion. But then Schaffer (2010)'s quantum master argument for priority monism and its revised version in Ismael and Schaffer (2020) both go through, because the other premises are all accepted by atomists like Lewis and Kim.[2] The many worlds approach thus undercuts atomism rather than lending it scientific support.

2.2 GRW's Challenge to Macro-Objects as Fusions

What prospects does atomism have in the objective collapse research program? Again, we must specify which ontology we have in mind for the dynamics. GRW_0 is the original wave-function monist ontology, but it both leads to various paradoxes (Tumulka 2018) and fails to provide any concrete atoms to fuse into concrete macro-objects (Allori et al. 2008). These problems with GRW_0 led to the matter-density ontology GRW_M (Ghirardi, Grassi, and Benatti 1995), but it proposes a smooth matter-density function, not a plurality of atoms which can enter into various fusions. Furthermore, it is susceptible to certain "tails" paradoxes (McQueen 2015) and it is not Lorentz-invariant (Esfeld and Gisin 2014). The currently relevant version of objective collapse mechanics is thus GRW_F, a relativistic multi-time version of the GRW dynamics which posits only flashes (i.e., instantaneous point-like events) in spacetime (Tumulka 2006). Here again there is an obvious problem for atomists: fusions of events are just events; only persisting objects can be fused into persisting objects. Even if this category mistake could be resolved, flashes in GRW_F are extremely sparse (Feldmann and Tumulka 2012), and each occurs in the proper time of its flash family rather than being compresent (Petrat and Tumulka 2014), so macro-objects formed by fusing them would fail to extend in space or persist in time. The objective collapse approach also seems to undercut atomism rather than lending it scientific support.

2.3 Bohmian Atomism

In contrast to Everettian and GRW theories, Bohmian mechanics seems to offer a plausible home for atomism. While some adherents to pilot-wave theory have denied the existence of a plurality of atoms (e.g. Albert 1996), the main-stream of Bohmian researchers hold to an ontology of distributed persisting concrete point particles. This plurality of fundamental objects in spacetime can serve as the atomic building blocks for the atomist's derivative fusions.

[2] These premises are completeness—duplicating the fundamental actual concrete object(s) and their fundamental relations must duplicate the cosmos—and priority—fundamental objects stand in a priority relation to their immediate mereological relation(s).

Additionally, the pilot-wave research program provides the resources to resist Schaffer's quantum master-argument for priority monism. Bohmians can hold either entitative or law-like best-system (Humean) views of the wave-function. Those without Humean sensibilities who take a more entitative view have little reason to accept Schaffer's recombinability principle that entanglement among distinct fundamental objects must involve local causation, and are free to replace it with a metaphysics of extrinsic relations (e.g. Esfeld 2004) and/or non-local causality (Egg and Esfeld 2014). On the other hand, those Bohmians with Humean sympathies strong enough to feel the force of recombinability will naturally gravitate towards the non-entitative Humean view of laws as well, on which entanglement is merely part of the best systematization of the entire spacetime mosaic of Bohmian particle positions (e.g. Miller 2014; Esfeld 2014). On this view entanglement lacks *any* modal force, because when the fundamental actual concrete objects (the particles) are rearranged freely in another possible world, a different nomic systematization results, so recombinability is simply false. The less Humean Bohmians will thus be relational holists, and the more Humean Bohmians will be nomic holists, but neither can be pressured into priority monism because on both views the particles are prior to the laws.[3]

3. Bohmian Atomism's Relativistic Problems

While at first blush this may seem like a vindication for atomists, atomism compounds the problems Bohmians already have with "fundamental" Lorentz invariance (Bell 1987; Hardy and Squires 1992; Bohm and Hiley 1995; Maudlin 1996). While this may count as a cost to be paid when weighing pilot wave theory against other realist alternatives, advocates do not see it as a serious drawback. The reason is that the preferred foliation of spacetime required by Bohmian mechanics[4] can both be defined from the wave-function (shared by all quantum theories) and is completely undetectable by experiment,[5] precluding any empirical conflict with special relativity (Tumulka 2021). Trouble arises, however, when the Bohmian particles are taken as mereological atoms and macro-objects as fusions of those particles. Those macro-objects must persist through time by either enduring or perduring, and on either option Bohmian atomism risks losing its previously impeccable realist credentials.

