Prime Matter and the Quantum Wavefunction

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Abstract

Prime matter plays an indispensable role in Aristotle's philosophy, enabling him to avoid the pitfalls of both naïve Platonism and nominalism. Prime matter is best thought of as a kind of infinitely divisible and atomless bare particularity, grounding the distinctness of distinct members of the same species. Such bare particularity is needed in symmetrical situations, like a world consisting of indistinguishable Max Black spheres. Bare particularity is especially important in modern physics, given the homogeneity and isotropy of space. With the importance of fields in classical, relativistic, and quantum physics, we have good reason to prefer something like Aristotle's continuous, infinitely divisible matter over indivisible particles. Mass and energy in relativistic physics also points in the direction of prime matter as the enduring substrate of these quantities. Recent work on Aristotelian interpretations of quantum mechanics, further underscores the contemporary relevance of prime matter.

Keywords: Prime matter, quantum mechanics, Platonism, nominalism, moderate realism, form, Aristotle, individuation, bare particular, cosmic monism, modal interpretation, Bohmian mechanics, Neo-Humeanism

Introduction

Aristotle introduced the concept of matter (*hulē*) into the philosophy of nature. The concept of Aristotelian matter is fundamentally a relational

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one: some M is the (bit of) matter[1] *of* some entity S. Aristotelianism is characterised by a hierarchy of levels, with *y* being the matter of *x*, *z* the matter of *y*, and so on. A substance (*ousia*), like an organism, has something as its proximate matter, like these flesh and bones.[2] Such proximate matter can have its own matter: this flesh has some earth, water, fire, and air as its matter. The majority of interpreters take Aristotle to posit the existence of an ultimate or *prime* matter, which is the matter of the elements and which does not itself have any form or matter. Prime matter results from the progressive stripping off of the various qualities and quantities of more proximate matter (*Metaphysics* Zeta 3 1029a10–34, and Theta 7 1049a24; *De Caelo* 36, 305a14–34). Prime matter has no intrinsic nature[3] of its own, beyond the bare potentiality to receive any nature or form (of a material substance) whatsoever.[4]

Needless to say, the idea of prime matter is a controversial one. The objections to it come in two waves. First, many have argued that the idea of a thing with no actual nature or character is paradoxical and even self-contradictory. Prime matter would seem to be a kind of bare particular, and the wider category of bare particular has come under similar fire – by Wilfred Sellars, for example. Second, prime matter would seem to be scientifically useless or redundant. It is always matter of some definite kind that does the real explanatory work. This was true even in Aristotle's own work.

I propose to defend prime matter on both counts. I will argue that prime matter is a coherent hypothesis and one that is necessary for carrying out Aristotle's alternative to Platonism and nominalism. And I will argue that prime matter does indispensable work even in contemporary physics – in particular, in quantum physics. In section 1, I will discuss Plato's crucial innovation, the introduction of universal entities, and explain Aristotle's (mostly friendly) critique of it. In section 2, I will sketch Aristotle's new theory of forms, a theory that requires prime matter as a principle of individuality. I argue in section 3 that any adequate physical theory of the universe relies (at least implicitly) on the positing of prime matter. In sections 4, 5, and 6, I relate prime matter to the interpretation of standard quantum mechanics and quantum field theory, and I conclude in section 7 with some thoughts about mereology and space.

1. Plato's Theory of the Forms

As Aristotle notes in the *Posterior Analytics* (73a21–30, 73b27–30), all scientific knowledge is of the universal. In modern science, this dimension of universality displays itself in the universal laws and equations of modern physics, as well as in the definitions of natural kinds in the other sciences. For these laws and definitions to be genuinely explanatory, they must be prescriptive and authoritative, not mere summaries of particular fact. Plato was the first to see this clearly, and this is what led him to develop his theory of the Forms. Particular phenomena unfold as they do, in regular and predictable patterns, because they imitate or participate in universal entities.

It is the sparse collection of Forms that defines the natural kinds of the world. These Form-determined kinds are the joints in nature along which a good scientific theory cuts. As Nelson Goodman discovered, we need natural kinds to guide scientific induction, distinguishing between genuine similarities (*green* emeralds) and adventitious, pseudo-similarities (*grue* emeralds). Plato's Forms are the constituents of the laws of nature, distinguishing laws from mere accidental generalisations.

Aristotle built his metaphysics on Plato's foundations. He introduced the notion of a substance (*ousia*, primary being), as the fundamental building block of reality. Everything in nature is either a substance, a part of a substance, or a mere heap of substances and their parts. Only substances enjoy a perfect degree of unity, along with a self-contained, definable nature. Rejecting atomism, Aristotle proposed that substances are divisible, and in this case the whole is greater than and prior to its parts.

In this new sort of ontology, Forms must do more explanatory work than they did for Plato. Plato's Forms (*ideai*) performed just one job: grounding the objective similarity or sameness of the many members of a natural kind. Aristotle's forms (*eidē*) must also ground the unity of a whole composed of many parts and the persistence through time of something undergoing continuous and intrinsic changes. A single Platonic Form for each natural kind lacks the flexibility and responsiveness needed to perform such varied tasks for each member of the kind. Aristotle insists (on what I take to be the right interpretation) that each substance have its own individual form.

In addition, Aristotle noticed a universal pattern in the classification of substances: the Porphyrean tree of genera, differentiae, and species. Each substance belongs to a unique, maximally narrow species (an *infima species*). Each such species belongs to a unique, maximally narrow genus, with each species in that genus sharing one differentia among a class of differentiae that are unique to that genus. This pattern repeats itself, with low-level genera belonging to a unique super-genus, and so on up the tree. This pattern is obvious in biological taxonomy, but it can also be found in chemistry and particle physics. So, for example, horses and pigs are *infimae species* of the genus mammal, which together with fish, birds, and amphibia make up the larger genus *vertebrate*, with the still larger genus of *animal*, and so on. Similarly, electrons constitute an *infima species* within the genus of first-generation leptons, which is a sub-genus of the genus *lepton*, which along with quarks make up the still larger genus of *fermion*.

Plato's theory of the Forms is unable to explain this structure. It can give us a class of natural kinds, but it cannot explain why those kinds should be organised in this sort of nested structure, instead of merely intersecting each other more randomly. As a consequence, Plato's natures are not uniquely definable in terms of genera and differentiae, with serious consequences for the possibility of scientific explanation.

2. Aristotle's New Theory of Forms

Aristotle needed to replace Plato's theory of Forms, according to which the member of each kind share a numerically identical Form, with a new theory in which each member of the kind has its own form, numerically distinct from the forms of the other members of the kind. However, he had to do so without falling into the morass of nominalism. There are, both historically and in contemporary metaphysics, two forms of nominalism: Ostrich Nominalism and Resemblance Nominalism.

Ostrich Nominalism is the view that simply rejects the need for explaining the existence of natural kinds as such. Things that belong to kind K1 are alike simply by being of kind K1, and those of K2 are alike simply by being of kind K2, and so on. There is, on this view, no universal explanation of what makes a kind *natural*. This leaves Ostrich Nominalists with no explanation for the difference between laws of nature and accidental generalisation, or between inductively projectible predicates (like 'green') and non-projectible ones (like 'grue').

Resemblance Nominalists do offer a general explanation of these facts, but they do it in a bottom-up fashion, appealing to a primitive relation of resemblance among particulars. This turns out to be a great deal more complicated, as a technical matter, than one might expect. In addition, it seems to get the order of explanation backward. Intuitively, two things are alike because they share some common character; they do not share that character because they resemble each other. Finally, there is the fact that exact resemblance is necessarily an equivalence relation: reflexive, symmetric, and transitive. Platonists can offer an explanation of this fact by appealing to shared participation in numerically identical Forms, while the Resemblance Nominalists must treat these facts as brute coincidences.

