Metaphysical Indeterminacy, Properties, and Quantum Theory

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Abstract: It has frequently been suggested that quantum mechanics may provide a genuine case of *ontic* vagueness or metaphysical indeterminacy. However, discussions of quantum theory in the vagueness literature are often cursory and, as I shall argue, have in some respects been misguided. Hitherto much of the debate over ontic vagueness and quantum theory has centered on the "indeterminate identity" construal of ontic vagueness, and whether the quantum phenomenon of entanglement produces particles whose identity is indeterminate. I argue that this way of framing the debate is mistaken. A more thorough examination of quantum theory and the phenomenon of entanglement reveals that quantum mechanics is best interpreted as supporting what I call the "vague property" construal of ontic vagueness, where vague properties are understood in terms of determinable properties without the corresponding determinates.

1 Ontic Vagueness and Metaphysical Indeterminacy

Traditionally the issue of metaphysical indeterminacy has focused on the sort of vagueness that arises in the sorites paradox. This paradox, which is attributed to the 4th century B.C.E. philosopher Eubulides of Miletus, runs as follows: Suppose you have *N* grains of sand forming a heap; taking one grain of sand from the heap should not turn the heap into a non-heap, nor should removing a second grain of sand, and so on. Yet clearly, after removing *N*–1 grains of sand—leaving only one grain behind—there is no longer a heap of sand. Is there some point at which the removal of a single grain of sand turned our heap into a non-heap? The problem lurking behind this paradox is that the notion of a heap is *vague*: while there are clear cases of heaps and non-heaps, there are borderline cases in which it is unclear whether the predicate 'is a heap' can be applied. The problem is certainly not confined to heaps: similar sorites arguments can be applied to 'tall,' 'bald,' 'child,' and 'red'—just to list a few of the favorite examples. Once you recognize the problem of vagueness, it is hard not to

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see it everywhere. Most analyses argue that this vagueness is simply due to a problem with either our knowledge (there is a precise number of grains where it is no longer a heap, we just don't know where that boundary is) or with our language (we've just never settled on what exactly the word 'heap' means). *Ontic* vagueness, by contrast, is the claim that, in some instances, the source of vagueness is the world itself.[1]

More recently, the term 'metaphysical indeterminacy' has been used to include other sorts of ontic vagueness that do not necessarily arise in sorites-type reasoning. Some have thus reserved the term 'ontic vagueness' just for those cases that are sorites susceptible (e.g., Williams 2008). In what follows, however, I will use the terms ontic vagueness and metaphysical indeterminacy interchangeably, since, as we will see below, this distinction has not been adopted by most of those who have discussed our example of interest: quantum particles and their properties.

Before turning to quantum mechanics and asking whether or not it supports the view that there is genuine vagueness in the world, one must, first, try to clarify the general thesis of metaphysical indeterminacy, and, second, more concretely make sense of what it might mean to say that an object or property is vague. In response to the concern that the very notion ontic vagueness might be unintelligible, two new theories of metaphysical indeterminacy have recently been proposed. The first, due to Elisabeth Barnes and Robert Williams (2011; Barnes 2010; Williams 2008), uses the machinery of possible worlds, in which each possible world is a fully precise world representing different admissible ways that a vague term, such as 'tall' could be made precise. Barnes explains:

> Ontic indeterminacy with respect to *p*, in this sense, consists in there being at least two worlds (precisifications) such that one is a not-*p* world and the other is a *p* world, and it is indeterminate which is the actualized world. (Barnes 2010, 615)

There are two important things to note about this approach for our purposes here: First, this approach locates the indeterminacy at what can be described as a 'meta-level;' each possible world is fully precise (involving no vagueness or indeterminacy) and instead the indeterminacy comes in when we try to identify one of these possible worlds as the actual world. Second, as George Darby (2010) and Bradford Skow (2010) have independently argued, insofar as this approach assumes that it is possible to have a fully specified world in which there is no indeterminacy, it is incompatible with a central theorem of quantum mechanics, which denies the possibility of

[1] While one can recognize a certain unity to the problem of vagueness, it seems unlikely to me that there will be a single solution (e.g., epistemicist, supervaluationist, or ontic) to cover all these diverse cases. As I shall explain further below, I think the quantum case is somewhat unique in calling for an ontic solution, and that one should not expect the quantum case to necessarily shed light on the problem of vague baldness, for example.

assigning definite values to all the properties of a quantum system simultaneously (as will be discussed in detail below). Hence if our project is to see whether quantum mechanics gives us reason to believe that there can be genuine ontic vagueness in the (actual) world, this particular approach to defining metaphysical indeterminacy appears to be a dead end.

More recently, an alternative approach to characterizing metaphysical indeterminacy has been introduced by Jessica Wilson (2013, 361) that locates the indeterminacy at what can be thought of as the 'object level' rather than a 'meta level.' Wilson's approach makes use of the distinction between determinables and determinates, whereby metaphysical indeterminacy involves an object's having a determinable property without having a unique property that is the determinate of that determinable. So, for example, an object might have the determinable property of 'being colored,' without having a determinate of that determinable, such as 'being red.' More formally, Wilson defines metaphysical indeterminacy as follows:

> What it is for an SOA [state of affairs] to be MI [metaphysically indeterminate] in a given respect *R* at time *t* is for the SOA to constitutively involve an object (more generally, entity) *O* such that (i) *O* has a determinable property *P* at *t*, and (ii) for some level *L* of determination of *P*, *O* does not have a unique level-*L* determinate of *P* at *t*. (Wilson 2013, 366)

The notion of levels is included in recognition of the fact that determinables may be determined at different levels of specificity (e.g., being 'red' at one level of determination and being a particular shade of red 'scarlet' at another level of determination).

How can an entity possess a determinable property without possessing any of the determinates of that property? Wilson argues that there are two ways this can happen, and hence that metaphysical indeterminacy can obtain. First, there might be what she calls a multiple relativized determination, which she illustrates with the example of an iridescent feather that changes from red to blue depending on the angle of viewing. Although the feather possess the determinable property of 'being colored' it does not possess any unique determinate of that property at a given time. In my view, this buys metaphysical indeterminacy too cheaply. There is nothing indeterminate about the world in the feather case: the surface properties of the feather that determine which wavelengths are absorbed and reflected and the nature of the light leaving the feather in any given direction is completely determinate. All this case illustrates is that color is a much more complex relational property than we usually recognize: it depends not only on the nature of the incident light (e.g., as my son loves to point out, his scarlet jacket is no longer red when we go through a tunnel with orange sodium lights), the angle of viewing (as this iridescence example shows), and, we may add, the relative state of motion of the object and the viewer (objects that are receding from you will have colors shifted toward the red end of the spectrum, and objects approaching you will appear blue-shifted).[2] In most cases we don't need to specify all these conditions because their effects are negligible, but strictly speaking they are all a part of the property that we deceptively call all too simply 'color.' There is nothing indeterminate about the world in these cases, however—the relevant properties are perfectly fixed and predictable.[3]

I find Wilson's second approach to metaphysical indeterminacy more plausible: namely, there is metaphysical indeterminacy when there is an entity with a determinable property, but no determinate for that determinable. Following the color example, this would be a case in which an object had the determinable property of being colored, but did not possess any particular color (even relativized) as the determinate of that determinable. Wilson doesn't claim that there are such colored objects, but this example does illustrate how strange a genuine ontic indeterminacy would be. As a worldly example of metaphysical indeterminacy along this second route she suggests that an electron whose spin is in a superposition of spin-up and spin-down may (on some interpretations) qualify as an entity with an undetermined determinable, and hence provide a case of genuine metaphysical indeterminacy in the world. Exploring this question, of whether quantum mechanics provides us with a case of genuine metaphysical indeterminacy, is the subject of this paper.

