THE NATURE OF SPACE IN THE QUANTUM WAVE-FUNCTION

A Polymathic Thesis in *Philosophy of Physics*

Abstract

The quantum wave-function is at the heart of quantum mechanics. It is the physical state of a quantum system before a measurement is taken. This wave-function is described mathematically by the formulation of matrix mechanics and represents the evolution of the quantum wave-function. In contemporary philosophy of physics, the wave-function's nature of space is hotly debated. Contemporaries such as David Albert, who posits an ontology which is based off the mathematical features of the wave-function, claim that the dimensionality of our physical space is proportional to 3N, where N is equal to the number of particles in the universe. Others such as Bradley Monton claim quantum mechanics to be a false theory from the outset due to its incompatibility with general relativity and posit a much more realist property-based-physics ontology. However, these ontologies have their problems. Albert's ontology takes the mathematics of the quantum wave-function at face value and disregards the distance properties of metric space to misconstrue the phase space nature of the 3N configuration space as a metric space. Monton, on the other hand, questionably grounds his thesis on the incompatibility of quantum mechanics with general relativity and on *common sense* rather than on observation and experimentation, as required by the scientific method. In this thesis, I discuss the viewpoints of Albert and Monton in detail and explore the nature of space in the quantum wave-function in an attempt to reach a better understanding of the fundamental nature of space in the quantum wave-function.

Introduction

The wave-function is at the heart of Quantum Mechanics. It is what Schrodinger's equation takes to describe the evolution of a quantum system (Griffiths 430). The wave-function is also meant to be the state of a quantum system before a measurement is made (the system is said to be in a superposition of quantum states). Is the wave-function real or is it merely an ontological tool used to represent a quantum system before a measurement is made? Is the wave-function a real physical entity—a probability field analogous to an electric field? What does quantum theory have to say about the nature of space, if anything?

Such questions are of interest to philosophers of physics who deal with the foundational issues of quantum theory. However, there is still much that is not understood about the nature of the wave-function. It can be represented by mathematical equations such as the Schrodinger equation but the ontological status, is still far from settled, as I will show in this paper (Allori 61). Furthermore, philosophers such as David Albert and Bradley Monton have their own viewpoints when it comes to the existence of the wave-function in our typical 3-dimensional space and the 3N dimensional configuration space in which the wave-function evolves.

Albert, a prominent philosopher of physics from Columbia University, argues for wave-function realism by positing that the space we live in is constituted by the 3N-configuration space in which the wave-function evolves (French 77). He concludes that our impression of living in a 3-dimensional world is "flatly illusory" (French 77). However, he moves too quickly, taking the mathematics at face value and developing an ontology of the wave-function and our reality that ignores some crucial facts. The very supposition of 3-

dimensional space was essential for developing the physics used to come up with quantum theory. Quantum theory presupposes, or at least appears to presuppose, 3-dimensional space in its experiments in order to produce meaningful results. For example, measurement results are typically pointer readings. But what is a pointer reading without a space in which the pointer is to be read? Another example is that in the two-slit and many other experiments, photographic specks from electrons are distinguished by their spatial locations on the photograph. More generally, the very background of measurement with respect to which quantum theory is tested and refined has, up to now, taken for granted that there is a 3-dimensional (or four, if Minkowski space is employed) metric space of possible positions of events produced by measurement procedures. From these results, mathematical models and equations are formulated to represent the physical phenomena. The logic here is that if our experiments are assumed to occur in 3-dimensional space and our mathematical formulation appeals to 3-dimensional space in order to represent the space of possible measurement results, then non-primitive variables (mathematical features) of the ontology in quantum theory such as configuration space should not be taken at face value and used to make ontological claims as Albert makes that disregard such presuppositions of measurement. In other words, one must be more careful when asserting claims such as that the nature of space is *illusory*. The mathematics is a representation of the physical phenomena that comes after the experiments are performed. Thus, I disagree with Albert's claim that we live in a 3N-dimensional configuration space and that the 3-dimensional world we live in is *illusory*. Furthermore, the mathematical structure of quantum theory is related in complex ways to the experimental data. It is arrived at through complex chains of reasoning and sometimes conventional choices of practical and mathematical utility, for example, and so we ought to be careful in simply reading it as a straightforward report of the ontological structure of reality, or even of measurement results. In short, the precise nature or structure of the mathematical model selected for use by theorists can be the result of many factors besides straightforwardly modeling all and only ontologically or physically real aspects of quantum systems.