3.1 Endurantist Bohmian Atomism in Special Relativity

While perdurantism has probably been the more popular option for philosophers of relativistic quantum mechanics, endurantism has been influentially defended by Rea (1998) and Esfeld (2015). The endurantist theory is that objects persist through time by being wholly present at each time when the object exists. Since the true arrow of time is hidden according to Bohmians, it is impossible to know the angle at which the hypersurface of simultaneity cuts the worldline of a particle. For an individual particle this poses no difficulty, but for Bohmian atomists, this means that the fundamental particles which compose a macro-object must be compresent—they must all exist in the three-dimensional slice created by the present hypersurface's crossing of the object's world-line. The simultaneity hypersurface is undetectable in principle, so the plurality of atomic particle-instants which compose a three-dimensional macro-object is also undetectable. Because an observer of the macro-object has a perceived time orientation at an unknown offset from the hidden true arrow of time, the observer's perceived

[3] While Esfeld (2020) calls these alternate descriptions, Ismael and Schaffer (2020) rightly see them as serious competitors.
[4] Or perhaps just a local synchronization (Berndl et al. 1996) or time-like vector field (Dürr et al. 2014)—but these are both just as hidden as the foliation would be.
[5] This undetectability shouldn't bother us (Maudlin 1996).

simultaneity slice is different from the true one, and the observer cannot ostensively refer to the true fusion of compresent particle-instants which is the wholly present object. In the atomist conception, this fusion *just is* the macro-object, so the Bohmian cannot observe enduring macro-objects and has no way to refer to them.

The issue becomes especially clear when particle number varies due to interactions. Take a macro-object in which two spacelike-separated ^{14}C atoms simultaneously undergo beta decay in the true rest frame. Before the beta decay, the macro-object comprises two more up quarks than it does after the beta decay. In the simultaneity slice of the object's worldline from the observer's rest frame, however, the beta decay (detected by its electron emission) on the left side of the object happens before the beta decay on the right side, while in the object's own rest frame the order is reversed. Both empirically detectable inertial frames have simultaneity slices of the object in which it has one more up quark than it did before the (actually simultaneous) beta decay, and one fewer up quark than it did after the (actually simultaneous) beta decay. Due to compositional extensionality, the fusion with the intermediate number of up quarks cannot be identical with either of the other two fusions. The observer's report therefore fails to refer to any enduring macro-object whatsoever.

A classical rather than quantum atomist need not face this difficulty, because the true simultaneity slice for a macro-object can just be stipulated as simultaneity in the rest frame of the object.[6] Observers can in principle calculate the simultaneity slices of the object in its rest frame from their relative motion, so they can refer to the true fusions of compresent particle-instants. The observer will never directly observe that compresent fusion due to relativity of simultaneity, but that certainly need not hinder ostensive reference, any more than an observer would be unable to refer to an object which she only saw from one side (one part) at a time.[7] The observer sees one atomic part of the object (or multiple parts so close together that relativity can be neglected), and can refer to the fusion of all the particles compresent with the observed part. An observer may also see parts of the object existing at different times, but that is no more mysterious than seeing a long-dead star. Similarly, a Bohmian absent atomism faces no difficulty because fundamental particles are point-like, so a hypersurface crossing the worldline of a particle at any angle results in the same three-dimensional slice and hence the same enduring object. The conflict with special relativity only arises for the atomist who resorts to Bohmian particles for a quantum ontology, and/or the Bohmian who resorts to mereological fusions of particles for a macro-ontology.

3.2 Perdurantist Bohmian Atomism in Special Relativity

While endurantism has its defenders, perdurantism has been the more popular view of persistence in the context of special relativity (e.g. Balashov 2009). The perdurantist theory is that objects persist through time by having a proper part present at each time when the object exists. Persisting objects are thus really four-dimensional fusions of three-dimensional temporal parts. In the words of Hales and Johnson (2003), "Perdurantism has a natural and beautiful fit with the facts of special relativity: [two

[6] Objects can be plausibly assumed to have (approximately) a single inertial frame, both because co-movement of parts is a criterion for objecthood and because exceptions involve high accelerations, and thus fall outside the question of Lorentz invariance of inertial frames.