Is there a third option, besides Platonism and nominalism? Yes, and Aristotle discovered it. This third alternative involves introducing an infinite number of bare particulars, the bits or parcels of prime matter (*Physics* I, 9 192a5-b35, *De Gen*. II 1 329a28–33, *Metaphysics* Zeta 3 1028b33–1029a33, *De Caelo* III, 6, 305a14–33).[5] Each bit of prime matter has an extremely sparse set of characteristics: namely, the property of being fundamentally distinct from all other bits of prime matter. In and of themselves, the bits of prime matter have no spatial, temporal, or mereological relations to each other, and none of them have any intrinsic qualities or quantities. They are bare individuators (*De Caelo* I, 9 278a10–12, *Metaphysics* Delta 6 1061b31–33, Zeta 8 1034a7, Iota 3 1054a33–35, Lambda 8 1074a33–34).[6]

Socrates and Callias belong to the same species, humanity. They each have their own forms. These two forms are numerically distinct, but they are not *fundamentally* distinct. Their mutual distinctness is grounded not in themselves but in the distinctness of the bits of prime matter associated with the two individuals.

Socrates' substantial form and Callias's substantial form are numerically distinct, but they are not distinct of themselves but only by virtue of the prior numerical distinctness of Socrates' matter and Callias's matter (together with the fact that some of Socrates' matter is contemporaneous with some of Callias's matter), as Aristotle explains in *Metaphysics* Zeta 8:

> τὸ δ' ἅπαν ἤδη, τὸ τοιόνδε εἶδος ἐν ταῖσδε ταῖς σαρξὶ καὶ ὀστοῖς, Καλλίας καὶ Σωκράτης: καὶ ἕτερον μὲν διὰ τὴν ὕλην (ἑτέρα γάρ), ταὐτὸ δὲ τῷ εἴδει (ἄτομον γὰρ τὸ εἶδος).
>
> The completed whole is Callias or Socrates, that is, such-and-such a form in these particular flesh-and-bones; they differ through their matter, for their matter is different, but they are the same by way of form, for the form is indivisible. (*Metaphysics* Zeta 8, 1034a7–9. My translation)

To say that they are "the same by way of form" (ταὐτὸ δὲ τῷ εἴδει) is not to say that their substantially forms are strictly identical (numerically one) but merely to say that the numerical distinctness of their forms is not metaphysically *fundamental*. Socrates and Callias are numerically distinct because their respective bits of matter are distinct, and the same is true of their substantial forms. The forms are the same in the sense that they would be one if the two relevant chunks of matter were *per impossibile* one.

Numerically distinct but conspecific substantial forms enjoy only a derived distinctness, in contrast to the fundamental distinctness that holds between any two bits of prime matter.[7] If, *per impossibile*, Socrates' prime matter were identical to Callias's prime matter, their two forms would be identical. They have a kind of counterfactual (or counterpossible) identity.[8]

Let me make clear what I mean by *counterpossible relations of identity*. This notion follows naturally from the idea that two species derive their mutual distinctness from something else (i.e., the distinctness/ contrariety of two differentiae), and from the idea that two substances in the same species derive their distinctness from something else (the fundamental distinctness of two bits of prime matter). If x and y derive their distinctness from the distinctness of z and w, then, if z and w were (*per impossibile*) identical, x and y would be identical.

It is these relations of counterfactual identity among the individual forms that gives the species its real and natural unity. The relation of being counterfactually identical in this way gives rise (in an appropriate logic of *per impossibile* conditionals) to a principled explanation of the reflexivity, symmetry, and transitivity of the relation. The order of explanation is correct: it is something intrinsic to the two men, their conspecific forms, that explains why they resemble each other.

How does Aristotle explain the Porphyrean tree? As he explains in *Metaphysics* Eta 6, the shared genus represents a shared form of potentiality, which the specific differences actualise (1045a24–35).[9] Socrates' form and the form of Bucephalus belong to the same genus. The two forms share a common potentiality, a potentiality to belong to any animal species. This common potentiality has been actualised in two incompatible ways in the two forms, explaining why they belong to a common genus but different species. We can say that the two forms are congeneric because they are not specifically different in and of themselves (fundamentally) but only in a derived way, in a way that is grounded in the contrariety of the two specific differences (rationality and fleet-footedness, let's say). If the two specific differences were not (*per impossibile*) contrary to each other, the two forms would be conspecific. This would-be or counterfactual conspecificity is what unites the animal species into a single genus. And, once again, we can use the counterfactual identity to explain why congenericity is an equivalence relation.

What are *differentiae*? They are a kind of causal power – power of a specifically formal kind. A formal power is a power to confer certain proper accidents on substances of the natural kind. Contrary differentiae are powers to confer contrary accidents.

We can repeat this process over and over, as we rise to higher and higher genera, re-creating the Porphyrean tree. But all of this depends on the bare particularity of the bits of prime matter at the first stage. It would be unreasonable to suppose that various universals (e.g., species) stand in a counterpossible relation of identity to one another because they belong to the same genus, while denying that various particulars could stand in such a counterpossible identity to each other when they belong to the same species. Both kinds of non-numerical sameness should be given the same sort of explanation.

In addition, only by positing individual substantial forms can we explain why *infimae species* are the ultimate species. To do that, we have to explain why the predication of accidents presupposes the predication of an *infima species*, and that explanation must refer to the fact that a substantial form corresponding to an *infima species* is a *complete* form, in the sense that it has a sufficient capacity to *per se* unity on a collection of parts and temporal stages. What makes the form of an *infima species* maximally specific is the fact that it has sufficient formal power to unify a substance both synchronically and diachronically. The explanation of the *per se* unity of a particular substance requires a particular substantial form. And we can't have multiple substantial forms in the same infima species without prime matter as the principle of individuation.

Prime matter has no nature in itself, but it does derive a nature from the substantial form that informs it. A form gives to its constituent bits of prime matter their spatial, mereological, and physical characteristics, along with their actual existence. So charactered, prime matter is enabled to persist from one moment to another. Bits of prime matter can even survive substantial change (the corruption of one substance and its replacement through the generation of one or more new substances). This enables prime matter to play one of the roles that Aristotle assigned to matter in *Physics* I: as the enduring substrate of substantial change. Since prime matter has no nature in itself, it has the potential of receiving any nature whatsoever (so long as it is a nature of a material substance). What nature a bit of prime matter has at a given time depends on the substantial form inhering in it and on the forms of the substances acting on it.

Since substances are composite, they have proper parts, each with its own location in space. Each part of a substance is paired by the substance's form with a bit of prime matter. Through this pairing, bits of prime matter acquire spatial location and mereological relations to each other. When a substance is internally symmetrical, the bits of prime matter within it individuate its individual parts from each other.

Substances can also extrude bits of prime matter into substances in their environment and absorb other bits (as in cases of organic growth or diminution). The distinctness of two substantial forms of the same species that exist at two different instants can thus be over-determined: first by the pair of distinct bits of matter they inform at the first instant, and then again by the pair of distinct bits of matter they inform at the second instant. This overdetermination isn't problematic, since it is coordinated by the persisting activity of the two substantial forms. They are enabled to inform distinct bits of matter at later times by virtue of their informing distinct bits at earlier times.

Leibnizians object to prime matter on the grounds that it introduces new degrees of freedom in the world, corresponding to the re-shuffling of the primitive bits of prime matter among the various substances and their material parts. What could explain why the prime-matter bits are distributed in the way that they are, rather than some alternative permutation?[10] It is certainly true that we can describe alternative scenarios in terms of permutation: e.g., a world in which substance S has the prime matter of S* and vice versa, making necessary adjustments to the prior and subsequent locations of these two bits in the new world. However, there's no reason for the Aristotelian to posit the real existence of such alternative possibilities, and so no reason to accept that there is a contingent fact here to be explained.