The other side of the debate about the nature of the wave-function and its implications about real physical space is held by Bradley Monton, another prominent philosopher of physics who is at University of Colorado-Boulder. He argues against the 3N-configuration space as the space all objects live in. Monton argues against Albert with a questionable claim that "our everyday commonsense constant experience is such that we're living in 3 spatial dimensions, and nothing from our experience provides powerful reason to give up that *prima facie* obvious epistemic starting point" (Monton 154). Monton begins his rebuttal against Albert by appealing to commonsense, a reference that has historically been repeatedly falsified. Obviously, physics does not and has not always conformed to common sense. The question is, when we reflect on the overall data, should we think that the observed phenomena provide evidence that our commonsense views concerning our embeddedness within 3-dimensional metric space is illusory?

Monton is correct to ask, however, what quantum mechanical experiments could be used to support the claim that we indeed live in a 3-dimensional world? Does quantum mechanics say anything about the world being 3-dimensional? I don't believe so. The notion of 3-dimensions is imposed onto quantum mechanics by our experimental presuppositions.

Physicists first take the quantum system or the wave-function to exist in 3-dimensions in order to better describe the system they are dealing with. The presupposition of 3-dimensions is a built-in assumption of quantum experiments and calculations and thereby transfers onto the *experimental ontology* (ontology used to make sense of the quantum mechanical experiment) of the quantum system. What this means for the wave-function is that, according to its *experimental ontology*, it is believed to exist in 3-dimensional space. However, the mathematics indicates that it evolves and exists in 3N-dimensional space, according to Albert. This brings about a conundrum as to the implications the wave-function has for the nature and existence of space.

In this paper I will argue against both Albert and Monton's views and investigate the wave-function's implications for the nature and existence of space. I will offer a different perspective on the nature of space from those of both Albert and Monton by examining a number of central questions concerning concepts of space and mathematical representations of physical systems. First, I will more carefully examine the concept of spatial relations in a configuration space, and compare such notions with the concept of a metric space, which serves as a paradigm instance of real, physical space. I will then connect these considerations to the distinction between mathematical and physical objects to support my view of the wave-function's implication for the nature of space.

What is the Wave-Function?

In a quantum mechanical system, the state of a system before it is measured is considered to be in a superposition of states with finite probability distributions (Ney 13). An observation made on the system is defined as a measurement that results in the system taking on a state from the possible probabilities of its superposition of states (Ney 12). These probabilities can provide information concerning either the position of a particle or its momentum (Einstein 697). A system's evolution of these states is represented mathematically by Schrodinger's equation. A particle's momentum and its position cannot be known simultaneously, as encapsulated by the Heisenberg Uncertainty Principle (Heisenberg 14).   This serves as an epistemic limit placed on the quantum realm that separates it ontologically from the classical realm, as Einstein famously posits in his hallmark paper on the incompleteness of quantum mechanics as a theory of physical reality (Einstein 698). These principles of the quantum mechanical world separate the classical world of desks, buildings, and planets from the quantum world of particles and subatomic particles. It is here at this scale that the rules of quantum mechanics are at play. In order to understand this world, physics employs the use of complex mathematical tools such as the use of Hilbert Spaces and Matrix Algebra operations (Griffiths 93). Elements of these matrices represent the observable states in a given quantum mechanical system and operations on these matrices represent the measurements made on the system (Griffiths 94). The probabilities that output from the wave-function give us a glimpse of the possibilities the system can be in for some given set of states. The wave-function is thus the state before a quantum mechanical system is observed (Albert 52). However, such a formulation does not make it clear as to whether or not the wave-function is actually a physical object or not, as will be explained below. The ontological status of the wave-function is thus a very hotly debated problem within the Philosophy of Physics.

The ontological status of the wave function remains in flux due to the philosophical problems it faces. Questions of its status as a physical object, a quasi-mathematical object, or a mathematical object are pertinent to addressing it. Why is the wave function's ontological status still being debated today? The answer to this question lies in the mathematical construction of the wave-function. The wave-function evolves in a special mathematical space called 3N-configuration space (Albert 52). This space represents all the possible states of a given quantum mechanical system and has the dimensionality 3N, where N is the number of particles in the given quantum mechanical system. For example, a two particle system would have a 6 dimensional configuration space and a 10^6 particle system would have 3×10^6 dimensions. This is the point at which the philosophical problems begin to become daunting. Given what classical physics and relativity have offered to our paradigm of the spatial properties of our world, how can we reconcile the fact that the wave-function evolves in a space that is proportional to the total number of particles in the universe when our previous physics theories suggest that we live in a 3-dimensional world? This is the crux of the issue at hand and this issue has taken various forms, as seen through the works of several philosophers of physics.