2 Vague Objects vs. Vague Properties

Traditionally there have been three different conceptions of ontic vagueness in the literature: two involving vague objects and one involving vague properties.

The first and most common understanding of vague objects is that of objects whose spatial boundaries are "fuzzy." Classic examples of vague objects of this kind are clouds and mountains. The reasoning is as follows: There is no sharp boundary between where Mount Rainier ends and the surrounding land begins, hence there may simply be no fact of the matter about whether a particular pine tree is on the mountain or not. The claim is that this vagueness is not due to any failure of our knowledge about Mount Rainier, nor due to any semantic vagueness about what 'Mount Rainier'

[2] Indeed specifying the color of an object becomes even more complicated when we include phenomena such as fluorescence (whereby objects may under certain conditions emit light, not just reflect it, such as when one's gin and tonic glows blue when viewed under a UV light, due to the quinine in the tonic water), but again I would argue that there is nothing indeterminate about the world here.

[3] In Wilson's defense, she admits that one is not forced to understand this example in the way she recommends (2013, 369).

means. Rather it is the mountain itself which is vague.[4] On Wilson's analysis, Mount Rainier is said to have a determinable boundary property, but not a unique determinate of that boundary property (in the sense of having multiple determinations of the boundary, rather than none, as in the feather case).

This fuzzy-boundary view of ontic vagueness has been challenged on a number of accounts. Some have questioned whether these purported vague objects (e.g., mountains, clouds, ships) are really objects at all (e.g., van Inwagen 1988, 1990). Others have charged that what these examples provide us with is merely a *superficial* vagueness. Rosanna Keefe and Peter Smith (1996), for example, write:

> Suppose our world is constituted by fundamental particles and fundamental properties both of which are entirely determinate. . . . Suppose additionally that the totality of these base-level facts fixes everything else. We would still have reason, for everyday purposes, to pick out and talk about various large collections of atoms (e.g., clouds or mountains) whose boundaries are left fuzzy. . . . Arguably, on this picture, any apparent ontic vagueness of the fuzzy-boundaried mountains etc. is merely superficial. (Keefe and Smith 1996, 56)

I find this critique of the fuzzy boundary view cogent. For everyday purposes we pick out certain striking geological features that we call "Mount Rainier," and these everyday purposes do not require us to specify (conventionally) some precise boundary for where the mountain ends and the surrounding valley begins. The fact that Mount Rainier fails to have a precise boundary does not, however, mean that the mountain is ontically vague. The geography of the region is precise, as are the atoms that make up this geography. There is, in these types of cases, no genuine ontic vagueness. As Keefe and Smith note, in order to have *genuine* ontic vagueness, one needs to consider a contrasting picture of the world in which the vagueness goes "all the way down."[5] If this is right, as I think it is, then the question of ontic vagueness becomes largely an empirical matter that should be approached through our best current scientific theory of fundamental particles.

Many philosophers have taken indeterminate identity, rather than fuzzy boundaries, to be the defining characteristic of vague objects. On this second conception, there is ontic vagueness if there is an object A and an object B such that it is indeterminate whether or not A is identical to

[4] See, for example, Tye (1990). Similar examples can be constructed regarding fuzzy *temporal* boundaries, such as the well-known case of the ship of Theseus undergoing repairs, or J. A. Burgess's (1990) example concerning the question of when a fetus becomes a human being.

[5] A similar point regarding superficial vagueness is made by Rosen and Smith (2004, 196–197), who go on to offer a more detailed account of what would count as "vagueness all the way down."

B. This conception of ontic vagueness has been famously challenged by Gareth Evans (1978), who has argued that the very notion of indeterminate identity is incoherent or self-contradictory. It is in response to Gareth's argument that the topic of quantum theory was first introduced into the vagueness literature. Although the details of Evans's argument will not be considered here, his argument can be informally summarized as follows: Suppose that A is indeterminately identical with B. Then A has the property of "being indeterminately identical with B." It is false, however, that B has the property of "being indeterminately identical with B," in other words, B lacks this property. Therefore, by the principle of the nonidentity of discernibles, A and B are not identical, which contradicts the initial hypothesis.

E. J. Lowe (1994; 1997; 1998; 1999) and Steven French and Décio Krause (1995; 1996; 2003) have tried to undermine Evans's argument by claiming that quantum theory provides a clear counterexample of a vague object. More specifically, while Lowe uses quantum mechanics to establish the *coherence and intelligibility* of ontic vagueness, French and Krause have gone a step further and taken quantum mechanics to demonstrate the *existence* of vague objects. Their arguments will be examined in the following section.

The interpretation of ontic vagueness in terms of vague objects is at the heart of both the "fuzzy boundary" and "indeterminate identity" approaches discussed above. There is, however, a third way in which the thesis of ontic vagueness can be viewed, and that is in terms of vague *properties*. In their essay, Keefe and Smith note that "although discussion of linguistic vagueness has focused on the semantics of vague predicates, discussions of ontic vagueness have said little about *properties*, the worldly counterparts of predicates. The debate has very largely concentrated on the possibility of vague *objects*" (Keefe and Smith 1996, 50). Not only does the vague properties view deserve more attention, but as I shall argue, it is also the most relevant conception of ontic vagueness in the context of quantum theory.

Although Mark Sainsbury (1994) ultimately rejects the idea that there is vagueness in the world, he lays the groundwork for what an adequate theory of property vagueness might look like. He argues that in order for there to be a substantive thesis regarding vague properties, one must reject both the view that every simple predicate is a property and the view that there are no properties at all. Sainsbury suggests two criteria for picking out genuine properties: First, only those predicates which have an indispensable role in science stand for properties; and second, only those predicates which do not supervene on other predicates stand for genuine properties (Sainsbury 1994, 76–77).[6] This approach seems once again to suggest that whether or not there is ontic vagueness is an empirical question,

[6] See also Lewis (1983).

and a question that should be answered by looking at our fundamental physical theory. Using Sainsbury's criteria, it would seem that the sort of properties that should be examined for genuine ontic vagueness are the properties recognized by quantum theory (position, momentum, mass, charge, spin, etc.).

Although this approach delimits the properties that are under consideration for vagueness, it is not yet clear what it means to say that a property is genuinely vague. Gideon Rosen and Nicholas Smith (2004) introduce a helpful model for thinking about vague properties using the example of color. The question here is the following: What does it mean to say that an object possesses a genuinely vague color property? Their model consists of a three dimensional solid, such as a sphere, in which each point of the solid represents a particular distinct color, and various regions on the solid correspond to various hues, such as red or blue (188). The region of the sphere that corresponds to the property "blue," for example, is going to have fuzzy boundaries; that is, there is no precise line or surface such that a point on one side is definitely blue and a point on the other side is definitely green.

Rosen and Smith then ask us to consider two beads: B and B*. Let B be a uniformly turquoise-colored bead. Although it may be a borderline instance of blue, the bead is not genuinely indeterminate in color—its color corresponds to a specific point (perhaps labeled point #174) on the color sphere. They call such a color a "point property," and contrast this with "blue," which is a not a point property (recall "blue" is an extended region of the sphere). The other bead, however, B*, really is indeterminate in color. They explain, "It might be clearly blue, as opposed to red or green. But when it came to saying which shade of blue it was, the question would have no clear answer" (Rosen and Smith 2004, 188). B* would be neither definitely color #174, nor definitely not color #174. Their analysis of B* is essentially that of Wilson's (2013) determinable-based account of metaphysical indeterminacy, and indeed they make reference here to the determinable-determinates distinction as a way to make sense of this case (Rosen and Smith 2004, 188).