3. The Scientific Necessity of Prime Matter

Are there alternative ways of realising Aristotle's Third Way without the use of prime matter? I know of only two. The central idea of Aristotle's via media between Platonism and nominalism concerns the individuation of substantial form. Aristotle proposes that this individuation is the function of bits of prime matter. One could suppose instead that forms are individuated by special, individuating properties: Scotus's haecceities, "thisnesses." Or, one could suppose that forms are individuated by qualitative, quantitative, and spatiotemporal relations of an ordinary sort. For the sake of time, I won't pursue the Scotist alternative of haecceities in any detail here, except to note that the idea of a *property* that is essentially *individuating* is almost certainly incoherent. In addition, Scotus's haecceities will not be able to play the role of the substrate of substantial change, as prime matter can. Haecceities are by definition non-transferable across substantial change. Finally, haecceities do not represent any kind of ontological economy, since we will need distinct haecceities for every proper part of every substance. And, in any case, the greater quantitative parsimony of the Scotist (resulting from the elimination of prime matter) is more than overwhelmed by its much greater ideological profligacy, requiring primitive predicates for every haecceity.

The other option is to adopt a kind of bundle theory of particulars: each particular substance can be identified with the bundle of general properties that it instantiates. On this view, it is impossible for two distinct substances to be indistinguishable. We must adopt Leibniz's principle of the identity of indiscernibles.

At this point, our scientifically articulated picture of the universe becomes relevant. The spatial framework of nature is homogeneous and directionless. In other words, it is characterised by a high degree of symmetry: locational, rotational, scalar. Both particles and fields are repeatable and similarly characterised by a number of symmetries. For these reasons, it is easy to find physically realizable models of the universe in which multiple bodies are mutually indistinguishable. Max Black described such a model in 1952 (Black 1952): a universe consisting entirely of two quantitatively and qualitatively indistinguishable iron spheres, rotating eternally around their common center of gravity. Or imagine a spherically symmetrical universe emerging from a perfectly smooth Big Bang. Consider a universe consisting of a single electron with its associated electromagnetic field. The field would be perfectly symmetrical around the electron. In order to distinguish the various parts of the field from each other, while avoiding Platonism and nominalism, we would have to find some individuating factor. Prime matter fits the bill. An even simpler model would be a world of empty spacetime, described in terms of general relativity. In each case, we can find multiple members of the same species (of material bodies or of empty space) which are indistinguishable in every way (qualitatively, quantitatively, geometrically).

For Aristotelian realists, there can be no conspecificity without bare individuators. So, in the absence of bare individuators (like bits of prime matter), we Aristotelian realists would have to rule out such worlds as metaphysically impossible. In fact, if Aristotelian realism is to be an acceptable theory of conspecificity, it should apply in *all* conceivable scenarios, even those that are for some other reason metaphysically impossible. Therefore, the argument for prime matter from such symmetrical worlds is independent of the postulation of their real possibility.

Could one take the regions of space or of spacetime to be the primitive individuators, instead of prime matter? One could, but only at the cost of denying the reality of motion.[11] Neither bits of absolute space nor bits of Minkowski spacetime are capable of motion. Yet science (as well as common sense) tells us that things move. In particular, substances (like organisms) move.

Even if one does substantialise space, this does not eliminate the need for prime matter. The various parts of space and spacetime are mutually indistinguishable. Space is homogeneous and highly symmetrical. Different parts of space have similar geometrical and topological properties. If we are going to maintain our commitment to Aristotelian realism, we need an explanation of these conspecific regions of space in terms of form and matter. The mutual distinctness of conspecific regions of space would have to be grounded in some underlying individuator, an individuator that lacks any nature of its own.

To summarise the argument so far:

1. Some kind of individuator is required in every conceivable world by Aristotelian realism, whenever there are two or more members of an *infima species*.
2. Given the isotropy of space, spatially symmetrical universes are conceivable.
3. Spatially symmetrical material substances are conceivable.
4. Given 2 and 3, there are conceivable worlds in which there are multiple parts of substances which belong to the sane *infima species* and which cannot be individuated their history or external relations
5. Given 1 and 4, Aristotelians must associate bare individuators with every spatially circumscribable part of any material substance. We can call these 'bits of prime matter'.

A superficially plausible objection to prime matter, from the perspective of contemporary philosophy, is that energy or mass-energy can do the metaphysical work of prime matter without any paradoxical bareness. If we thought of mass-energy as a kind of stuff that persists through all substantial change, so the argument goes, we could suppose that any two bits of mass-energy are primitively distinct from each other, and we could use mass-energy rather than prime matter as the principle of individuation. Or we might simply identify prime matter with mass-energy.

A number of physicists and philosophers of physics have argued recently that this conception of mass-energy is mistaken – in particular, it is incompatible with special relativity (Lange 2002, Maudlin, Okon, and Sudarsky 2019). In relativity, the kinetic energy of a particle is not absolute but dependent on a frame of reference. Consequently, it is impossible to identify in a frame-independent way where the various bits of mass-energy are supposed to be at any given point of time. All we can say is that the invariant mass-energy of each closed system as a whole is conserved in a frame-independent way, and this conservation is a product of a particular kind of global time symmetry (as shown by Noether's theorem).[12]

From an Aristotelian perspective, this critique is absolutely right.[13] Mass-energy is a particular *quantity* (an accident); it is not a thing or a stuff. Things *have* mass-energy; mass-energy doesn't have anything. However, the principle of the conservation of mass-energy does point to the need for a persistent substrate in all cases of substantial change. If whole things could simply go out of existence without residue or pop into existence without precursor, these creation and annihilation events would violate the conservation of mass-energy. So, such conservation laws do point to the need for a substrate and so to the need for something like prime matter.

Quantum mechanics also provides us with some reason to distinguish between prime matter and quantities of mass or mass-energy. On at least some interpretations of quantum mechanics, the uncertainty principle can apply to the quantity of energy in a system (Aharonov, Popescu, and Rohrlich 2016). This would mean that it would be possible for an isolated system to enter into a superposition of states, where the states assign different quantities of mass-energy to the system as a whole. If so, this would force us to distinguish between the prime matter, which exists in each of the states, and the quantity of mass-energy it contains, which varies from state to state. Some physicists and philosophers have argued that wave collapse and measurement events can cause failures in the conservation of energy (Gisin and Zambrini Cruzeiro 2018, Carroll and Lodman 2021). If correct, this would also require a substrate that endures through these quantitative fluctuations, and this substrate must be prime matter. The quantity of mass-energy would be a quantitative determination of the unqualified prime matter. In the short term, the quantity of mass-energy contained in the prime matter could be observed to fluctuate. If matter weren't prime, if it had essentially a particular amount of mass-energy, then such matter could not (by definition) survive such fluctuations.

So, it's a mistake to think of energy or mass-energy as any kind of *matter* (in the Aristotelian sense). We could, however, speak of *massive body* or *massive bodies* as a form of *proximate* matter. Massive body might be a kind of high-level genus, to which we can assign various narrower species of body, breaking the genus down by different forms of physical and chemical composition.

4. Prime Matter and Thermal Substances

Over the last ten years, I have been developing a neo-Aristotelian, hylomorphic interpretation of quantum theory (| Author 2021a, 2021b, 2022a, 2022b). My approach relies heavily on the work of a number of scientists and philosophers of science who have argued for the strong irreducibility of chemistry and thermodynamics to quantum microphysics (Bishop and Atmanspacher 2006, Emch and Liu 2005, Hendry 2006, Kronz and Lupher 2005, Liu 1999, Primas 1983, Ruetsche 2011, Sewell 1986 and 2002, Strocchi 1985, Woolley 1988). In order to account for phase transitions and other cases of spontaneous symmetry breaking, quantum chemists make use of infinite and non-separable quantum models,[14] in which substances are represented as composed of an infinite number of infinitesimal particles. Thanks to the constraint of the Stone-von Neumann theorem (von Neumann 1931),[15] such non-separable models are needed in order to obtain multiple superselection sectors, which can represent different values of chemical and thermodynamic parameters (e.g., temperature, entropy, chemical potential). These models are needed, not just to avoid computational complexity or to enhance conceptual intelligibility, but because without the introduction of an infinite number of sub-systems, we cannot obtain the mathematical structure needed to represent faithfully the real chemical and thermal features of the system.