However, the debate has not yet been settled because there are a myriad of issues at play given the very fundamental and foundational issue of the wave-function's spatial nature. Albert posits that our 3-dimensional space is *illusory* because the mathematics highly suggests we live in this 3N-configuration space, whereas people like Monton suggest we can reconcile 3N-configuration space by exploiting unique mathematical properties and shaping the ontology to fit our view of 3-dimensional space. However, there are difficulties with both of these views, as I will discuss below. One thing is certain: the wave-function is at the heart of quantum mechanics and addressing its status will give us a better picture, of not only of its nature, but also of quantum mechanics

What is Wave-Function Ontology?

Ontology deals with the philosophical study of reality and existence (Hofweber). In this paper, when the term *ontological* is used what is meant is simply that it concerns the nature and/or existence of (the wave function/space/the topic of discussion). The wave-function represents the state of a physical object as something like a complex field evolving through a high-dimensional mathematical space otherwise known as 3N-configuration space (Albert 53). This is one of the central aspects at issue when we attempt to discern the wave-function's ontological status. This raises the question: how can we think of a quantum system as embedded in 3-dimensional metric space if the way that it is best represented within our physical theory appeals to a much higher dimensional, and non-metric configuration space? This question forces us to more carefully examine our understanding the nature of the wave-function's space, and also of our background or presupposed metric space. There are two main approaches to this. The first view is held by Dr. Albert, who contends that since the wave-function evolves through the higher-dimensional space of 3N-configuration space, our physical space is actually a subspace of the 3N-configuration space (Albert 55). The second view is held by Monton, who contends that the 3N-configuration space is just a mathematical representation that describes the wave-function and is not to be taken in a literal sense to have any physical implication on the nature of our physical space. These are two competing ontologies that will be thoroughly discussed in this paper.

In light of this debate and understanding the nature of wave-function ontology with respect to the implications on the nature of space, in order to fundamentally understand the distinctions between these competing ontologies, one has to understand the types of spaces involved and their respective properties. There are two distinct spaces that are discussed in these ontologies: state spaces and metric spaces. Both of these spaces are mathematical in nature and are used to represent our physical space in the world around us. The nature of these two distinct spaces will be discussed further on.

All in all, wave-function ontologies are meant to help us to understand the nature of the wave-function. In the philosophy of physics, it is very easy to confuse the mathematical structure and nature of the physical theories as having a one-to-one relationship with the physical world. For example, it is easy to confuse mathematical spaces with physical spaces. Thus, it is paramount for understanding the various ontologies of the wave-function to distinguish different fundamental notions of space and in particular to note the distinctions between mathematical space and physical space as well as the distinction between mathematical objects and physical objects. This elusive distinction, as Resnik concludes in his work, is attributed to the longstanding problem of competing ontologies for various theories in physics (Resnik 369).

What is 3N-configuration Space?

As has been shown in the previous section, the evolution of the wave-function occurs in a mathematical space called 3N-configuration space where N is the number of particles in the given system (Albert 53). This particular configuration space is the mathematical space in which all the possible states of a quantum system exist (Albert 53) and will henceforward be designated as quantum configuration space to distinguish it from classical 3N-configuration space. Each point in this quantum configuration space has an amplitude and phase (Albert 53). Thus, our universe would have a configuration space with an extremely large number of dimensions. This configuration space is at the heart of the debate about the wave-function and the nature of space. However, the 3N-configuration space isn't a metric space like Euclidean space is; rather it is a Hilbert vector space. Furthermore, what is unique about the configuration space is that it is not a metric space like Minkowski space or Newtonian 3-dimensional space. For example, in classical mechanics the background space is a single metric space. There is a property of *distance* that can be applied within this space and thus it is this distinction that draws the line between physical metric space and quantum configuration space. In the quantum (as well as classical) configuration space, there is no property of *distance*—each particle has an amplitude and phase associated with it that is represented by complex numbers. In physical metric space, each point is represented by three or four real numbers. This is another distinction. In quantum configuration space, the amplitude and phase that represents each point are complex numbers which are outputted as real numbers when an observation or a mathematical operator is operated on the given configuration space. In other words, in the quantum configuration space, there is no notion of a physical distance between points that can be measured in the physical world due to the unique mathematical nature of the quantum configuration space. These unique properties of quantum configuration space have some unique implications for the wave-function. These implications will be discussed in the next section.