With their example of the two beads, B versus B*, Rosen and Smith are pointing to an important distinction. However, I think the way they choose to characterize that distinction is mistaken. The conclusion they draw is that there are some properties—so-called point properties—such that vague instances of these properties make the object which has that property into a vague object. They write, "Our paradigm for the indeterminate object is an object that possesses length, but no determinate length, or colour, but no determinate colour" (2004, 198). The reason I object to this characterization is that it collapses an important distinction between objects and their properties. Why should we believe that a single vague property—even if it is a "point property"—turns a determinate object into a vague object? It seems perfectly intelligible that an object could have one of its many properties be a vague property without itself being a vague object. Although the bead B* has a vague color, there are plenty of other properties of the bead, such as its shape, size, and texture, that are all perfectly determinate. Furthermore, it is also the case that the *identity* of B* is determinate: despite its vague color, there is no difficulty in saying, for example, that this bead is the same bead that used to be on my necklace. Only the color property of B* is vague, not the object itself.

In my view, a clearer and more accurate way of characterizing the difference between Rosen and Smith's B and B* is to say that while B* is a *genuine* instance of a vague property, B is not. The case of B can quite easily be handled by a non-ontic theory of vagueness, such as supervaluationism.[7] The problem in this case really does seem to involve merely some sort of semantic indecision about what we mean by "blue." It does not seem, however, that the supervaluationist can tell the same sort of story about B*. A genuinely vague property would be a strange animal indeed.

Rather than the view that a particular vague property makes a vague object, a more plausible characterization of vague objects is in terms of objects whose *identity* is indeterminate.[8] It is this latter characterization of vague objects that has, until now, been at the center of the debate over whether quantum mechanics supports an ontic theory of vagueness.

3 Quantum Theory and Ontic Vagueness: The Current Debate

Discussions of vagueness in quantum theory have predominantly focused on the following example introduced by Lowe: "A free electron *a* is captured by a certain atom to form a negative ion which, a short time later, reverts to a neutral state by releasing an electron *b*" (1994, 110). Lowe rightly goes on to note that "according to currently accepted quantum-mechanical principles there may simply be no objective fact of the matter as to whether or not *a* is identical with *b*" (110). The idea roughly is that when electron *a* is absorbed it becomes "entangled" with the other electrons in the atom, and as a result of this interaction, electron *a* loses its identity.[9] On the basis of this example Lowe concludes, "Standard quantum-theoretical treatments of certain types of particle-interaction suggest that we *can* intelligibly countenance ontically indeterminate identity statements, contrary to the widespread philosophical opinion that vagueness must reside in our

[7] Supervaluationism, recall, regards vagueness as a sort of "semantic indecision," a failure to be precise about the meanings of our words. Recognizing that there are several possible legitimate ways in which the meanings of our words (such as "heap" or "blue") can be made precise, the supervaluationist tries to take into consideration all possible precisifications of a word. See, for example, Lewis (1986, 244).

[8] It may be difficult to draw a sharp line between vague objects (á la indeterminate identity) and vague properties, since on some views an object's identity depends on its properties. Nonetheless I believe that such a distinction is fruitful and ought to be maintained.

[9] The notion of entanglement will be explained in detail in the following section.

linguistic representations rather than in the world" (110). There are four points worth briefly noting about this argument. First, the key feature of quantum theory that Lowe identifies as being responsible for this resultant indeterminate identity is entanglement. Second, insofar as entanglement is the relevant mechanism, Lowe's limitation of his argument to specifically electrons, rather than extending it to all quantum particles (such as protons, neutrons, or photons), is misguided.[10] Third, Lowe is concerned specifically with the indeterminate identity construal of ontic vagueness. Fourth and finally, Lowe's conclusion is not that quantum particles *are* vague objects, rather that quantum mechanics shows that indeterminate identity is *intelligible*.

French and Krause (1995; 1996; 2003) have taken Lowe's argument one step further, arguing that quantum particles are in fact vague objects. They begin by distinguishing two ways that quantum particles can be viewed: either as individuals or as nonindividuals. While the latter view has become the orthodoxy among many physicists and philosophers of physics, French and Krause argue that it is nonetheless perfectly consistent to view quantum particles as individuals (that is, it is a case of the metaphysics being underdetermined by the physics). In the context of their discussion of quantum particles as individuals, they rightly emphasize that one should not conflate the issue of distinguishability with the issue of individuality: just because there may be no means by which to distinguish one electron from another, for example, does not mean that those electrons are not individuals.

In their series of articles, French and Krause claim that no matter which view of quantum particles one adopts (individuals or nonindividuals), one is led to the conclusion that they are vague objects with indeterminate identity conditions.[11] They explain:

> If the two particles are regarded as individuals, then such vagueness is a result of the existence of non-supervenient relations, which effectively cast a 'veil' over the set of entities. If, on the other hand, it is insisted that individuality must be given up in this domain, then the particles are vague in an even more fundamental sense. . . . The source of this metaphysical vagueness in all cases is the 'entangled' states which quantum particles enter into. (French and Krause 2003, 116–117)

[10] This point has also been noted by French and Krause (1995, 20). Lowe has since explained that his motivation for restricting his argument to electrons is in response to those who—rightly or wrongly—claim that electrons are somehow better candidates for qualifying as individuals.

[11] French and Krause also go on to argue that these nonindividuals (lacking self identity) are nonetheless objects, and that they are best described using the technical apparatus of quasi-set theory, though this is not an issue that will be pursued here.

In the next section I will explain how it is that entangled states exhibit the "nonsupervenient relations" that French and Krause are referring to, though I will argue that they are mistaken in thinking that these nonsupervenient relations lead to a loss of identity. The key point for our discussion here, however, is that French and Krause, like Lowe, take entanglement to be the key feature of quantum theory responsible for the particles' indeterminate identity.

Lowe's example has been criticized by Harold Noonan (1995) and Katherine Hawley (1998), both of whom argue that it is incoherent to maintain ontic indeterminacy in the example he describes, and that, more generally, quantum theory fails to provide us with an intelligible case of ontically indeterminate identity statements. Noonan's criticisms are based—not on a closer examination of quantum theory or entanglement—but rather, on the following two challenges.[12] First, Noonan fails to see any difference between the quantum case and the more familiar examples of purported ontic vagueness. The challenge here is to show that there really is something distinctive about quantum theory when it comes to vagueness. Second, he argues that in order for the electron example to provide a refutation of Evans's argument,[13] Lowe needs to establish that the electron names '*a*' and '*b*' are precise designators. With regard to the first challenge, Lowe (1997) responds that the usual sorts of cases are not analogous to the quantum case because there is nothing in those cases that plays the role of entanglement. With regard to the second challenge Lowe admits in a later paper, "I am now contending that I misdescribed the example in supposing that '*b*' determinately designates a unique electron" (Lowe 1999, 329). He maintains, however, that this does not undermine his claim that this quantum case is a coherent example of ontic indeterminacy of identity. He writes, "[C]learly on this account '*b*' and 'the emitted electron' are vague designators: but this is not to make a concession in favour of the semantic account of vagueness in such cases, since the fact that these designators are necessarily vague has an ontic explanation" (329). This ontic explanation is once again the phenomenon of entanglement. According to Lowe entanglement not only undermines precise particle labels, but also leads to an irrevocable loss of identity: he writes, "what I think I ought now to acknowledge is that, once particles have become entangled, they can never thereafter become determinately distinct again" (328). While this "point of no return" view of entanglement is quite common, it is, as I shall argue in the next section, a misunderstanding.