[7] Nonetheless this may still seem paradoxical, as the "objects of observation" will never directly align with the objects of reality, but this problem affects all endurantists in special relativity (Hales and Johnson 2003) and is merely a kind of optical illusion rather than implying a failure of reference.

observers at high relative velocities] can both speak of [a macro-object]; both agree on what it is and what its history was; they disagree only on questions of simultaneity." This is because all observers see different three-dimensional projections of the same four-dimensional object.

How should atomists view the relationship between these four-dimensional objects and their atomic parts? One option is to assume that each atomic part persists by having a point-like temporal part at each time, and that these persisting particles are what fuse into the four-dimensional object, without the whole needing to have three-dimensional temporal parts. This view seems problematic for several reasons, however. First, according to Sider (2001), a proper formulation of perdurantism requires that *all* parthood be time-relative, parthood-*at*. If the macro-objects immediate proper parts are supposed to be the perduring atomic particles, then according to Sider it doesn't have parts at all—and so according to the atomist doesn't exist. Second, the view implies that even if macro-objects exist they certainly don't persist, in which case we can't discuss their histories, let alone agree about them. How are we to write descriptions of quantum experiments without mentioning, e.g. "the state of the detector before…"? Third, macro-objects can change their parts, whereas fusions have theirs necessarily (van Inwagen 2006), so parts of macro-objects must be time-indexed (Sider 2001). Perdurantism clearly requires the traditional formulation, in which the immediate proper parts of a perduring four-dimensional object are its three-dimensional temporal parts. The atomist must then take each of those three-dimensional temporal parts to be a fusion of the instantaneous temporal parts of its particles.

Which, then, is the Bohmian supposed to take as the time-slices of the four-dimensional object, given relativity of simultaneity? The natural answer is to take three-dimensional slices orthogonal to the true arrow of time, but of course this is ineluctably hidden. The simultaneity slices drawn by observers will not be the correct ones, even if those observers are in the same inertial frame as the macro-object, because the observers do not know the angle at which the true hyperplane of simultaneity cuts the worldline of the object. The perdurantist Bohmian atomist is then left in the same unfortunate situation as the endurantist. No ostensive reference is possible to the temporal parts of the perduring macro-object, because they are merely fusions, and the observer can have no knowledge of which instantaneous temporal parts of the composing particles are compresent. For the reader who agrees with Sider (2001) that parthood is always time-relative, this objection already seems fatal: observers cannot refer to temporal parts, so they cannot refer to any parts at all, leaving them unable to refer to macro-objects which are mere fusions of such parts. Even if macro-objects can be sensibly discussed, though, their histories cannot be, since those are changes with respect to successive temporal parts.

What of the possibility of treating temporal parts as observer-relative? Take as many arrows of time as there are observers moving at high relative velocities, and use each of these foliations to slice the macro-object into temporal parts. Each of these time-relative pluralities of temporal parts fuse into a four-dimensional macro-object with the same overall characteristics, and each observer can transform observations into the rest-frame of the object when a consistent history is needed. Observers then only disagree on the simultaneity slices, just the "natural and beautiful" picture put forward by Hales and Johnson (2003). No one need worry about which inertial frame is the true hidden one in order to recover the correct empirical results, because those results do not rely on which three-dimensional perspective one has. This presumes, however, that different observers have some way of agreeing on which time-slice-fusions of particle-instants count as parts of the four-dimensional macro-object. Take the earlier example of beta decay in a ^{14}C atom, in this case part of a C_{60} buckyball or perhaps a sample of pure diamond. The quark and electron-instants which are prior to the decay in the true rest frame are fused into temporal parts of the carbon object. Those after the decay are not part of the object, because $C_{59}N_1$ is not a buckyball. Because simultaneity is observer-relative, which particle-instants count as part of the buckyball is observer-relative, so different observers do not actually see the same four-dimensional shape. The temporal parts they see overlap each other, but they are not identical nor are they parts of the same four-dimensional objects. They see the same four-dimensional world, but they are unable to carve it into macro-objects in the same way. Inertially moving observers holding to Bohmian atomist perdurantism thus find themselves unable to refer to the same objects.