Metric vs. Classical/Quantum Configuration Space

As has been outlined in the previous section, there is a deep distinction between metric or physical and quantum configuration space. The distinction arises from the mathematical structures that define these two types of spaces. The idea of a configuration space comes from graphically condensing the information of a system of N particles to a system of N points in a 3-dimensional space where each point in this 3-dimensional space can be represented by an ordered N-tuple corresponding to the number of N particles (Ney 16). For example, for a two particle system where N=2, in a 3-dimensional graphical representation of the configuration space, every point would have X ,Y, and Z coordinates X1, Y1, and Z1 and X2, Y2, and Z2, and so on and so forth for N particles. Thus, the configuration space in the quantum regime has 3N-dimensions. In addition, in quantum systems, the parameters of each point are characterized by the phase and amplitude with complex numerical values (Ney 16). This is the formulation of quantum configuration space. However, quantum configuration space is an essential part of the way in which the wave-function is expressed mathematically and physically.

Classical configuration space is quite similar and is characterized by the same sort of logic. In classical configuration space, the same idea is applied to condense the physical properties of particles, namely their position and velocities to a vector in the configuration space, and thus can represent the entire state of the system in the same way that quantum configuration space is expressed. However, there is a key ontological distinction between the purpose and use of configuration space in each regime. In the quantum regime, configuration space represents the evolution of the state of a quantum system with N particles because a wave-function is physically in a superposition of states. The superposition of states and the given probabilities of each particle to take on a value of position and momentum, are two of the main distinctions that differentiate classical configuration space from its quantum counterpart. In the classical configuration space, the particles are not in a superposition of states—there are definite values they can take based on their determinate states. This is the key ontological distinction and it will be useful in understanding the various perspectives offered in this paper.

In addition, the key difference between metric and configuration space in the quantum and classical regime, is that fundamentally, there is no metric notion of *distance* in the configuration spaces. The notion of distance in a metric space applies in a physically relevant sense, but it does not apply in a physically relevant sense for configuration spaces. Configuration spaces do not deal with spatial coordinate representations in the same respect as metric spaces—they deal with the states of a system rather than the individual physical points of the system. More clearly stated, a metric space is a space of spatial points and a configuration space is a space of states. For example, a configuration space would have all the possible velocity or momentum values that could exist for each spatial point. Using the configuration space coordinates, and performing a mathematical operation on the configuration space that calculates distance is not physically meaningful in this sort of space. Performing such an operation on a configuration space is akin to finding the distance between two states in the space of states. This isn't the same as finding the distance between two points in a physical space. For example, in the quantum configuration space, each spatial point is represented by a probability value. Calculating the distance between two probabilities does not mean the same as calculating the distance between two points in physical space.

Thus, in a metric space it is physically meaningful to calculate the distance between points because the points are representing a physical space. In a configuration space, the points are representing possible velocities, momentum, or probability values for each spatial point, thus attempting to calculate the distance between two such points will not yield the same physical meaning as it does for metric spaces. This is the fundamental distinction between configuration spaces and metric spaces and it will be used in the further sections to better understand Albert and Monton's views.

Mathematical Objects vs Physical Objects applied to 3N-configuration Space and Physical Space

In order to understand the ontological status of configuration space, distinctions between mathematical objects and physical objects have to be made. These distinctions will be applied to 3N-configuration space and physical space.

According to Charles Chihara, a prominent philosopher at University of North Carolina-Chapel Hill, in his book "A Structural Account of Mathematics", mathematical objects are causally inert and therefore do not exist in our physical world (Chihara 16). In order to understand this statement, the idea of a mathematical object has to be understood. Chihara defines the mathematical object as being a mathematical construction which operates and is defined to exist in the platonic "mathematical universe" (Chihara 16). This *mathematical universe*, is not causally connected to our physical universe (Chihara 16). What does this have to do with our debate about the nature of space for the wave-function? The distinction between a physical object and a mathematical object is blurred when talking about the wave-function because the wave-function is mathematically constructed as evolving through the higher dimensional space of 3N-configuration space, while existing in our physical space of 3-dimensions. This property of the wave-function makes it a quasi-mathematical object. Resnik likens many objects in physics to quasi-mathematical entities or entities with properties that are mathematical and physical (Resnik 371). For example, the wave-function has many mathematical properties and many physical properties. Similarly, a quantum particle would also be classified as a quasi-mathematical object, according to Resnik, since quantum particles do not have definite locations in space-time, velocities, momentum, masses, spin, or other properties relating to space-time (Resnik 370). Thus, the main issue at hand is how the wave-function has properties of a physical and mathematical object.