I have argued that this sort of necessity, when tied to the use of such non-separable models (i.e., models in which the system has infinitely many non-trivial sub-systems), gives us good grounds for denying that chemical and thermodynamic facts supervene on the microphysical facts. Consequently, we have grounds to deny that the sort of substances that are involved in our experimental sciences (both our instruments and the subjects of study) are really *composed of* microphysical entities like sub-atomic particles, atoms, and even molecules. I don't deny the reality of such entities, but I do deny that they are *material parts* of ordinary substances. They are instead *powers* of those substances – powers to act and to react on a microscopic scale with other substances. Substances do have material parts, but these parts are not microphysical phenomena but entities with a full complement of chemical, thermodynamic, and condensed-matter features. What parts a substance can be composed of is determined by its specific substantial form.

Quantum particles are never substances, nor are they actual material parts of substances. First of all, such particles lack individual identity. Quantum statistics (both Bose-Einstein and Fermi-Dirac) differ from classical statistics precisely in the fact that they do not require us to assign identities to individual particles. Instead, the individual cases that are treated as equally probable are defined in terms of the numbers of indiscernible particles of various kinds that are involved. Second, the use of infinite, non-separable models in quantum chemistry and thermodynamics indicates that ordinary substances are in fact composed of continuous matter, with individual atoms or molecules present only virtually. Third, fractions of quanta play an important role in physics in the fractional quantum Hall effect (discovered by Robert Laughlin). This reinforces the idea that the parameter *number of particles* is not naively a counting or cardinal number of a set of individual particles but rather an irreducible quantitative measure of undivided quantum systems. Fourth, particles typically lack the sort of determinate trajectories that would enable us to meaningfully re-identify the same particle at different points in time. Finally, the powers of quantum particles are defined entirely in terms of their probabilistic propensities to interact with quasi-classical instruments (measurement devices). Unitary evolution of a quantum system (according to the Schrödinger equation) has nothing to do with the intrinsic character or even the "real" location of individual particles, but only with the evolution of the probabilities corresponding to these propensities to produce certain measurement results. Particles are thus not intrinsic parts of a substance but only extrinsic dispositions for the substance to act upon other substances in definable ways.[16]

In my model, prime matter can play its traditional role as the substrate of substances and their "integral" or material parts. Matter should not be associated directly with either physical particles or with fields (or mass-energy). These entities (or states) are more correctly classified as accidents of power that belong to substances and to their material parts.

Proximate (physico-chemical) matter in organisms and inorganic substances can be exhaustively characterised in terms of an inventory of basic sub-atomic particles, atoms, molecules, and larger dynamic structures (like convection cells). Living organisms ground the individual identities of some molecules and atoms, by virtue of conferring specific functions to them (e.g., iron atoms in hemoglobin molecules). Things are typically less determinate in inorganic substances.

I have argued (Koons 2020 and 2020b) that accidents can survive the demise of the substance to which they belong. (This seems to be true only of certain kinds of accidents: powers, rather than quantities or qualities.) On this view, for example, the photons arriving now from distant stars and galaxies are merely particular powers of those distant celestial bodies, many of which no longer exist. What cannot happen is for a photon or other physical particle to *begin to exist* independently of any substance. Each such particle is, throughout its existence, dependent for its identity and nature on its originating substance.

Philosophers of physics in recent years have engaged in a vigorous debate about which is metaphysically fundamental: particles or fields. From an Aristotelian perspective, both answers are wrong. What are fundamental are substances, including many of the familiar middle-sized objects of everyday life. Both particles and fields are accidents of substances. They are bundles of powers, both active and passive. We can, if we wish, speak of particles as *parts* of substances, but we must understand this as involving a kind of metaphysical composition, that is, the combination of a substance with certain qualities, quantities, and powers. Particles are not *material* parts of anything (for the reasons given above). The number of particles of various kinds (e.g., the number of electrons, protons, and neutrons) "contained" by a substance is an important quantitative determination of that substance, one that explains the rest mass and net charge of the substance as a whole. This does not require us to reify individual particles as material parts of the whole. Substances and their material parts contain, as metaphysical components, various bundles of indistinguishable particles, each bundle being assigned some numerical value (possibly fractional, in the case of the fractional quantum Hall effect). These numerical values should *not* be treated as the cardinality of a set of distinct individuals. These bundles are individuated by the substance or material part of a substance to which they belong. Individual identity belongs first to substances, then to their material parts, and only lastly to bundles of indistinguishable particles.

Hasn't modern science shown us that we must think of bodies as really composed of individual atoms and particles? Isn't that the lesson, for example, of Einstein's account of Brownian motion? And if bodies are not composed of particles, why does quantum thermodynamics take the continuum limit of models of interactions at the atomic and molecular level? I can reply that particles, atoms, and molecules are *virtual* parts of substances, in the sense that substances act as if they were (in a way) composed of such entities. However, the lesson of the Stone-von Neumann theorem is that the behavior of chemical substances involves a kind of summation over the infinitely many potential interactions between real material parts of the substance at the atomic and molecular level. We are forbidden to reify the atoms and molecules as enduring entities with individual identities.

A field is a set of spatially-indexed active powers. Each field belongs to a substance or to a material part of a substance. In this respect, the physical world is quite different from the world as Aristotle imagined it. Substances extend virtually (by means of fields) into the surrounding space without limit. Each part of a field is individuated by the substantial part to which it belongs and the region of space in which it is located. The regions of space are individuated from each other in turn by their relations to the locations of substances and substantial material parts.

This means that there are as many electromagnetic fields in the universe as there are material parts of corporeal substances. When we measure the strength of "the" electromagnetic field in a particular region of space, we are actually measuring the net strength of the sum of all the EM fields belonging to all the material parts of substances throughout the universe.

That this is the right way to think about fields is supported by the Bohm-Aharonov effect. The Bohm-Aharonov effect (Aharonov and Bohm 1957) is a consequence of quantum mechanics,[17] according to which the exact quantum state of a complex system can have a differential effect on a body that is located in a region in which the strength of the composite EM field is zero. This shows that finding a region in which the strength of the composite EM field is zero is not the same thing as finding a region of space from which all EM fields are absent. According to my model, there are a very large number of fields, many with non-zero strengths, in any region whose composite field shows a net strength of zero there.

How does prime matter ebb and flow through our actual universe? Physicists don't make any explicit reference to it. Nonetheless, the conservation of mass and energy points to a tacit assumption of contemporary physics: physical things come from somewhere. They don't simply "pop" spontaneously into existence (setting aside elementary particles, which are not substances or material parts of substances in the neo-Aristotelian scheme). When one thermal substance increases in rest mass, it always does so by absorbing some identifiable part of one or more other thermal substances, and the prime matter of those parts is then incorporated into the absorbing substance.

5. A Cosmic Wavefunction?

One last issue. Is there (on my account) a cosmic quantum wavefunction? Would such a function represent anything real? I believe that my account is consistent with either answer. We could embrace a pluralistic approach to physical theories (like that of Cartwright 1999), according to which every true physical theory has application only to particular situations, with particular boundary conditions. Given this approach, a supposedly cosmic wavefunction could not represent any physical reality. Quantum phenomena would always be contextual in nature. Such a pluralistic approach would best be combined with a neo-Copenhagen account of measurement. Wavefunctions would collapse indeterministically according to Born's rule whenever the quantum particles associated with one substance interact effectively with some non-quantal feature of the "measuring" substance. The contextual wave collapse theory of George Ellis and Barbara Drossel (Drossel and Ellis 2018) would provide a plausible mechanism for this model, given the crucial role of thermodynamic features (heat baths, heat sinks) in their account. Simpson (2021) has begun to articulate a hylomorphic model based on this theory.