More recently George Darby (2010) has raised the objection that for quantum mechanics to provide a counterexample to Evans-type arguments it must be shown that quantum particles involve vague identity, rather than just an *inapplicability* of the concept of identity. He illustrates this point

[12] Noonan offers a third challenge, namely, that one can construct an Evans-type argument using non-identity involving properties; however, this issue will not be pursued here.

[13] Evans's argument was summarized at the beginning of Section 2.

with the familiar analogy to electronic money: "[I]t seems odd to say that it is *unsettled* or *indeterminate* whether one electronic euro is identical to another; identity doesn't *apply* to electronic euros, and indeterminacy is not the same as *inapplicability*" (Darby 2010, 230; emphases original). More specifically he directs this objection to French and Krause's way of understanding quantum particles as non-individuals. He concludes that more work is needed to properly connect metaphysical indeterminacy with quantum theory.

The current debate over ontic vagueness and quantum theory seems to be largely at an impasse; while these defenders of quantum ontic vagueness all identify entanglement as the crucial feature, neither Lowe nor French and Krause offer a detailed analysis of what it is about entanglement that is supposed to entail an indeterminate identity for entangled particles. If this debate is to move forward, then, we must take a closer look at what is distinctive about quantum mechanics and come to a deeper understanding of the nature of entanglement. After examining more carefully the relevant features of quantum theory, I shall argue that, while Lowe, French, and Krause are right that quantum mechanics supports an ontic theory of vagueness, they are mistaken in thinking that it is the indeterminate *identity* construal that is supported.

4 Are Either Quantum Particles or Their Properties Vague?

Insofar as ontic vagueness is a claim about our world (as opposed to a claim about our knowledge or language) it is an empirical thesis that can be fruitfully explored by examining our best current fundamental physical theory: quantum mechanics. Vagueness in the quantum domain, if found, would be a vagueness that "goes all the way down," avoiding one of the primary criticisms of many current examples of ontic vagueness that seem to be merely vague descriptions of a fundamentally definite world.

There are several different features of quantum mechanics that offer prima facie evidence that there is genuine vagueness in the world. As was just seen in the previous section, however, discussions of quantum theory in the vagueness literature have focused almost exclusively on entanglement. Despite the view that this is the crucial quantum phenomenon, discussions of entanglement have been cursory and, as I shall argue, in certain respects misguided. In assessing the implications of quantum mechanics for ontic vagueness, not only is a deeper examination of entanglement required, but also a broader discussion of the other features of quantum theory that are relevant to this debate. In keeping with the current literature on this topic, I shall consider here only the *standard* interpretation of quantum mechanics (sometimes referred to as the 'orthodox' or 'Copenhagen' interpretation)[14] and *nonrelativistic* quantum mechanics.[15]

There are four features of standard nonrelativistic quantum theory that are particularly promising for defending an ontic theory of vagueness:

(1) Quantum statistics
(2) Lack of space-time trajectories for quantum particles
(3) Failure of value definiteness
(4) Entanglement

Although these four features are not entirely independent, they are conceptually distinct and important enough to examine in turn.

4.1 Quantum Statistics

Historically, quantum statistics have provided one of the primary motivations for the claim that quantum particles have an indeterminate identity, or that they should not be considered individuals at all. One of the founders of quantum theory, Erwin Schrödinger, writes:

> The elementary particle is not an individual; it cannot be identified, it lacks 'sameness.' . . . In technical language it is covered by saying that the particles 'obey' a newfangled statistics. . . . [T]he unsuspected epithet 'this' is not quite properly applicable to, say, an electron, except with caution, in a restricted sense, and sometimes not at all. (Schrödinger 1950, 197)[16]

There are two kinds of quantum statistics: Fermi-Dirac and Bose-Einstein, for the two general classes of particles: fermions and bosons respectively. Quantum particles can be taxonomized on the basis of their spin, which is one of their intrinsic (i.e., state independent) properties.[17] Particles with

[14] One might object that the standard interpretation of quantum mechanics is only an instrumentalist theory, and that it only makes sense to inquire into the metaphysical implications of a "realist" theory of quantum mechanics, such as Bohm's hidden-variable interpretation. I think this objection is a mistake: For any theory one can take either a realist or instrumentalist attitude towards it (e.g., Ptolemy's astronomy was once thought to be a realist theory, describing how the solar (or, rather, geo-) system really is, while others (such as Osiander and contemporary surveyors) take it instead to be only an instrumentalist theory, providing nothing but a means for calculation). In this paper I am taking a realist attitude towards the standard interpretation, and asking what the world would be like if this interpretation were true. Those who think that there can only be realist interpretations of theories such as Bohm's, conflate "realist" with "resembling classical mechanics" (see, for example, McMullin 1984).

[15] Although such a discussion is beyond the scope of this paper, the lessons drawn here will still hold—and perhaps even become more pressing—in the context of relativistic quantum field theory.

[16] This paper is reprinted in Castellani (1998); the page numbers refer to this 1998 anthology, which provides an excellent introduction for anyone who is interested in what implications physics has for our understanding of material objects, their identity and individuality.

[17] To clarify, whether a particle is, for example, spin-0, spin-1/2, or spin-1 is an intrinsic state independent property; being "spin-up" or "spin-down" along one of the three directions (x, y, z), however, is a dynamical degree of freedom—a state dependent property.

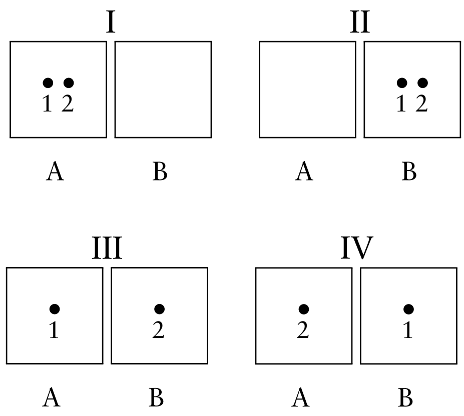

FIGURE 1. (Classical) Maxwell-Boltzmann Statistics

half-integer spin (such as electrons, protons, neutrons, and quarks) are known as fermions, and particles with integer spin (including zero spin) are known as bosons (such as photons, gluons, and helium-4 atoms).[18]

The differences between these two quantum statistics and classical statistics (the latter is also known as Maxwell-Boltzmann statistics) is often explained by means of the following simple example. Consider two particles labeled "1" and "2" and two boxes, labeled "A" and "B," which represent two states the particles can be in. Classically there are four ways these particles can be distributed over the two boxes as in Figure 1. Under the usual equiprobability assumption, we say that the likelihood of finding the particles in any one of these states is 1/4. If our particles are bosons, however, this method of counting yields the wrong results—results that are in conflict with well-confirmed experiments. According to Bose-Einstein statistics, there are only three ways to distribute the particles among the boxes as in Figure 2. It seems that for bosons, 1 in A and 2 in B versus 2 in A and 1 in B are not recognized as distinct states of affairs. Again with the equiprobability assumption, each of these three possibilities gets assigned a probability of 1/3. If our particles are fermions, the situation is even worse; there is only one way to distribute the particles among the boxes as in Figure 3. This is because, according to the Pauli exclusion principle, no two fermions can be in the same state (box). As with bosons, 1 in A and 2 in B versus 2 in A and 1 in B are not recognized as distinct states of affairs. It is this feature—shared by both bosons and fermions—that leads some

[18] Some quantum particles are made up out of other quantum particles. For example, protons and neutrons are composed of three quarks. If a particle is made up out of an odd number of fermions then it is itself a fermion; if, however, the particle is made up out of an even number of fermions then it is a boson, such as the helium-4 atom, which is made up out of two electrons, two protons, and two neutrons. This ability to combine fermions to make a boson provides another reason to doubt the too common claim that we should treat fermions and bosons differently when it comes to the issue of individuality.