As in the endurantist case, these issues need not afflict the Bohmian sans atomism or the atomist sans Bohmianism. Sans Bohmianism, the atomist can again use the rest frame of the macro-object to generate simultaneity slices and hence its temporal parts. This option is unavailable to the Bohmian because the temporal parts generated by the privileged arrow of time must count as genuine temporal parts. The Bohmian sans mereological atomism need only speak directly of point particles, which have the same temporal parts in every foliation, and can hold some criterion other than compositional extensionality for the identity of macro-objects. It is the Bohmian atomist who has compounded the problems of special relativity.

3.4 Relativity’s Implications for Bohmian Atomism

The Bohmian mereological atomist thus can only consistently refer to persisting particles, not to persisting macro-objects, which is objectionable on several levels. First, part of the appeal of Bohmian mechanics was supposed to be its ease in describing approximately classical macro-objects (Bohm and Hiley 1995; Allori et al. 2014). Second, the need to connect the objects of physical theorizing to macro-objects is not only important for recovering the folk picture of the world (which may be irrecoverable), but for recovering the manifest image used in scientific theorizing (Maudlin 2011). Physicists must be able to refer to things like detector states in order to make progress in physics. Third, our evidence for the very existence of fundamental particles is based on reference to macro-objects like oil droplets and cloud chambers. A metaphysics of physics which cannot undergird such successful reference thus fails at being empirically coherent. Often, philosophers of physics flirt with the limits of coherence in order to stay close to the work of practicing physics, but interest in Bohmianism is driven not by the practice of physics but rather by the demand for empirical coherence and hence for primitive ontology in spacetime. I therefore suggest that Bohmians should reject being yoked to mereological atomism, and should instead find some other strategy for connecting Bohmian particles to macro-objects.

4. Conclusion

Atomists in the second half of the twentieth century—whether physicists like Feynman, metaphysicians like David Lewis and Kim, or philosophers of physics like Post—have tended to present their position as a deliverance of modern science. Nonetheless, relativistic quantum mechanics (one of the most successful scientific theories ever) brings this claim sharply into question. Of the three mainstream realist interpretations of quantum theory, neither Everett’s many worlds nor GRW’s objective collapse seem to provide fundamental particles which can be mereologically fused into macro-objects. While Bohm’s pilot-waves do provide such atomic particles, the fusions they compose are not macro-objects to which relativistic observers in inertial reference frames can reliably refer. Bohmian atomism thus fails to provide the connection between the scientific and manifest images which both motivated pilot-wave research in the foundations of physics and atomist claims in metaphysics. Bohmianism might be adequately Lorentz-invariant and have a clear primitive ontology, but it must look further for a metaphysical account of how that primitive ontology constitutes macro-objects. Atomists, meanwhile, must have strong metaphysical motivations to overcome the lack of support for their view among mainstream realist interpretations of quantum mechanics. Certainly metaphysicians ought not take atomism as a deliverance of modern science.

5. References

Albert, David Z. 1996. "Elementary Quantum Metaphysics." In *Bohmian Mechanics and Quantum Theory: An Appraisal*, edited by James T. Cushing, Arthur Fine, and Sheldon Goldstein. Vol. 184. Boston Studies in the Philosophy of Science. Dordrecht: Springer Netherlands. http://link.springer.com/10.1007/978-94-015-8715-0.

Allori, Valia, Sheldon Goldstein, Roderich Tumulka, and Nino Zanghì. 2008. "On the Common Structure of Bohmian Mechanics and the Ghirardi-Rimini-Weber Theory." *The British Journal for the Philosophy of Science* 59 (3): 353–89. https://doi.org/10.1093/bjps/axn012.

———. 2014. "Predictions and Primitive Ontology in Quantum Foundations: A Study of Examples." *The British Journal for the Philosophy of Science* 65 (2): 323–52. https://doi.org/10.1093/bjps/axs048.