However, I think a monistic approach is also viable. One could take the cosmic wavefunction as representing the causal powers at the quantum level of all of the universe's substances and substantial material parts. We must deal explicitly with the problem of quantum entanglement. Can one substance become entangled at the quantum level with a second, separate substance? The answer is clearly Yes, as was demonstrated by Yurke and Stoler (1992a and 1992b). This means that the cosmic wavefunction cannot simply be a function of the intrinsic states and spatial relations of the world's substances and their material parts. In addition, we must take into account relations of entanglement among these substantial entities.

Consequently, there are irreducibly *coordinated* causal powers. There are substantial entities with irreducibly *joint* potentialities, both active and passive.

An analogy with social philosophy might be useful here. Aristotle clearly held that individual human beings are substances. No substance can contain other substances as parts, so cities and other social groups are not substances. The existence and nature of a city depends on the existence and nature of its citizens. Citizens are not mere fragments of a city. How do groups differ from substances? Substances have natures or essences that are fundamental facts about the world, facts that determine the substance's basic powers and its persistence conditions, and that fully ground the substance's capacity for entering into groups. The nature of such groups, in contrast, is fully determined by the natures of its participants, although the existence of groups involves the instantiation of irreducibly relational facts (over and above spatial relations) among the members.

However, Aristotle was not an ontological individualist (see, for example, his discussion of man as a political animal in *Politics* I, 1253a8–40, or his discussion of the friend as a second self in *Nicomachean Ethics* IX, 1170b3–19). He thought that citizens possessed causal powers that were irreducibly *social* in nature. Membership in a city confers new powers and potentialities on the individual. The city makes certain kinds of action on the part of individuals (like *voting* or *paying taxes*) possible. In the same way, quantum entanglement affects the quantum-level powers and potentialities of individual substances in ways that are irreducibly relational. The substances of the universe form large groups of mutually entangled entities, and the nature of these groups must be considered in predicting and explaining quantum phenomena. It's possible that all substances belong to a single, cosmos-scaled *entanglement group*, where an *entanglement group* is a minimal set of substances that is closed under mutual entanglement. If so, a cosmic wavefunction would be needed to account for the effects of entanglement.

If we adopt this second, monistic version of my account, we can combine it with Alexander Pruss's recent Traveling Forms model (Pruss 2018). To trace the development of Pruss's model, we must start with some difficulties with the Everettian Many Worlds approach. There are two central difficulties with the Many Worlds interpretation: how to identify the distinct branches or worlds that co-exist in the model, and how to make sense of assigning probabilities less than one to any branch (given that all branches are equally real).

(See Maudlin 2010 and Author 2018 for more details on each problem.) David Albert and Barry Loewer (1988) offered the Many Minds interpretation in response to these two problems. On the Many Minds interpretation, each human body is associated with an infinite number of distinct minds. When the world "branches," some minds go down each branch, with the probability of a given mind taking a given branch determined by Born's rule. The presence of minds with different experiences defines and differentiates the various branches. Jeffrey Barrett (1995) simplified the Albert-Loewer model by associating only a single mind with each body, with the result that all branches but one are inhabited by mindless "zombies." Barrett called his model Traveling Minds.

Both models suffer from obvious defects. They both involve a troubling independence of the mind from the body, and both have nothing to say about branching events that occurred before the emergence of human minds. Pruss uses hylomorphism to resolve these problems. Instead of associating minds with human bodies, Pruss assumes that branches are associated with substantial forms, resulting in composite substances. This eliminates the odd mind/body dualism. Barrett's zombie branches are replaced by branches in which the particles exist in some manner but fail to compose any substances. We could call them *compositional zombies*. More helpfully, we could describe non-actual branches as scenarios involving substances and their relations that were potential outcomes of past history which were never in fact actualised.

If we assume (as Aristotelians must) that the universe has always been composed of substances, then the second problem with the Many Minds and Traveling Minds models disappears as well.

Pruss shows, in a very interesting development, that his Traveling Forms model is a way of providing a metaphysical foundation for the modal interpretation of quantum mechanics. Like Bohmian mechanics, the modal interpretation is a one-world interpretation, and one in which there are no Copenhagen-like collapses of the wavefunction. Unlike the Bohmian interpretation, the modal interpretation does not privilege particle position. Instead, which determinables take on actual, determinate values changes as the universe evolves.

Bacciagaluppi and Dickson (1999) proposed a dynamics for the modal interpretation which is indeterministic, which fits with Pruss's Traveling Forms model. As Pruss explains, we can take the species of the substantial forms as fixing which quantum determinables must be actualised in each situation. Here is how Pruss adapts the Bacciagaluppi-Dickson dynamics:

> Consider the set $\mathcal{O}$ of all the observables O(x, D) that correspond to the substances x and their determinables D. "Branches" of the multiverse now correspond to eigenvectors of all the observables in $\mathcal{O}$. At any given time t, the actual values of the observables in $\mathcal{O}$ define a vector $|a_t>$ in the Hilbert space corresponding to the wavefunction.
>
> Then, what makes it be the case that a particular form inhabits a branch is that the actual maximally specific determinates of all the species-based determinables pick out a set of values of all the observables in $\mathcal{O}$, and a set of values of all the observables together with the actual value of the wavefunction picks out a joint eigenvector vector $|a_t>$ of the observables in $\mathcal{O}$ that corresponds to a "branch." (Pruss 2018, 118)

What is the ontological status of the universal wavefunction itself? It could be coded in a single cosmic form, as in Simpson's theory of Cosmic Hylomorphism (Simpson 2021), developed originally for the Bohmian theory of quantum mechanics, which I shall discuss below. This would be the one exception to Aristotle's rule – the one case in which a substance contains other substances as parts. Or, we could adopt a Leibnizian picture in which the form of each substance encodes all the information about the cosmic wavefunction. This involves massive overdetermination, but perhaps that is the price that has to be paid in order to inhabit the same universe. Or, most promisingly, we could introduce an addition to Aristotle's ontology: non-substantial, relational *group forms*, accidental forms that are *shared* by a group of substances.[18] Each maximal set of mutually entangled substances could participate in such a group form, which would encode all the information about the particles contained in members of the group.

What is the role of prime matter in Pruss's model? Or, more precisely, what *should* its role be? As I argued above, I do not think that we should associate prime matter with individual particles, or even with sets of indistinguishable particles. Instead, prime matter should be associated with substances and with the material parts (both actual and potential) of those substances. Particles (or, more precisely, sets of indistinguishable particles) must be thought of as bundles of active and passive causal powers possessed by substances and their material parts.

What are these substances and material parts like, and how do they differ from particles? Material parts always have definite locations, and they always possess definite chemical, solid-state-physical, and thermodynamic properties. There are always sets of particles that belong virtually to each material part. In principle, there is no limit to how large or small a substance or a material part of a substance can be, but in practice we are able to observe and manipulate material parts only above a relatively large scale.

I conjecture that the actual material parts of living organisms can be typically much smaller than we find in inorganic substances. This is because the functional organisation of the cell is able to localise molecules and even atoms, assigning definite teleofunctions to them. This enables some atoms, like the iron atoms at the heart of hemoglobin molecules, with a definite and enduring identity.

6. Prime Matter and Bohmian Mechanics

In this section, I will focus on an alternative approach to combining Aristotelianism and quantum mechanics: Simpson's theory of Cosmic Hylomorphism: a cosmic-substance version of Bohmian mechanics (Simpson 2021).[19] Simpson's model allows for a meaningful cosmic wavefunction.