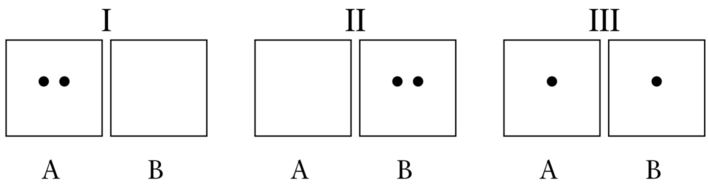

FIGURE 2. (Quantum) Bose-Einstein Statistics

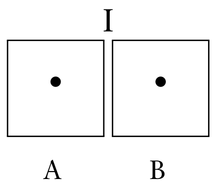

FIGURE 3. (Quantum) Fermi-Dirac Statistics

philosophers and physicists to conclude that quantum particles do not have a determinate identity or individuality.[19,20] Thus we have an example of a feature of quantum theory (namely, the fact that quantum particles are the sort of objects that obey quantum statistics)—apart from the phenomenon of entanglement—that challenges the view that quantum particles of the same kind have a determinate identity.

One might question, however, whether these quantum statistics really force one to deny that quantum particles are individuals with a determinate identity, such that if the particles trade boxes, the result is not a distinct state of affairs. A key assumption in the derivation of the quantum statistics is that each composite state for the two particles is equiprobable. If one abandons this assumption, one can, for example, recover the Bose-Einstein statistics for particles with a determinate identity by assigning to the four classical possibilities (given in Figure 1) the following probabilities: 1/3 probability each to configuration I and II, and a 1/6 probability each to situation III and IV. Since configurations III and IV are qualitatively identical (i.e., experimentally indistinguishable) one can simply add these two probabilities to recover the experimentally observed quantum statistics.[21]

[19] For a more technical discussion of this issue, making use of the quantum formalism, see, for example, Redhead and Teller (1991, 1992). For a response to Redhead and Teller's conclusion that quantum particles are not individuals see Huggett (1997).

[20] Darby (2014, 93) also discusses the relevance of quantum statistics to ontic vagueness, arguing once again against French and Krause's view that the meaninglessness of the identity of the particles is not the same as exhibiting a case of "ontic unsettledness."

[21] Reichenbach (1956) notes that one implication of this strategy for maintaining the identity of quantum particles is that the two particles are no longer causally independent: For example, if one boson ends up in state A, there is a higher probability that the other boson will also end up in state A—no matter how far apart the two particles are. Reichenbach, who was writing

J. Tersoff and D. Bayer (1983) have shown that this strategy can be generalized and made mathematically rigorous.[22] This result suggests that quantum statistics alone do not force us to adopt the view that quantum particles lack a determinate identity

4.2 Lack of Space-Time Trajectories

A second feature of quantum theory that might be invoked to support the indeterminate identity construal of ontic vagueness is the fact that quantum particles do not follow definite space-time trajectories. Quantum particles of the same "species" (e.g., electrons) share all the same intrinsic properties—they are qualitatively indistinguishable.[23] French (1989), for example, has argued that this fact undermines a strong reading of the principle of the identity of indiscernibles.[24] It is worth noting, however, that this is also the case for *classical* particles. An important difference that arises between the classical and quantum cases is that classical particles can be distinguished by means of their space-time location or trajectory, while quantum particles typically cannot. French (1989) has used this to argue that even a *weak* reading of the principle of the identity of indiscernibles fails for quantum particles.[25] Suppose we detect an electron at time t_1, at point A, and at some later time, t_2, we detect an electron at point B. One might ask whether the electron detected at B is the same electron that was at A. One classical way of answering this question, namely by determining if the electron followed a continuous path from A to B, is not available to us in the quantum case. The lack of trajectories in quantum mechanics can be seen as a consequence of the fact that such a trajectory would precisely specify both the position and momentum of the particle. According to Heisenberg's uncertainty principle, which specifies a necessary tradeoff between the precision of a particle's position and its momentum, however, this is impossible.[26] One might then argue that without such a differentiating property, quantum particles are left with an indeterminate identity.

almost a decade before Bell's landmark work on quantum nonlocality (Bell 1964), took this feature to be a sufficient reason for rejecting this approach.

[22] Rather than the equiprobability assumption, they consider a uniform random distribution of probability weightings—an assumption they take to be weaker, and hence arguably more "natural."

[23] Physicists typically refer to them as "identical" particles, though they are more properly described as "indistinguishable" particles.

[24] The strong version of the principle of the identity of indiscernibles (PII) considers only intrinsic properties. Weaker versions of the PII include use of spatial and/or relational properties.

[25] It is important to note that these indistinguishable particles always remain *numerically distinct* in nonrelativistic quantum mechanics.

[26] Mathematically Heisenberg's uncertainty principle is stated as $\triangle x \triangle p \geq i\hbar$. I will not enter here into the subtleties concerning the question of whether the uncertainty relations can be applied to individual particles or whether they apply only to ensembles of particles.

One must always be cautious, however, in drawing strong metaphysical conclusions from these sort of features of quantum physics. Just because we have lost a way to identify or individuate particles does not imply that the particle in question is no longer an individual, nor that it lacks a determinate identity. Such an inference would require substantially more than is offered by the experimentally well-confirmed results of quantum theory.[27]

Both of the features of quantum theory discussed thus far (quantum statistics and a lack of space-time trajectories) were seen to pose a prima facie threat to the determinate identity of quantum particles, and hence, potentially to offer support for the indeterminate identity construal of ontic vagueness. If one's aim is simply to establish the coherence of the idea of vague identity, then these features of quantum theory are a good place to start. If, however, one wants to make the stronger claim that these two features of quantum theory demonstrate that quantum particles are in fact vague objects, then, as we have seen, this inference fails. The third and fourth features of quantum theory (failure of value definiteness and the phenomenon of entanglement), I argue, are relevant, not to the indeterminate identity construal of vagueness, but rather, to the *vague property* construal.

4.3 Failure of Value Definiteness

In quantum theory, the kinds of properties or property types (such as color) are referred to as observables and the various ways these properties can be (e.g., blue) are called the values.[28,29] Value definiteness is the classical intuition that no matter what state a particle is in, all of its observables (e.g., position, momentum, spin along the x-direction) have precise values at all times.[30] The quantum mechanical principle that replaces value definiteness

[27] A consideration of David Bohm's empirically equivalent hidden-variable interpretation of quantum theory, for example, reveals that neither the formalism nor the empirical content of quantum theory forces one to reject the view that quantum particles follow definite space-time trajectories at all times. The situation one is confronted with in quantum mechanics is an underdetermination of the physical theory (or interpretation) by the empirical evidence. For an introduction to Bohm's theory and a discussion of these issues see Cushing (1994). Regrettably, a discussion of the many various alternative interpretations of quantum theory and their implications for ontic vagueness is outside the scope of this paper, though it is an important project that should be carried out.