Balashov, Yuri. 2009. "Pegs, Boards, and Relativistic Perdurance." *Pacific Philosophical Quarterly* 90 (2): 167–75. https://doi.org/10.1111/j.1468-0114.2009.01334.x.

Bell, John S. 1987. *Speakable and Unspeakable in Quantum Mechanics*. Cambridge University Press.

Berndl, K., D. Duerr, S. Goldstein, and N. Zanghì. 1996. "Nonlocality, Lorentz Invariance, and Bohmian Quantum Theory." *Physical Review A* 53 (4): 2062–73. https://doi.org/10.1103/PhysRevA.53.2062.

Bohm, David, and Basil J. Hiley. 1995. *The Undivided Universe: An Ontological Interpretation of Quantum Theory*. 1 edition. London: Routledge.

Crull, Elise M. 2013. "Exploring Philosophical Implications of Quantum Decoherence." *Philosophy Compass* 8 (9): 875–85. https://doi.org/10.1111/phc3.12058.

Dürr, Detlef, Sheldon Goldstein, Travis Norsen, Ward Struyve, and Nino Zanghì. 2014. "Can Bohmian Mechanics Be Made Relativistic?" *Proc. R. Soc. A* 470 (2162): 20130699. https://doi.org/10.1098/rspa.2013.0699.

Egg, Matthias, and Michael Esfeld. 2014. "Non-Local Common Cause Explanations for EPR." *European Journal for Philosophy of Science* 4 (2): 181–96. https://doi.org/10.1007/s13194-013-0081-2.

Esfeld, Michael. 2004. "Quantum Entanglement and a Metaphysics of Relations." *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 35 (4): 601–17. https://doi.org/10.1016/j.shpsb.2004.04.008.

———. 2014. "Quantum Humeanism, or: Physicalism without Properties." *The Philosophical Quarterly* 64 (256): 453–70. https://doi.org/10.1093/pq/pqu030.

———. 2015. "Quantum Physics and Presentism." In *Re-Thinking Time at the Interface of Physics and Philosophy: The Forgotten Present*, edited by Albrecht von Müller and Thomas Filk, 231–48. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-10446-1_11.

———. 2020. "A Proposal for a Minimalist Ontology." *Synthese* 197 (5): 1889–1905. https://doi.org/10.1007/s11229-017-1426-8.

Esfeld, Michael, and Nicolas Gisin. 2014. "The GRW Flash Theory: A Relativistic Quantum Ontology of Matter in Space-Time?" *Philosophy of Science* 81 (2): 248–64. https://doi.org/10.1086/675730.

Feldmann, William, and Roderich Tumulka. 2012. "Parameter Diagrams of the GRW and CSL Theories of Wavefunction Collapse." *Journal of Physics A: Mathematical and Theoretical* 45 (6): 065304. https://doi.org/10.1088/1751-8113/45/6/065304.

Feynman, Richard P., Robert B. Leighton, and Matthew Sands. 2015. *The Feynman Lectures on Physics: Mainly Mechanics, Radiation, and Heat*. New Millennium Ed. Vol. 1. 3 vols. New York: Basic Books.

Fine, Kit. 1992. "Aristotle on Matter." *Mind* 101 (401): 35–57.

Ghirardi, G. C., R. Grassi, and F. Benatti. 1995. "Describing the Macroscopic World: Closing the Circle within the Dynamical Reduction Program." *Foundations of Physics* 25 (1): 5–38. https://doi.org/10.1007/BF02054655.

Hales, Steven D., and Timothy A. Johnson. 2003. "Endurantism, Perdurantism and Special Relativity." *The Philosophical Quarterly (1950-)* 53 (213): 524–39.

Hardy, Lucien, and Euan J. Squires. 1992. "On the Violation of Lorentz-Invariance in Deterministic Hidden-Variable Interpretations of Quantum Theory." *Physics Letters A* 168 (3): 169–73. https://doi.org/10.1016/0375-9601(92)90569-8.

Inwagen, Peter van. 1995. *Material Beings*. Ithaca, NY: Cornell University Press.

———. 2006. "Can Mereological Sums Change Their Parts?" *The Journal of Philosophy* 103 (12): 614–30.