David Bohm's interpretation of quantum mechanics assigns a definite and enduring identity to each subatomic particle (Bohm 1951). Doing so requires several significant departures from the Copenhagen interpretation. First, the quantum wavefunction must be construed as a *pilot wave* (as proposed by Louis de Broglie), something actively guiding the movements of particles. Second, the unavoidable non-locality of quantum takes an especially stark form, with the positions of particles in one region of space having *instantaneous effects* on the movements of other particles at arbitrary distances. This is in contrast to the more limited non-locality of the Copenhagen interpretation, in which superluminal influence is limited to the coordinated disappearance of certain possibilities (in a so-called *collapse* of the wavefunction). Finally, many physical properties (like spin) cannot be understood as local and intrinsic features of particles. Instead, particles have only one feature intrinsically: their trajectory through space and time.

As is the case with other interpretations, philosophers who embrace Bohmian mechanics must choose one of several options for understanding the nature and source of causal power. They can (i) embrace neo-Humeanism, in which powers are determined by laws, and laws are merely the best systematisation of the actual history (past, present, and future) of the universe, or (ii) they can reify the laws themselves, treating laws as entities that somehow confer causal powers on the corresponding particulars, or (iii) they can opt for the Aristotelian option, grounding causal powers directly in the natures or *forms* of substances.

The Neo-Humean option has been a popular one, adopted recently by Michael Esfeld (2017). The second option has not been pursued in recent years, due to the troubling gap between the universal entities in the laws and the particular entities that are somehow governed by them. Simpson (2021, 2023a, 2023b) has argued that an Aristotelian version of Bohmianism is the most attractive option. As Simpson develops this model, the universe constitutes a single Aristotelian substance with a single substantial form, by which it acquires a nature. It is the substantial form that is ultimately responsible for choreographing the movements of particles.

What is most interesting in the present context is the fact that on any primitive-ontology version of Bohmianism, prime matter (or something like it) plays an indispensable role. On such interpretations of Bohm, each particle on the Bohmian picture is an atomic bit of prime matter. Particles lack any intrinsic qualitative or quantitative feature. Moreover, any two particles are primitively distinct from each other. Here is how Simpson summarises the situation:

> The matter in [the Bohmian version of primitive ontology] is 'primitive' in three senses: first, it cannot be read off the formalism of standard quantum mechanics, or deduced from any other concept or the vocabulary of a given theory, but is posited for the sake of empirical adequacy; secondly, it is a '*materia prima*, having no intrinsic physical properties at all' [Esfeld et al. 2017: 135] (or, at least, no intrinsic properties that can be picked out by our best physical theories); thirdly, every physical phenomenon is ontologically explained and reduced to the motion of the primitive matter. (Simpson 2021: 2)

Given the sparse nature of the particles, what explains why they behave in a way that is correctly describable by the elegant mathematics of quantum mechanics? The Neo-Humeans reply that there is no explanation of this fact. It is simply a brute fact that they do behave in a manner accurately describable by the laws of quantum mechanics, and it is because of this brute fact that we can say that the laws 'explain' the corresponding behavior. Even more problematically, Neo-Humeans cannot explain the persistence of particles through time nor the spatiotemporal continuity of their trajectories (Simpson 2020). Those who reify the laws would answer that it is the laws themselves that ensure the correct behavior of the world's particles. But how can some abstract fact involving only universals be the causal explanation of that behavior? Only Aristotelians can offer a satisfactory answer: the particles behave as they do because they are informed by a cosmic substantial form of the appropriate kind. The substantial form is both prior to the phenomena to be explained and concrete enough to be a causal factor.

The Neo-Humean version of Bohmianism also inherits the characteristic disadvantages of the Mill-Ramsey-Lewis account of laws of nature that is at the center of Neo-Humeanism itself (Koons and Pickavance 2017, 99–105). On the Mill-Ramsey-Lewis account, it is metaphysically impossible for laws of nature to obtain in small worlds, worlds in which the number and variety of events is too impoverished to make the relevant law of nature the best (simplest and most comprehensive) description of that world (see Simpson 2023c). The Mill-Ramsey-Lewis account introduces an ineliminable element of anthropocentricity into the definition of a law of nature, since what counts as the best theory of a world's history depends essentially (on that account) on our standards of theory evaluation. Finally, Neo-Humeans have failed to provide a fully satisfying account of the local direction of time (Koons and Pickavance 2017, 599–605).

Simpson uses the term 'power-atoms' to refer to Bohmian particles in his model. Here is how Simpson describes of the form of the cosmic substance:

> I propose that this [quantum-mechanical] law expresses the metaphysical power of the cosmic form to manifest a cosmic process, which underpins the diachronic identity of the cosmic substance. The cosmic form manifests this process by means of a structure of grounding relations, which unite the power-atoms to the cosmic form, by which it imposes powers upon the power-atoms at each moment. (Simpson 2021: 14)

As Simpson explains, the Aristotelian version of Bohmianism is well suited to explaining why non-local causation does not threaten special relativity by means of superluminal signaling:

> Does this instantaneous change unlawfully violate the superluminal ban on signalling? I think not. The cosmic form which unites itself to the power-atoms, by grounding the causal powers of the configuration, is the formal cause of the unified substance, rather than an efficient cause of an extrinsic organisation that is imposed upon the particles. The power-atoms, thus 'empowered', are at once united as integral parts of a single whole, rather than separate entities that must be micro-managed according to a physical mechanism. I submit that an instantaneous 'formal' cause of the non-local correlations that are associated with the phenomenon of quantum

> entanglement is not unlawful in the way that an instantaneous 'efficient' cause seems to be… The power to choreograph the trajectories of the particles according to the Bohmian law is something intrinsic to the nature of the cosmos. It is efficient causes, not formal causes, which must dutifully abide by the superluminal ban. (Simpson 2021: 21)

Simpson's hylomorphic Bohmianism isn't fully Aristotelian (as he recognises), because it posits a single, cosmic substance. Aristotle was a champion of the middle-sized, like organisms. However, there is no reason why a hylomorphic Bohmian couldn't posit a multiplicity of separate substances. On this model, the movements of particles would be choreographed jointly by the substantial forms of groups of entangled substances (the *entanglement groups* that I mentioned earlier). The relations of mutual entanglement would constitute a kind of group *accident*, which would in turn ground the relevant reduction of the pilot-wave equation for motion. In the extreme case, the whole cosmos might constitute a single entanglement group, in which case we would have a single pilot-wave equation (as in Bohm's own formulation).

Such a revised hylomorphic Bohmianism would come closer to my own model, the difference being that the hylomorphic Bohmian would recognise individual particles as material parts of substances, something which I deny. I have my own objections to the Bohmian interpretation (see Koons 2022: 170–176), but this issue has no relevance to the reality of prime matter, which is common to both models.

7. The Mereology of Space and Quantum Prime Matter

In response to Zeno's paradoxes, Aristotle proposed that every substance has, at every instant of time, only finitely many actual material parts, although every corporeal substance is potentially divisible into any number of parts, without limit. In other words, substances always have finitely many actual material parts but infinitely many potential material parts. Some bit of prime matter is associated with every material part of a substance, both actual and potential. (Merely potential bits of prime matter and merely potential parts of a substance are both parts of reality. To be non-actual is not to be unreal but simply to lack a certain kind of status within reality.)

This multiplication of bits of prime matter is important for two reasons. First, consider cases of homogeneous moving or spinning continua, such as the homogeneous spinning disks of C. D. Broad

(Broad 1925: 36–7), Saul Kripke (Shoemaker 1984: 242–7), and David Armstrong (1980). In some such cases, the spinning disk will have no actual parts. To ground the fact that the disk is spinning and spinning in a certain direction and velocity, we have to take into account the location at each instant of each of the infinitely many potential parts of the disk. Each of these parts will need its own complement of prime matter.