There is much to discuss regarding the status of the wave-function's existence in the *mathematical universe* or in the physical universe, but the key issue is its ontological status as it relates to physical space. Though, it may be a quasi-mathematical object; however, it is fundamentally a physical state that can be measured in physical experiments in our 3-dimensional space. As such, it is important to examine the extent we should use this distinction between mathematical objects and physical objects to discern the ontological status of the wave-function.

So far, there has been much discussion about the various distinctions and properties of the wave-function. These are tools that will help in understanding the wave-function in a more precise manner. The preceding discussions are auxiliary to the discussions that Albert and Monton have presented for the nature of space of the wave-function. The amplitudes of the wave function are akin to mathematical objects rather than definite properties of the system as in the case of classical electric fields. This is certainly a distinction that pits quantum wave-functions against the classical view of our physical world. However, this distinction outlines the potential for the quantum wave-function to be a more quasi-mathematical object than its classical counterparts. The notion of the wave-function being a quasi-mathematical object can be applied in the debate surrounding the wave-function's nature of space.

Current views of the Wave-Function

The previous sections have alluded to the mathematical and physical description, the properties, the distinctions, and thus the ontological status of the wave-function. As has been indicated, the wave-function is an interesting object that exhibits physical and mathematical properties that combine to make its ontological status a debatable topic in the philosophy of physics. However, there are many competing views as indicated in the anthology about the wave-function, “The Metaphysics on the Wave-Function of Quantum Mechanics”(Ney, Albert). This anthology has collected pertinent articles concerning the nature of space of the quantum wave-function. The current views of the wave-function’s ontology first and foremost deal with the nature of 3N-configuration space as a defining feature of the wave-function and arrive at the ontologies based on the interpretations of the properties of the wave-function. In the next sections, I will primarily examine Albert and Monton’s ontologies. These ontologies are opposite to each other, but they are at the intersection of the debate concerning the nature of 3N-configuration space for the wave-function.

These ontologies also need to be related to the scientific method. The notion of building an ontology based on the experiments of physics is something that has been explained by Valia Allori through the concept of primitive and non-primitive variables (Allori 64). Allori posits that primitive variables are the variables that are held by multiple theories to be common, whereas the non-primitive variables are variables of a theory that are not held in common by competing theories (Allori 65). With respect to the wave-function, competing theories hold the 3N-configuration space in common.

Albert’s Wave-Function Ontology

In this paper, I have outlined two of the current viewpoints and have presented the tools with which these viewpoints will be examined. One of the main viewpoints that I am arguing against is Albert's wave-function ontology. I will present his ontology of the wave-function in detail in this next section.

Albert's thesis is that the 3-dimensional world we live in is "flatly illusory". His motivation stems from raising the ontological status of 3N-configuration space from a mathematical-representational space to a physical space due to its deep mathematical structure supporting the wave-function. The wave-function evolves through the 3N-configuration space, and Albert contends that it is this attribute that our 3-dimensional objects arise from. In other words, the tables, chairs, and desks of our 3-dimensional world all arise as projected subspaces from the 3N-configuration space the wave-function exists and evolves in. Albert uses the concept of a *world particle* to represent the wave-function of the universe (Albert 54). This world particle is visualized as existing in a high-dimensional 3N-configuration space that, according to Albert, is ultimately our physical space. Every particle within the universal world particle is a projected subspace of the greater 3N-configuration space. For example, a desk in our 3-dimensional physical space is a projection of this higher dimensional 3N-configuration space. The process by which the subspaces are mapped and projected onto our 3-dimensional space is also not clearly identified. However, the fundamental issue in need of understanding is that Albert uses this mathematical structure of the wave-function to craft his wave-function ontology to mirror the mathematics first rather than the physical phenomena. He appeals to the mathematics to posit physical claims. I will discuss why this course is misguided in greater depth below.