[28] Somewhat more technically, observables (e.g., spin in the x-direction) are represented by mathematical objects called operators (e.g., the Pauli spin-x operator); these operators have eigenvalues (e.g., +1/2 or −1/2), which represent the possible values for the observable (e.g., spin-up or spin-down).

[29] As Antigone Nounou (2012; Anastopoulos and Nounou 2014) has argued, there remains substantive metaphysical work to be done in sorting out the nature of properties in quantum theory.

[30] Value definiteness is also sometimes referred to as the "Precise Value Principle." A more thorough discussion of this principle can be found in Hughes (1989, Ch. 6).

(on the standard interpretation) is that a quantum system can be ascribed a *definite* value for a particular property only if the state of that system is in what is known as an "eigenstate" of the operator associated with that property. This is known as the "eigenstate-eigenvalue link."[31] It is also the case, according to quantum theory, that not all properties are compatible, in the sense that they can be ascribed definite (precise) values at the same time.[32] The best known example of incompatible properties involves position and momentum, which according to Heisenberg's uncertainty principle cannot be assigned precise values at the same time.[33] Another way of putting this (in light of the eigenstate-eigenvalue link) is that there is no state that is both an eigenstate of the position operator and an eigenstate of the momentum operator.[34] This means that a particle cannot have a *definite* position and a *definite* momentum at the same time.

Consider the following simplified example. Imagine a world in which there are only two positions, x_1 and x_2, and two momenta, p_1 and p_2. Suppose the particle has a definite momentum—p_1. In this case we can say that it definitely does *not* have momentum p_2. Is there anything we can say about the particle's position? Instead of saying that it is definitely not at x_1 and definitely not x_2, quantum theory tells us that it is *indeterminate* whether it is at x_1 or x_2.[35] One might be tempted to interpret this indeterminacy epistemically, and claim that it is simply due to our ignorance; that is, the particle really is at x_1 or x_2—we just do not know which. It turns out, however, that there is a powerful mathematical theorem—the Kochen-Specker theorem—that rules this naive epistemic interpretation out.[36]

[31] Alternative interpretations of quantum theory deny this eigenstate-eigenvalue link. One of the motivations for these alternative interpretations is to avoid the indeterminate properties of the standard interpretation. Bohm's interpretation, for example, does this by privileging the property of position.

[32] One can determine which kinds of properties are compatible (i.e., can simultaneously be ascribed definite values) by seeing whether the operators associated with these properties commute: if they commute then they are compatible; if they don't commute then they are not compatible. Two operators, A and B, commute if $AB-BA = 0$; they don't commute if $AB-BA \neq 0$. This noncommutative structure is one of the key features of quantum mechanics that makes it fundamentally different from classical mechanics.

[33] Position, X, and momentum, P, do not commute: $XP-PX = i\hbar$.

[34] Strictly speaking, position and momentum (insofar as they are continuous physical quantities) do not have eigenstates. This has led some, such as Paul Teller (1979) to argue that one cannot represent a particle in QM as having a perfectly precise (sharp) position; for an alternative view, however, see Halvorson (2001).

[35] Two brief points should be emphasized here. First, "indeterminate"(or "indeterminacy") here should not be confused with "indeterminism." I take the latter (like determinism) to be a dynamical notion about how states change over time. In calling a property indeterminate, I mean that it is indefinite. Second, despite the inability to ascribe a position to the particle, the *existence* of the particle is never in question.

[36] Applying the Kochen-Specker theorem to continuous quantities (such as position and momentum) rather than just discrete quantities (such as spin directions) is a bit tricky, but can be done (Clifton 2000). Once again, the possibility of alternative interpretations of quantum

Very briefly, one can intuitively understand the Kochen-Specker theorem as follows. Consider the quantum property known as spin: one can measure the spin of a quantum particle, such as a photon (which is a spin-1 particle and so a boson), in three orthogonal directions: S_x, S_y, S_z. When we measure the square of the spin component in each of these three directions, quantum mechanics requires that one of these directions gets the value 0, while the other two directions get the value 1 (because we know $S_x^2 + S_y^2 + S_z^2 = 2$). The Kochen-Specker theorem then shows that there is no consistent way to assign zeros and ones to all the possible spin directions, such that this constraint is satisfied; we run into the contradiction that one and the same spin direction needs to be assigned two incompatible values.[37] In other words, there is no consistent way to ascribe definite values to all the properties of a quantum system—it is not just a problem of our ignorance of what those values are. Using Wilson's (2013) determinable-based account, we would say that although the photon has the determinable property of spin, and even a determinate of that determinable at one level, namely, being a spin-1 particle (rather than spin-1/2, for example), at a further level of determination, it fails to have a definite value for the projection of that spin in a given spatial direction, that is, it fails to be spin-up (+1) or spin-down (−1) in some x-direction.[38] Thus it seems we have in (standard) quantum theory a genuine case of an *ontic* indeterminacy or indefiniteness of properties.[39]

mechanics complicates the story. Theories such as Bohm's are able to recover something like an epistemic interpretation of the uncertainty relations by paying the price of making those properties *contextual* and robustly nonlocal. For a nontechnical introduction to Bell's theorem and nonlocality see Bell (1981). An accessible introduction to the Kochen-Specker theorem can be found in Held (2003). It should be emphasized, however, that these two theorems apply to *any* interpretation of quantum theory.

[37] So, for example, if we measure S_x^2 with S_y^2 and S_z^2, then it needs to be 0, but if we measure S_x^2 with two other (primed) directions $S_{y'}^2$ and $S_{z'}^2$, then it needs to be assigned the value 1. Hence, we cannot assume it has a definite value prior to measurement—it is indeterminate whether it is 0 or 1. One of the assumptions of the K-S theorem is that S_x^2 should have the same value irrespective of whether it is measured with S_y^2 and S_z^2 or with the primed directions $S_{y'}^2$ and $S_{z'}^2$. This assumption is known as non-contextuality.

[38] This will occur when it does have a definite value for the spin projection in another direction, such as the y-direction or z-direction. One might object that the *projection* of the spin in some direction should not be counted as a property in the same sense as the spin itself (a loose analogy might be thinking of "the projection of the length of an object in the x-direction"); I thank Antigone Nounou for raising this challenge. On the other hand, one might just think of the projection of the spin as a further level of determination of the spin property, in accordance with Wilson's multiple levels: for example, the photon would have the determinable property of spin, with the determinate of being spin-1 at one level, and at a further level of determination have spin +1 (up) in the x-direction. One potential complication of this approach is that while being a spin-1 particle is a state-*independent* property, being spin +/−1 (up or down) in the x-(or y or z) direction is a dynamical state-*dependent* property. For these reasons, position and momentum might be better examples of vague properties than spin projections.

[39] Instead of the epistemic and ontic interpretations, one might try to adopt a "gag rule" interpretation according to which, if our particle has a definite momentum, one cannot say

Returning to the more familiar example discussed above of a particle with a definite momentum, we can say that in such cases its position is a vague property. This association of quantum property indefiniteness with ontic property vagueness becomes even clearer when considering cases such as the following: In quantum theory, it is more typically the case that the degree to which the particle's momentum is specified allows us to say, for example, that the particle is located *somewhere in this room*, although it is not possible to say that it is located at any particular point in the room. In other words, while it makes sense to talk about the particle having the property of position (that is, to say that the particle is in the room) that property cannot be ascribed a definite (precise) value.[40] On the determinable-based account of metaphysical indeterminacy, the position of the particle in the example described is a vague property: while the particle possesses the determinable property of position, it does not possess a determinate value for that determinable. Such a situation is analogous to the example of the bead B* (discussed at the end of Section 2), which, while clearly blue, could not be said to be any particular shade of blue.