Second, prime matter is needed as the substrate of substantial change, and any corporeal substance can be divided into remnants in infinitely many ways. So, again, we must be able to identify the prime matter associated with each potential part before the substance's destruction.

In Aristotle's philosophy of nature, we can identify each potential part of a substance with a sub-region of the substance's location. This would seem to satisfy both requirements – that of grounding any internal motion within the substance, and that of providing a substrate for substantial change associated with the excision of the corresponding part of the substance.

Does such an account still make sense in the context of quantum mechanics? We still need prime matter associated with each sub-region of the substance's location to satisfy the first requirement (grounding internal motion). On my model, and also on that of the hylomorphic Bohmians, each substance has a definite location at each point in time. And in cases of substantial change, we can identify each of the post-destruction remnants with some sub-region of the original substance's location at the instant of destruction – think of cutting a worm into several pieces, for example. Given that every substance has a definite location at each moment (even though its associated particles – which are not among its material parts – do not), we can always identify which spatial region of the original substance is transferred to the new substance in each interval of time.

Notes

1. The phrase 'prime matter' in English (*hulē* in Greek, *materia* in Latin) is a mass noun, but for my purposes, the crucial notion is an identifiable bit or parcel of prime matter. As we shall see these 'bits' are needed as the ultimate individuators of substances in the same species.
2. These too should be read as referring to particular *bits* of flesh, earth, etc.
3. This is not to deny that we can make true generalisations about prime-material entities – for example, that they lack natures and are self-identical. By *nature* I mean (following Aristotle's *phusis*) a principle of rest and motion, a ground for active and passive causal powers.
4. 'By "material" (*hulē*) I mean that which is in itself (*kath hauto*) not a particular thing or a quantity or anything else by which things are defined (*horisthai* – determined). For there is something of which each of these is predicated and

whose being is different from any of the predicates (*katēgoriōn*). Everything else is predicated of primary being (*tēs ousias*); whereas primary being must be predicated of being-a-material (*hulē*). Hence, in the last analysis a subject is itself (*kath hauto*) not a particular something (*ti*) or quantity or anything of the sort; not even their negations, for the negations, too, would belong to it only accidentally.' (Hope 1952: 133–4).

5. See Suppes 1974, Robinson 1974, Code 1976, Cohen 1983, Fine 1992, Byrne 1995.
6. The word 'individuation' is somewhat unfortunate. What bits of prime matter ground is the numerical distinctness of two members of the same species. Strictly speaking, a bit of prime matter does not explain the *individuality* of a substance, if 'individuality' signifies 'indivisibility'. It is the substantial form, and not the prime matter, that makes a material substance an individual (a *tode ti* in Greek), but it is the prime matter that grounds the substance's numerical distinctness from other species in the same species, and this is what I mean by *individuation*.
7. Why cannot proximate or signate (partially formed) matter be the ultimate individuator? Because, if we are to apply Aristotle's moderate realism to the particular instances of these qualities and quantities, there will have to be bare individuators that ground the numerical distinctness of these instances. And these bare individuators will be parcels of prime matter. When Thomas Aquinas talks of *signate matter* as the individuator, I believe that he is using the 'determinate dimensions' of space as a device enabling us to refer to particular parcels of prime matter. It is these particular parcels, and not prime matter *in general*, that individuates.
8. One complication that Aristotle does not consider: what individuates two individuals of the same species if there is no time (or time in a world) during which they both exist? It cannot be any two bits of prime matter, since there is no time-slice of either substance whose distinctness from the other substance at that time could be grounded in prime matter. We need to have a disjunctive theory of individuation, in which two substances of the same species are individuated either by two bits of prime matter (if there is a world and a time in which they co-exist) or by the contrariety of the two non-overlapping world segments (if they do not exist in any overlapping world segments). This amounts to the thesis that members of the same species are individuated jointly by their prime matter and their causal history (described qualitatively).
9. 'But if, as we say, there is a material (*hulē*) and a form (*eidos*), and the material is a power (*dunamis*), whereas the form is operation (*energeia*), the explanation sought avoids the difficulty [of explaining the unity of the definition]. For the difficulty is the same as that which would arise if "bronze sphere" were the definition of "cloak"; "cloak" would then mean "bronze sphere", and the question would then arise how the unity of the cloak can be explained by two things, sphere and bronze. But for us there is no difficulty, because the one word denotes the thing's material [matter], and the other, its form (*morphē*). What, then, can explain how what was potentially becomes actual, except the effective agent (at least for things that are generated)? There is no other factor that explains how a potential sphere becomes an actual spere; since the two kinds of being (what it means to be a material and what it means to be a form) define precisely this relation of potential-actual.' (Hope 1952: 178–9).
10. Thanks to an anonymous referee for posing this objection.
11. My objection is not to substantialising space, but to refusing to substantialise things that move through space.
12. Brian Pitts (2021) has argued that a global conservation of energy is problematic in general relativity.

13. See also Oderberg (2022), who notes some difficulties with a simple identification of prime matter with energy.
14. A non-separable model makes use of a non-separable Hilbert space. A separable space has a countable dense subset: a set that contains at least one element of every nonempty open subset of the space. To be non-separable, it is necessary but *not sufficient* for the model to have infinitely many degrees of freedom. See Kronz and Lupher (2005: 1242–3).
15. John von Neumann and Marshall Stone proved that finite systems admit of only one irreducible Hilbert-space representation (von Neumann 1931). An algebraic representation is *irreducible* if and only if it does not have any proper sub-representations that are closed under the relevant functions. Stone and von Neumann proved that any two irreducible groups of the appropriate kind (one-parameter unitary groups) are *unitarily equivalent*. Two representations or groups are *unitarily equivalent* when there is a unitary transformation of one into the other (a transformation involving a *unitary* – that is, a linear, amplitude-preserving – operator). In this case, the two representations can be treated as simply two different ways of representing the same physical situation, analogous to the way that changes in units of measurement or the location of the axes of space produce physically equivalent representations.
16. As I will explain in the next section, the Bohmian interpretation invalidates the assumptions of the fourth and fifth of my arguments. Nonetheless, it reintroduces prime matter as a constituent of individual particles, as we shall see presently.
17. Wallace (2009) argues that the phenomenon is not *essentially* quantal.
18. This seems to be Aquinas's view, as pointed out by an anonymous referee: S. Th. Ia, Q39, a3,
19. Not to be confused with Simpson's hylomorphic interpretation of Contextual Wave Function Collapse Theory.

References

Aharonov, Yakir and David Bohm (1957) 'Significance of Electromagnetic Potentials in the Quantum Theory,' *Physical Review* 115(3): pp. 485–491.

Aharonov, Yakir, Sanu Popescu, and Daniel Rohrlich (2016) 'On conservation laws in quantum mechanics,' arXiv:1609.05041 [quant-ph].

Albert, David Z. and Barry Loewer (1988) 'Interpreting the Many-Worlds Interpretation,' *Synthese* 77: pp. 195–213.

Armstrong, David M. (1980) 'Identity through Time,' in Peter van Inwagen, ed., *Time and Cause: Essays Presented to Richard Taylor*, Dordrecht: D. Reidel: pp. 67–78.

Bacciagaluppi, G. and Dickson, M. (1999), 'Dynamics for Modal Interpretations,' *Foundations of Physics* 29: pp. 1165–201.

Barrett, Jeffrey A. (1995) 'The single-mind and many-minds versions of quantum mechanics,' *Erkenntnis* 42: pp. 89–105.

Bishop, Robert C. and Harald Atmanspacher (2006) 'Contextual Emergence in the Description of Properties,' *Foundations of Physics* 36 :pp. 1753–1777.

Black, Max (1952) 'The Identity of Indiscernibles,' *Mind* 61: pp.153–64.

Bohm, David (1951) Quantum Theory, *Englewood Cliffs*, NJ: Prentice-Hall.

