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THE PROBLEM OF TIME IN QUANTUM MECHANICS

By

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THESIS

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Introduction

The nature of time is a debated issue in philosophy. Some philosophers have concluded that time does not exist. For example, J.M.E. McTaggart in the early 20th century claimed that time was illusory. He defined time as the appearance of temporal order. He argued that the positions that make up this temporal order were arranged into two series: the A series and the B series. Whereas the A series was ordered according to the positions' properties such as *being present* or *being two days past*, the B series was ordered according to the positions' two-place relations such as *two days earlier than* or *simultaneous with.* McTaggart argued that there was an inherent contradiction in any position *t* in the A series because it had to possess the properties of being past, present, and future all at once. This contradiction meant that the A series was not possible. Furthermore, since the order in the B series was dependent on the relations positions had to each other in terms of the properties that constitute the order in the A series, there could not be a B series either. As a result, time was illusory (McTaggart, 1993).[1] Regardless of the conclusion philosophers come to about the existence of time, they make assumptions and debate about the topology of time. For example, McTaggart's argument holds only if time is assumed to be a single, continuous, linear temporal order of events. While some philosophers argue that time is an entity independent of the things that occupy it, others argue that it is relational. Philosophers such as McTaggart, Plato, and Augustine have a view called "Platonism with Respect to Time", "Absolutism with Respect to Time", or "Substantivalism with Respect to

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[1] Parmenides and Zeno of Elea also argued that change was illusory. Parmenides argued that since *nothing* was logically impossible, and change required a transition from nothing to something, there could not be anything that changed. This implied that the whole universe was static. Since there was no change, there could not be time. Taking this idea from Parmenides, Zeno argued that it was impossible to get from one point to another because of the assumed continuity of space. Thus, he also concluded that motion was illusory (Cohen, Curd, & Reeve, 2000).

Time”.[2] Such philosophers argue that time is like a background, an empty container, or a substance that has a separate existence from the objects that occupy it[3]. As such, the properties of time are uniform throughout and are unaffected by the motion of other objects.[4] However, not all philosophers share this view on the nature of time. Philosophers such as Aristotle, Leibniz, and Descartes argued that time should be defined in terms of relative change or motion. This view of time is referred to as “Reductionism with Respect to Time” or “Relationism with Respect to Time”. Such philosophers argue that time is defined by the relations between events or things that undergo change or motion (Markosian, 2008).[5]

The debate in philosophy about the nature of time mirrors the debate that occurs in physics. While some physicists claim that time is illusory, some claim that time is an independent entity and still others claim that time is relative. Some physicists like Julian Barbour (2008) claim that time as an independent entity is an illusion.[6] In “The Nature of Time”, he states, “Unlike the Emperor dressed in nothing, time is nothing dressed in clothes. I can only describe the clothes” (p.2). Among the physicists that have treated time as absolute is Newton. In the 17th century, Isaac Newton claimed that there were two types of time: absolute time and relative time. Whereas absolute time referred to an entity or uniform background that existed independently of the physical bodies, relative time referred to the quantitative values obtained

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[2] Although these philosophers share McTaggart’s view on the nature of time, not all will agree with his conclusion that time is illusory.

[3] Under this view, time is also separated from space.

[4] By objects, I mean any physical system.

[5] Such views are also held with respect to space. However, since the focus of this thesis is time, I will not discuss in detail philosopher’s views on space.