Ismael, Jenann, and Jonathan Schaffer. 2020. "Quantum Holism: Nonseparability as Common Ground." *Synthese* 197 (10): 4131–60. https://doi.org/10.1007/s11229-016-1201-2.

Kim, Jaegwon. 2002. "The Layered Model: Metaphysical Considerations." *Philosophical Explorations* 5 (1): 2–20. https://doi.org/10.1080/10002002018538719.

Lewis, David K. 1991. *Parts of Classes*. Edited by John P. Burgess. B. Blackwell.

Maudlin, Tim. 1995. "Three Measurement Problems." *Topoi* 14 (1): 7–15. https://doi.org/10.1007/BF00763473.

———. 1996. "Space-Time in the Quantum World." In *Bohmian Mechanics and Quantum Theory: An Appraisal*, edited by James T. Cushing, Arthur Fine, and Sheldon Goldstein. Vol. 184. Boston Studies in the Philosophy of Science. Dordrecht: Springer Netherlands. http://link.springer.com/10.1007/978-94-015-8715-0.

———. 2011. *Quantum Non-Locality and Relativity: Metaphysical Intimations of Modern Physics*. 3rd ed. Malden, MA: Wiley-Blackwell.

McQueen, Kelvin J. 2015. "Four Tails Problems for Dynamical Collapse Theories." *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics* 49 (February): 10–18. https://doi.org/10.1016/j.shpsb.2014.12.001.

Miller, Elizabeth. 2014. "Quantum Entanglement, Bohmian Mechanics, and Humean Supervenience." *Australasian Journal of Philosophy* 92 (3): 567–83. https://doi.org/10.1080/00048402.2013.832786.

Ney, Alyssa. 2021. *The World in the Wave Function: A Metaphysics for Quantum Physics*. New York: Oxford University Press.

Petrat, Sören, and Roderich Tumulka. 2014. "Multi-Time Wave Functions for Quantum Field Theory." *Annals of Physics* 345 (June): 17–54. https://doi.org/10.1016/j.aop.2014.03.004.

Post, Heinz. 1975. "The Problem of Atomism." *The British Journal for the Philosophy of Science* 26 (1): 19–26.

Rea, Michael C. 1998. "Temporal Parts Unmotivated." *The Philosophical Review* 107 (2): 225–60. https://doi.org/10.2307/2998484.

Schaffer, Jonathan. 2010. "Monism: The Priority of the Whole." *The Philosophical Review* 119 (1): 31–76.

Sider, Theodore. 2001. *Four-Dimensionalism: An Ontology of Persistence and Time*. Oxford ; New York: Oxford University Press. https://www.oxfordscholarship.com/view/10.1093/019924443X.001.0001/acprof-9780199244430.

Simons, Peter. 1987. *Parts: A Study in Ontology*. Oxford, England: Oxford University Press.

Tumulka, Roderich. 2006. "A Relativistic Version of the Ghirardi–Rimini–Weber Model." *Journal of Statistical Physics* 125 (4): 821–40. https://doi.org/10.1007/s10955-006-9227-3.

———. 2018. "Paradoxes and Primitive Ontology in Collapse Theories of Quantum Mechanics." In *Collapse of the Wave Function: Models, Ontology, Origin, and Implications*, edited by Shan Gao. Cambridge: Cambridge University Press. http://dx.doi.org/10.1017/9781316995457.

———. 2021. "Bohmian Mechanics." In *The Routledge Companion to Philosophy of Physics*, edited by Eleanor Knox and Alastair Wilson. Routledge.

Varzi, Achille C. 2017. "On Being Ultimately Composed of Atoms." *Philosophical Studies* 174 (11): 2891–2900. https://doi.org/10.1007/s11098-016-0816-y.

Wallace, David. 2020. "Lessons from Realistic Physics for the Metaphysics of Quantum Theory." *Synthese* 197: 4303–18. https://doi.org/10.1007/s11229-018-1706-y.

Wallace, David, and Christopher G. Timpson. 2010. "Quantum Mechanics on Spacetime I: Spacetime State Realism." *The British Journal for the Philosophy of Science* 61 (4): 697–727. https://doi.org/10.1093/bjps/axq010.