Broad, C. D. (1925) *Mind and its Place in Nature*, London: Kegan Paul.

Byrne, Christopher (1995) 'Prime matter and actuality,' *Journal of the History of Philosophy* 33 (2): pp.197–224.

Carroll, Sean M. and Jackie Lodman (2021) 'Energy Non-Conservation in Quantum Mechanics,' arXiv:2101.11052v2 [quant-ph]; *Foundations of Physics* 51 (4): pp. 1–15.

Cartwright, Nancy (1999) *The Dappled World: A Study in the Boundaries of Science*, Cam- bridge: Cambridge University Press.

Code, Alan (1976), 'The Persistence of Aristotelian Matter,' *Philosophical Studies* 29 (1976): pp. 357–67.

Cohen, Marc (1984), 'Aristotle and Individuation,' *Canadian Journal of Philosophy* Suppl X: pp. 41–65.

Drossel, Barbara and George Ellis (2018), 'Contextual Wavefunction collapse: an integrated theory of quantum measurement,' *New Journal of Physics* 20(11): pp. 113–25.

Emch, Gérard G. and Chuang Liu (2005), 'Explaining spontaneous symmetry breaking,' *Studies in History and Philosophy of Modern Physics* 36(1): pp. 137–163.

Esfeld, Michael (2017), 'A Proposal for a Minimalist Ontology,' *Synthese*: pp. 1–17.

Fine, Kit (1992), 'Aristotle on Matter,' *Mind* 101: pp. 37–57.

Gisin, Nicolas and Emmanuel Zambrini Cruzeiro (2018) 'Quantum measurements, energy conservation and quantum clocks,"' *Annalen der Physik* 530 6: 1700388.

Hendry, Robin Findlay (2006), 'Is There Downward Causation in Chemistry?' In *Philosophy of Chemistry: Synthesis of a New Discipline*, D. Baird, E. Scerri, and L. McIntyre, eds. (Dordrecht: Springer): pp. 173–189.

Hope, Richard (1952), *Aristotle: Metaphysics*, *Ann Arbor*, MI: University of Michigan Press.

Koons Robert (2018), 'The Many Worlds Interpretation of QM: A Hylomorphic Critique and Alternative,' in *Neo-Aristotelian Perspectives on Contemporary Science*, Robert C. Koons, William M. R. Simpson, and Nicholas Teh, eds., London: Routledge: pp. 61–104.

Koons Robert (2020), 'Remnants of Substances: A Neo-Aristotelian Resolution of the Puzzles,' *Quaestiones Disputatae* 10(2): pp. 53–68.

Koons Robert (2021a), 'Thermal Substances: A Neo-Aristotelian Ontology for the Quantum World,' *Synthese* 198: pp. 2751–2772.

Koons Robert (2021b), 'Powers ontology and the quantum revolution,' *European Journal for Philosophy of Science* 11(1): pp. 1–28.

Koons Robert (2022a), "Essential Thermochemical and Biological Powers," in *Neo-Aristotelian Metaphysics and the Philosophy of Nature*, William M. R. Simpson, Robert C. Koons, and James Orr, eds. (London: Routledge, 2022).

Koons Robert (2022b), *Is Thomas Aquinas's Aristotelian Philosophy of Nature Obsolete?*, South Bend, IN: St. Augustine Press.

Koons Robert and Pickavance Thimothy H. (2017), *The Atlas of Reality: A Comprehensive Guide to Metaphysics*, Malden, MA: Wiley Blackwell.

Kronz, Frederick M. and Tracy A. Lupher (2005) 'Unitarily Inequivalent Representations in Algebraic Quantum Theory,' *International Journal of Theoretical Physics* 44(3):pp. 1239–1258.

Lange, Marc (2002), *Introduction to the Philosophy of Physics: Locality, Fields, Energy and Mass* (Oxford: Blackwell).

Liu, Chuang (1999) 'Explaining the Emergence of Cooperative Phenomena,' *Philosophy of Science* 66 (Proceedings):pp. 92–106.

Maudlin, Tim (2010) 'Can the World be Only Wavefunction?' in *Many Worlds? Everett, Quantum Theory and Reality*, S. Saunders, J. Barrett, A. Kent, and D. Wallace, eds., Oxford: Oxford University Press, pp. 121–143.

Maudlin, Tim, Elias Okon, and Daniel Sudarsky (2019) 'On the Status of Conservation Laws in Physics: Implications for Semiclassical Gravity,' arXiv:1910.06473 [gr-qc].

Oderberg, David (2022), 'Is Prime Matter Energy?' *Australasian Journal of Philosophy*, 101 (3), pp. 534–550.

Pitts, J. Brian (2021) 'Conservation of Energy: Missing Features in its Nature and Justification and Why They Matter,' *Foundations of Physics* 26(3): pp. 559–584.

Primas, Hans (1983) *Chemistry, Quantum Mechanics, and Reductionism: Perspectives in Theoretical Chemistry*, Berlin: Springer-Verlag.

Pruss, Alexander R. (2018) 'A Traveling Forms Interpretation of Quantum Mechanics,' in *Neo-Aristotelian Perspectives on Contemporary Science*, Robert C. Koons, William M. R. Simpson, and Nicholas Teh, eds., London: Routledge: pp. 105–22.

Robinson, Howard M. (1974) 'Prime Matter in Aristotle,' *Phronesis* 19 (1): pp. 168–188.

Ruetsche, Laura (2011), *Interpreting Quantum Theories: The Art of the Possible*, Oxford: Oxford University Press.

Sewell, Geoffrey L. (1986) *Quantum Theory of Collective Phenomena*, Oxford: Clarendon Press.

Sewell, Geoffrey L. (2002), *Quantum Mechanics and its Emergent Macrophysics*, Princeton, N. J.: Princeton University Press.

Shoemaker, Sydney (1984), *Identity, Cause, and Mind*, Cambridge: Cambridge University Press.

Simpson, William M. R. (2021), 'Cosmic hylomorphism: a powerist ontology of quantum mechanics' *European Journal for the Philosophy of Science*, 11, 28, https://doi.org/10.1007/s13194-020-00342-5.

Simpson, William M. R. (2023a), *Hylomorphism*, Cambridge: Cambridge University Press.

Simpson, William M. R. (2023b), 'Cosmic hylomorphism vs Bohmian dispositionalism: implications of the "no-successor problem"' with J. Pemberton, in *Quantum Mechanics and Fundamentality: Naturalizing Quantum Theory between Scientific Realism and Ontological Indeterminacy*, Berlin: Springer.

Simpson, William M. R. (2023c), 'Small Worlds with Cosmic Powers,' *The Journal of Philosophy* 120(8): pp. 401–20.

Strocchi, Franco (1985) *Elements of Quantum Mechanics of Infinite Systems*, Singapore: World Scientific.

Suppes, Patrick (1974) 'Aristotle's Concept of Matter and its Relation to Modern Concepts of Matter,'? *Synthese* 28: pp. 27–50

von Neumann, John (1931), 'Die Eindeutigkeit der Schrödingerschen Operatoren,' *Mathematische Annalen* 104: pp. 570–588.

Wallace, David (2009) 'QFT, Antimatter, and Symmetry,' *Studies in History and Philosophy of Modern Physics* 40: pp. 209–22.

Woolley, R. G. (1988) 'Quantum Theory and the Molecular Hypothesis,' in *Molecules in Physics, Chemistry, and Biology*, Vol. I, Jean Maruani, ed. (Dordrecht: Kluwer Academic): pp. 45–89.

Yurke, Bernard and David Stoler (1992a), 'Bell's-inequality experiments using independent-particle sources,'? *Physical Review A* 46(5): pp. 2229–2234.

Yurke, Bernard and David Stoler (1992b), 'Einstein-Podolsky-Rosen Effects from Independent Particle Sources,' *Physical Review Letters* 68(9): pp. 1251–1254.