Monton's Wave-Function Ontology

Bradley Monton is another philosopher who offers his ontology for the quantum wave-function. He begins by supposing that quantum mechanics is false because it is incompatible with general relativity and then proceeds to stating the dimensionality of physical space (Monton 154). He appeals to *commonsense* to support his claim that the dimensionality of physical space is three (Monton 154). Monton proceeds with these claims to argue against Albert's thesis that physical space is in reality a 3N-dimensional space. His presupposition in making these claims is that quantum mechanics is false because it cannot correctly predict time dilation in a strong gravitational field under the physics of general relativity. Then Monton asks, "How does one determine the ontological content of a theory?"

Monton claims if a theory can be presupposed to be true then "the ultimate arbiter of the ontological content of the theory is reality itself" (Monton 155). He uses this as his *epistemic starting point* to provide an analysis of what can be ontologically stated about scientific theories. In addition, he claims that an entire theory such as quantum mechanics may not be false but its auxiliary hypothesis may be false. This idea touches upon primitive and non-primitive variables of a theory and what it takes for a given theory to be accepted. The problem with quantum mechanics, Monton professes, is that there are many versions of it such as string theory, M-theory, and quantum gravity all competing to arrive at the closest compatible formulation reconciling quantum mechanics and relativity. Because there isn't a physical theory that properly addresses the issue of compromising quantum mechanics and relativity, a physics-based-metaphysics for quantum mechanics cannot be properly formulated. However, Monton does not leave the debate of the dimensionality of space of the wave-function at a standstill simply because he maintains that quantum mechanics is false—he offers a subtle yet clarifying argument against 3N-dimensional space.

Monton begins his argument against 3N-dimensional space by using a semantic view of scientific theories. This semantic view, according to Monton, requires that scientific theories consist of two parts: a mathematical model and a set of theoretical claims about how the mathematical model represents reality (Monton 160). In order to elucidate this semantic view, Monton connects this with analogies of two representations of quantum mechanics: Hilbert spaces and Schrodinger's wave-function. In the Hilbert space representation, the quantum state of a system is represented by vectors in Hilbert space while in the Schrodinger representation, the quantum state of a system is represented by a wave-function that evolves through 3N-configuration space. Monton takes these analogies further by stating:

> One could put forth a theoretical hypothesis saying that Hilbert space is physically real, and there really is a line of a particular length pointed in a particular direction in that space. Similarly, one could put forth a theoretical hypothesis saying that 3N-dimensional space is physically real, and there really is a wave-function field evolving in that space. (Monton 161)

Monton thus brings up an excellent point, grounding the debate in a more physical approach to the metaphysics of the quantum wave-function. In essence, he distinguishes the utility of the mathematical representations of a scientific theory from its physical relevance. Now, the metaphysical implications of these distinctions themselves can be discussed further but that is not the focus of this paper.

His conclusion based on these points is that there is an N-particle system that evolves in 3-dimensional space and there is a certain property of this N-particle system that is represented by either a 3N-dimensional space or a Hilbert space. Fundamentally, this property is what can be known about the quantum wave-function as it exists in 3-dimensional space. In other words, according to Monton we cannot confuse the ontological status of the mathematical representations of our theories with what we are trying to represent physically. However, although Monton does have good points, his account of quantum mechanics as a false theory of the world due to its incompatibility with general relativity and moreover his appeal to *commonsense* are a bit oversimplified. In particular, his reasoning for believing that the dimensionality of our space is 3 based on *commonsense* is unclear. I will discuss the issues with Monton's ontology of the quantum wave-function below.

Why elevating 3N-configuration space to a physical space is misguided

I will now pose my arguments against Albert's views and go into detail as to why I do not think that his 3N-configuration space ontology is sound.