When discussing quantum mechanics, it is particularly important to distinguish between saying that the *position is vague* or *indefinite* and saying that the *position is fuzzy*. While quantum mechanics supports the former claim, it is incompatible with the latter. In our two-position-universe example, it would be a mistake to think of the particle as being smeared out over x_1 and x_2, in the sense that we would expect to find some evidence or piece of the particle at each location. Despite Schrödinger's attempts to offer such an interpretation in the early days of quantum theory, this view was ultimately shown to be untenable.[41] Thus, by vague properties I mean properties that are indeterminately possessed, not properties that are fuzzy.

4.4 Entanglement

The fourth feature of quantum theory that one might appeal to in defending an ontic theory of vagueness—and the one that has been at the heart of the debate—is entanglement. As discussed in Section 3, entanglement is typically interpreted as supporting the indeterminate identity construal of vagueness. I want to argue here, however, that this interpretation is mistaken. Instead, I shall argue that—like the failure of value definiteness discussed above—entanglement is more properly construed as offering support for vague properties.

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anything at all about its position. Many physicists have believed themselves to be following Niels Bohr in saying that the very concept of momentum simply does not apply in these situations. The reasons why I think this is mistaken and that it still makes sense to ascribe the determinable property of position even without a precise determinate of that position, are given below.

[40] It is important to note that the Heisenberg uncertainty principle does *not* rule out having an *indefinite* position and an *indefinite* momentum at the same time.

[41] See Teller (1979, 357) for a discussion.

To say that two particles are entangled is to say that there is a nonclassical correlation between their properties. While traditionally entanglement was interpreted as a "spooky action-at-a-distance" or "mysterious holism," recent developments in physics have gone a long way toward developing a more robust metaphysics of entanglement. The temptation to interpret entangled particles as having an indeterminate identity comes from two sources: first, the way that entangled states are mathematically represented, and second, the fact that the composite system exhibits properties that do not seem to be analyzable in terms of the properties possessed by the individual components.

Consider two particles, A and B. If the particles are in a so-called "pure state," then each particle can be represented by a wavefunction: ψ_A and ψ_B. Instead of representing the state of each particle individually, one can also represent the composite two-particle system by another wavefunction, Ψ_{AB}. If the two particles are *unentangled*, then the composite state is just the cross product of the states of the components: $\Psi_{AB} = \psi_A \otimes \psi_B$; the state is then said to be factorizable. If the particles are entangled, however, then the state of the composite system *cannot* be written as the cross product of a definite state for A and a definite state for B. In fact, this is how an entangled state is defined: a pure state is entangled if and only if it cannot be factorized: $\Psi_{AB} \neq \psi_A \otimes \psi_B$. It seems that for entangled particles, the individual particles no longer have a definite state, only the whole composite system does. It is understandable how this limitation on the mathematical representation of the state might lead someone to believe that the individual particles have now lost their identity.

There are a number of reasons, however, why this "loss of determinate identity" interpretation of entanglement—though very common—is mistaken. First, although one typically speaks of *particles* being entangled, a more accurate characterization would be to say that certain *properties* of the particles (namely some subset of those properties that are "degrees of freedom") are entangled. For example, the statement "The two electrons are entangled," is really just shorthand for "The momenta (or positions or spins or energies, etc.) of the two electrons are entangled." This is made even clearer by the fact that one can just as well entangle two (or more) properties of a *single* particle (such as entangling a particle's position with its spin). In doing so, the identity of that one particle has in no way been compromised. In the case of multiple particles, typically only one or two properties of the particles will be entangled.[42] Even in the case where all the degrees of freedom are entangled (a so-called hyper-entangled state), there will still remain other properties of the particles (such as mass and charge) that are not—and can never be—entangled.

Consider again two particles A and B. Suppose that these two particles have become entangled in the spin degree of freedom. This means that

[42] It was only recently—and with much difficulty—that particles simultaneously entangled in several properties were created in the lab (see Kwiat 1997 for a discussion).

neither A nor B can be assigned a definite spin—in this situation spin is a vague property. What makes entanglement different from the failure of value definiteness discussed in Section 4.3, is that these vague properties now also exhibit (nonlocal) correlations.[43] It is important to recognize, however, that there are other properties of A and B, such as their masses, charges, and positions, for example, that remain definite and distinct throughout.[44] This is analogous to the bead B*, which despite its vague color, has other definite properties (such as the shape, size, and texture of the bead) and an identity which is clearly determinate. Likewise, in the present case of two particles with entangled spin, we have no reason to believe that they have lost their determinate identity, despite the fact that their spins are now vague. While this fact can be obscured by the usual way of mathematically representing an entangled pair, (i.e., by a single composite wavefunction, Ψ_{AB}) there are other ways of mathematically representing the state of the particles that makes their continued determinate identity more evident.[45]

A second reason why one should be suspicious of the view that entanglement means a loss of identity comes from the fact that it is not just indistinguishable particles (particles of the same kind) that can become entangled: one can just as well entangle *distinguishable* particles, such as an electron and a proton. The fact that these particles are entangled does not mean that the electron ceases to be an electron nor that the proton ceases to be a proton. This entanglement will in no way diminish their distinguishability or identity. What it will diminish is the ability to ascribe a definite value of the entangled property to either of the particles individually.

This brings us to the other source of temptation (mentioned above) to view entangled particles as particles with an indeterminate identity: entangled particles can collectively exhibit properties that are not analyzable in terms of the properties possessed by the individual particles. This is the "nonsupervenient relations" referred to in the quotation from French and Krause given in Section 3. This feature of entangled states can be brought out by the following example. Suppose an electron and a proton

[43] By nonlocal correlations I mean something like the following: the spins of A and B might be correlated such that if one is measured to be "spin up" then the other instantly becomes "spin down"—no matter how far apart the two particles are. On the standard interpretation, a vague property can become a determinately possessed property upon measurement. Because these nonlocal correlations cannot be used to send a signal, they are taken to be compatible with special relativity.

[44] Over a long enough time-scale some dispersion will enter into the particle's position; this phenomenon, however, is completely independent of entanglement.

[45] Instead of representing the state of system by a wavefunction, $|\Psi_{AB}>$, one can always represent it instead by a density matrix, ρ_{AB}. For this example of particles with definite positions and entangled only in spin, one can reveal the determinate states of the particles with regard to the other properties by "tracing" out the spin degree of freedom (for both particles) to reveal a new factorizable state: $Tr_{spin}\rho_{AB} = \rho'_A \otimes \rho'_B$. The primes indicate that it is no longer a complete description of the all of the properties (vague or definite) of the particles (i.e., we have neglected the spin). This factorizable state can equivalently be written $\psi'_A \otimes \psi'_B$.

become entangled in the position degree of freedom. It may be possible to ascribe to the two-particle system a definite *difference* of positions (x_A–x_B), without being able to ascribe a definite position to either particle individually. For example, the particles might definitely be ten meters apart, even though neither particle by itself has a definite position.[46] In cases such as this, it makes sense to ascribe to the particles the determinable property of position, even though there is not a precise determinate of that determinable. Once again, it is important to remember that according to quantum mechanics, this fact cannot be attributed to a failure of our knowledge (i.e., it is *inconsistent* on the standard interpretation to say that the individual particles really do each have definite positions, and that we are just ignorant of what those positions are). While this situation is certainly surprising, and perhaps relevant for discussions of holism and nonsupervenient properties, it does nothing to impugn the identity of the individual particles; it only undermines our ability to ascribe definite values to certain properties.