The idea of space being 3N is a misguided idea because the way vectors are appointed mathematically are through mathematical operations and in turn are used to represent physical properties of the system. In order to make a scientific model of what the physics of a phenomena is, one imposes mathematical models onto the experimental situation. A physical interpretation is one that appeals to the primary primitive variables of the system (ex: position, momentum, spin) being described and adds non-primitive mathematical variables (configuration space, Hilbert space, projective Hilbert space), which are by-products of the mathematics that is being used to describe the physical system. One shouldn't confuse the mathematical objects and operations that are being used to describe the physical system with actual properties of the physical system. This is a representational problem. Especially when one is dealing with mathematical properties of the wave-function, which exists by virtue of the state after observation of the quantum system. For example, given the distinctions discussed between mathematical objects and physical objects above, it can be surmised that elevating 3N-configuration space to a physical space is like elevating the numbers in the Kelvin temperature scale to be real features of the physical phenomena of temperature. Fundamentally, the numbers on the kelvin temperature scale are only representative properties of the physical phenomena of thermal energy. Although quantum configuration space has a greater utility than classical configuration space in respect to quantum mechanics, it can be said that the utility of the 3N-configuration space in quantum mechanics lies in its ability to mathematically represent the evolution of the physical states, albeit through a higher-dimensional space. This representation, however, is in the form of a space that describes the state of all possibilities. Furthermore, since 3N-configuration space represents the state of all possibilities of the quantum system, it is not meaningful to assign a notion of *distance* as it is meaningful for a metric space. The phase-space nature of 3N-configuration space is different from metric space in that in metric space there is a physical notion of distance whereas in the former assigning a notion of *distance* does not provide any physically relevant properties. It is not clear what the notion of *distance* in a phase-space like 3N-configuration space would correspond to physically, since it is a space of all possible states. In other words, it would not be clear as to what it means to calculate what the *distance* between two given states of positions is in a space that represents only the space of all possible states. For example, this would be akin to attempting to calculate what the *distance* between two points in a mathematical space which represents various temperatures of a gas enclosed in a box. This space represents the collection of all possible temperatures of the gas. However, attempting to appeal to the property of distance in this *temperature* mathematical space does not mean the same thing with respect to a metric space. If a calculation of the *distance* between two possible temperatures were to be made, the *distance* calculated would only mean the distance between those two points in this space with respect to the temperature phase-space. This would not correspond to a physically relevant property about the system since the mathematical formulation of phase-space isn't the same as it is for a metric space. In Euclidean or Minkowski metric spaces, it is physically relevant to calculate the distance between two points in these spaces as it is a physically relevant operation and a fundamental operation for the idea of a change in position. In 3N-configuration space this sort of calculation would be unclear and not physically relevant. Thus, the notion of elevating 3N-configuration space overlooks the fact that 3N-configuration space is fundamentally a phase space and not a metric space, since distance is not a physically relevant property in a phase space.

Furthermore, another problem with Albert's argument, is that he uses the mathematical objects and properties of the wave-function and presumes them to be literal elements of our reality. This arguments assumes that our mathematics of quantum mechanics is reflected one-to-one in the physical world. This is not the case because mathematical objects do not have any causal powers in the physical world, in the sense that they do not interact with physical systems. One cannot take the mathematics as literal; the mathematics of physics is merely a representational tool used to describe the results of experiments that have been verified for a given theory of the physical world. The mathematics we use to describe the wave-function (Hilbert space) as a space, is a mathematical formalism that is convenient to use to describe our physical world, or more precisely, our physical experimental results. If Albert's argument were true, then we would be able to observe experimentally that we live in a 3N-dimensional world; however, that is yet to be confirmed. Relativity says we live in a 4-dimensional manifold of space-time and we have some experimental evidence for this. Albert's thesis does not, to my knowledge. Albert appeals to the metaphysical aspects of mathematical objects to further his case that the world is 3N; but, how can one take objects that have no physical properties, no causal powers, and do not exist in our space-time to literally impose the view that we live in a 3N-dimensional world? Albert's argument that 3N-dimensional space is the real space we live in is a bit misguided. As can be inferred, I am taking a realist approach to this debate from the onset.

We should not undermine the presuppositions of 3-dimensional space we take in our experiments with the metaphysical claims we make from purely looking at the mathematics. A physical theory assumes, or the data of a given experiment assumes 3D-space and then a scientific and mathematical model is made from it. This model presupposes the notion of a 3-dimensional space. Our epistemic access is defined and limited by such a presupposition. For example, any quantum mechanical experiment that is done has a *built-in* assumption that it is being done in 3-dimensional space since our measurement devices are assumed to be in 3-dimensional space when the experiments are conducted. This line of reasoning extends into all the physical experiments that are done with regards to measurement devices. Thus, making a metaphysical claim that "3-dimensional space is illusory" and that "3N configuration space is the true reality" undermines the very data that presupposed 3-dimensional space. In that respect, Albert is misguided in making such metaphysical and ontological claims about quantum mechanics based off the pure mathematical formalism that represents the experiments that have led to the theory of quantum mechanics.