A third challenge to the indeterminate identity interpretation of entanglement comes from recent work in quantum information theory, which has come to view entanglement not as a mysterious holism, but rather as a physical resource (analogous to energy) that can be measured, redistributed, and used to perform work. An important part of this shift in our understanding of entanglement is the recognition that entanglement is not an "all or nothing" affair. Even if we confine ourselves to a *single* property, there are various *degrees* to which two or more particles can be entangled in that one property, ranging from "maximally entangled" to "not entangled at all." Much of the recent work on the foundations of quantum information has been focused on trying to produce an appropriate measure of the amount, or degree, of entanglement for a state. It has also come to be realized that entanglement is not an irreversible "point of no return" for particles; one can experimentally manipulate the degree of entanglement, making the particles more or less entangled. For example, Bennett et al. (1996) have shown that one can take a large number of electrons that are all partly (that is, "a little bit") entangled with each other, and concentrate that entanglement into a smaller number of maximally entangled electrons, leaving the other electrons unentangled. This process is known as *entanglement distillation*.[47] Conversely, one can take a pair of maximally entangled electrons and spread that entanglement out over a

[46] To use the terminology introduced earlier, this situation will occur when the state of the composite system is an eigenstate of the (X_A–X_B) operator, but not an eigenstate of either the X_A or X_B operators. Cases such as this show why the "gag rule" interpretation (footnote 39) is not adequate: even though particle A is not in an eigenstate of the position operator, we can still say something meaningful about that particle's position, namely that it is 10 meters away from particle B.

[47] It is also sometimes referred to as "entanglement concentration" or "entanglement purification."

larger number of electrons (so that they are now only partly entangled) in such a way that the total entanglement is conserved. This process is known as *entanglement dilution*.

The fact that entanglement comes in degrees provides one of the strongest challenges to Lowe's and French and Kraus's arguments that entanglement renders the identity of the particles indeterminate, or, in other words, that entanglement makes quantum particles into vague objects. Identity does not admit of degrees: two entities are either identical or they are not—it does not make sense to say that they are more or less identical.[48] As we have just seen, however, entanglement does admit of degrees—two particles can be more or less entangled. This suggests once again that identity is not the right way in which to cash out the metaphysical import of entanglement.

The phenomenon of entanglement does, however, fit quite naturally with the vague property construal of ontic vagueness: both are concerned with the definiteness of certain properties and both admit of degrees. Just as two electrons (or rather, certain properties of those electrons) can be more or less entangled, so too can one make sense of the claim that a particular property is more or less vague (e.g., an object's color is definite enough to be called "blue" but not definite enough to be a particular shade of blue). Using again Wilson's terminology, although it makes sense to ascribe a determinable property to the quantum particle, there is some level L at which it fails to have a precise determinate of that determinable. In sum, these considerations show that the quantum phenomenon of entanglement is best understood as supporting the vague property—not indeterminate identity—construal of ontic vagueness.

Both the quantum phenomenon of entanglement, and the failure of value definiteness more generally, give us a model for what genuinely vague properties in the world would look like. The failure of value definiteness, recall, means that all of the dynamical properties of a quantum particle cannot have precise values at the same time—the precision of some properties comes at the price of the vagueness of others. This inability to ascribe definite values to properties also occurs in the context entanglement: namely, those properties that are entangled also no longer have precise values. In both of these cases, the inability to ascribe precise values cannot be attributed to a failure of our knowledge about those properties, nor to any semantic indecision about what it means to say, for example, that a particle has the property of position or momentum. The vagueness of these properties is genuinely ontological.[49]

[48] Even if we grant that identity can be indeterminate, this is quite different from saying that identity comes in degrees. To say that identity comes in degrees is a much stronger claim, implying that identity can be quantified in some sense, and it does not simply follow from the claim that it is indeterminate whether A is identical to B.

[49] Of course, in tying the argument for vague properties to a specific interpretation of an empirical theory, our reasons for believing in genuine ontic vagueness in the world are only

5 Conclusion

On the approach I have adopted here, whether there is genuine ontic vagueness in the world is an empirical question that can be fruitfully explored by examining our fundamental scientific theories. Answering the question of whether quantum mechanics supports an ontic theory of vagueness is complicated by the fact that there are (at least) three different ways that the thesis of ontic vagueness can be construed and (at least) four different features of quantum theory that one might appeal to. By way of conclusion let me summarize the key points that I have made in trying to answer to this question.

In discussing ontic vagueness I argued that it is important to distinguish between vague objects and vague properties, and further, that it is a mistake, pace Rosen and Smith (2004), to conclude that if one property—even a "point property"—is vague, then the object itself is vague. Two possible definitions of vague objects were considered: fuzzy boundary and indeterminate identity. As discussed Section 2, the fuzzy boundary view of vague objects seems to be, at best, a superficial ontic vagueness, and, at worst, not a genuine ontic vagueness at all. The more plausible definition of a (genuinely) vague object is an object whose identity is indeterminate. In Section 3 we saw that it was this definition of vague objects that has been the focus of the debate regarding quantum mechanics and ontic vagueness.

In defending ontic vagueness, Lowe (1994; 1997; 1998; 1999) and French and Krause (1995; 1996; 2003) have used the quantum phenomenon of entanglement to argue that quantum particles have an indeterminate identity. In response to these claims, I argued that the mere fact that two (or more) particles are entangled is not a sufficient reason for saying that their identity is indeterminate. I offered three arguments for why we should not think that entanglement is about identity at all: First, strictly speaking, properties—not particles—are entangled, and the result of this entanglement is that those properties become indefinite. Second, one can just as well entangle distinguishable particles (e.g., an electron and a proton) as particles of the same kind (e.g., two electrons), and doing so in no way undermines the identity of those particles. And third, entanglement—unlike identity—comes in degrees. My claim is not that quantum particles have a determinate identity, only that entanglement *per se* gives us no reason to doubt that they do. Thus, if entanglement is to support an ontic theory of vagueness, one should not look to the indeterminate identity construal.

However, in disagreeing with Lowe, French, and Krause about the proper way to interpret entanglement, I am not siding with their opponents. *Pace* Hawley (1998) it *is* coherent to maintain indeterminate identity in the example Lowe describes, though not for the reason Lowe gives. As I showed in Section 4.1, the best argument for indeterminate identity comes

as good as our reasons for believing that quantum theory, as standardly interpreted, is an accurate description of the world.

from the fact that quantum particles are the sort of objects that obey quantum statistics. Furthermore, *pace* Noonan (1995), I *do* take there to be important differences between the usual sorts of purported examples of ontic vagueness and those examples derived from quantum theory. The features of quantum theory that make it distinctive were spelled out in some detail in Section 4. In sum I take the indeterminate identity view of vague objects to be coherent (though not necessarily true), and I do think that quantum mechanics gives us good reasons to believe in ontic vagueness (when it is properly construed).

Finally, I offered another way in which quantum mechanics can be said to support an ontic theory of vagueness. Unlike most previous work on vagueness and quantum theory, this approach focuses on vague properties rather than vague objects, where a vague property is understood within Wilson's (2013) framework as a determinable property without a precise determinate of that determinable. More specifically, I showed that, on the standard interpretation of quantum mechanics, the failure of value definiteness and the phenomenon of entanglement are best interpreted as supporting the view that, in certain situations, quantum properties are vague properties. Although this analysis, insofar as it considers only one possible interpretation of quantum mechanics, does not establish the existence of vague properties in the world, it does show that such metaphysical indeterminacy is both coherent and a possible (i.e., empirically adequate) description of our world.

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