Ontological inconsistencies of Monton

I have previously agreed with many of Monton's points; however, Monton does not fully provide his wave-function ontology with a clear foundation. His assumptions leave a lot up for debate and are not quite clear as to their philosophical groundings.

The main function of Monton's wave-function ontology is to provide a more *intuitive* grounding for the wave-function's dimensionality of physical space. Monton appeals to a mathematical formulation for 3-dimensional space but problematically suggests that one should "look around" to "see" that the world we live in is 3-dimensional (Monton 154). Such a claim is philosophically incomplete and confusing. Monton may have been appealing to his intuitions and then appears to attempt to ground his wave-function ontology in mere observation. Unfortunately, this is not how theories of physics are developed. In contemporary physics, there is a deep sense of scientific rigor in verification and falsification of theories via observation and measurement. Appealing to *commonsense* to provide a rebuttal to Albert's wave-function ontology is not much different from Albert skipping to the mathematics of the wave-function to provide his realism for the quantum wave-function. Furthermore, Monton refutes quantum mechanics entirely and claims it is a false theory of our world simply because it cannot be reconciled with general relativity. This is because he assumes general relativity is a more *superior* theory in regards to its implications on physical space since general relativity provides predictions of the nature of our physical space, whereas quantum theory doesn't consistently provide predictions for our physical space. This inherent presupposition is what Monton uses to craft his own wave-function ontology. Monton then takes his presumption that quantum mechanics is a false theory and then posits his *physical-property-based wave-function-ontology* which states that the nature of space of the quantum wave-function is characterized by a physical property within the wave-function. This is an interesting point. The wave-function indeed does have a physical property within its 3N-configuration space mathematical model if it can be somehow likened to metric space. Although Monton alludes to this *physical-property-based-wave-function-ontology*, he does not quite make it clear how this physical property can be used in his wave-function ontology. For example, there are many physical properties in the formulation of the wave-function such as the 3xN formulation of the mathematics as posited by Peter J. Lewis, a Philosopher of Physics at the University of Miami, who interprets the 3N-dimensional configuration space as being a space that is fundamentally a 3-dimensional space but operates in this 3xN-dimensional space. However, Monton doesn't quite use that sort of property; he instead uses the fact that the wave-function is represented by an eigenstate with a particular eigenvalue that is an observable over the mathematically representative 3N-configuration space. This isn't a new formulation of the quantum mechanical wave-function; it is just the natural interpretation of the matrix formulation of the quantum wave-function. Monton does go on to craft his argument around the notion of mathematical entities like 3N-configuration space representing observables of a physical system. His point in using the *physical-property-based-wave-function-ontology* is more to define the debate about the nature of space of the quantum wave-function. His realist approach to the quantum wave-function is an outcome that grounds the ontological status of the wave-function. Ultimately, he does not properly begin his ontology with clear grounding and does not address how the physical property of the eigenvalue and eigenstate link to allow his ontology to address the dimensionality of physical space.

Conclusion

All in all, the ontological status of the quantum wave-function is far from settled. It is a debate that must be redefined, which was my aim in this paper. I believe redefining the debate with respect to the notion of what type of space can be ontologically interpreted from the quantum wave-function has allowed for some progress in what can be discussed in regards to the nature of space of the quantum wave-function and ultimately the space of our reality. As has been shown in my argument against Albert, the notion that 3N-configuration lacks a physical notion of distance as it holds in metric space is one of the central talking points in this debate. Furthermore, the methodology used in my argument is based upon the key assertion of how measurements in physics and science are made. Measurements are made by assuming that our measuring instruments are embedded in 3-dimensional space. These instruments then give us data from which we craft our physical theories, which can include mathematical representations of the phenomena. Then an ontology can be crafted. However, along this route of coming up with the ontology, the data that was used to craft the physical theory, presumed that the measurement devices were embedded in a 3-dimensional space, so this base assumption is still a part of whatever ontology that is crafted of the given physical theory. In the future, a methodology could be used that is more aligned with the base assumptions taken during experimental data collection in order to guide the ontology of the given physical theory. This would allow one to avoid the confusion of reading ontologies from the mathematical structures.

Lastly, the next steps in understanding the nature of space of the quantum wave-function is to start with a proper formulation of what a physical space fundamentally means ontologically, what constitutes a physical versus merely representational space, and what the natural mathematical formulation if the quantum wave-function indicates about the nature of our physical space. An ontology based on these grounding principles will potentially provide a more refined view of the quantum wave-function.

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