[6] For a detailed account of Barbour’s argument, please refer to his book *The End of Time* (2000).

from the measurement of the succession of events. That is, Newton distinguished between the real nature of time (absolute time) and the way time could be perceived (relative time). According to Newton both absolute time and absolute space were necessary in order for there to be absolute motion.[7] This was because absolute motion could only be determined by something stationary—i.e. by something that was absolutely at rest.[8] Newton believed that not having this foundation would lead to an infinite regress because an infinite amount of relative motions would have to be added to obtain an absolute value for motion. In order for true motion to be generated or altered, a force had to be applied to a body. The application of this force was both a necessary and sufficient condition for absolute or true motion to occur. However, the application of forces such as gravity was neither necessary nor sufficient for relative motion.[9] This is demonstrated in *Prong A* and *Prong B.* In Prong A, Newton focuses on showing how the application of a force is not necessary for relative motion. He imagined a scenario similar to the following: a body A is surrounded by a group of bodies B. If the same amount of force is applied to all the bodies in B, the position of the bodies in B will remain the same relative to each other, but A will be in relative motion to B. This scenario shows how if motion is relative, then motion can occur without the application of any force. In Prong B, Newton focuses on showing how the application of a force is not sufficient for relative motion. This can be shown by a similar scenario as the one described above. If the same amount of force is applied to both A and B, then the position of all the bodies will remain the same relative to each other. Thus, there is no

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[7] Absolute time and absolute space are these foundations.

[8] For Newton, something was absolutely at rest only if it was at rest with respect to all the bodies in the universe.

[9] Newton uses the rotating bucket experiment to prove something similar. He wanted to show how an effect such as centrifugal endeavor (the degree that the water climbs up the sides of the bucket) is necessary and sufficient for true rotational motion to occur but not for relative rotational motion.

relative motion. This scenario shows how if motion is relative, then it cannot occur despite the application of force.[10]

Newton's view on the nature of time and space was dominant in physics and was the standard approach to time and space in classical mechanics until the 20th century (Rynasiewicz, 2004). However, in 1905, Einstein demonstrated that both time and space were relative. In the theory of special relativity, he showed that an absolute measure of simultaneity was not possible. He also established the interdependence between time and space and the relational nature of space-time. As a result, Newton's absolute space and absolute time were replaced by Minkowskian space-time. Furthermore, Einstein also demonstrated with the theory of general relativity that physical bodies affect the structure of space-time. Thus, space-time cannot exist independently of physical bodies (Einstein, 2005).[11]

Regardless of the whether physicists have had an absolute or relational approach to time, they have tried to find a method to measure time that is dependent on physical events. For example, despite Newton's claim about the necessity of absolute time, he realized that a measure of absolute time could not be obtained other than by using relative time (Rynasiewicz, 2004). In

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[10] It is interesting to note how Newton's concern about how the causes of true motion such as forces and the effects of true rotational motion such as centrifugal endeavor are not necessary or sufficient for relative motion are manifested in the Twin Paradox four centuries later. In the Twin Paradox, one of two identical twins, Twin A, is sent on a rocket traveling at the speed of light while the other twin, Twin B, stays on Earth. From the frame of reference of Twin A, it is Twin B that is moving away at the speed of light. From the frame of reference of Twin B, it is Twin A that is moving away at the speed of light. However, when Twin A returns to earth, Twin B has aged considerably more than Twin A. If relational motion is real motion, then both twins should have aged at the same rate because from each other's frame of reference, it is the other twin that is traveling at the speed of light while he is at rest. However, it is only Twin A that has aged faster than Twin B (Torretti, 1999).

[11] This will be explored in greater detail in the implications section of this thesis.

particular, astronomers have been trying to find an accurate way to measure time since ancient times. For example, having found that there is a 15 minute discrepancy between solar time and sidereal time, Hipparchos preferred to use sidereal time to predict lunar eclipses because it proved to be more accurate. This was until astronomers noticed that the moon had an effect on the rotation of the Earth in the 1890s. However, it wasn't until 1952 that ephemeris time[12] replaced sidereal time as the preferred measure of duration. Ephemeris time was a more accurate measure of duration because it took into account Newton's gravitational law as it applied to the solar system.[13] Ephemeris time was obtained by using the energy of this system. The total energy of the system E is given by the sum of the system's kinetic energy T and its potential energy V. It is a system's potential energy that is defined in terms if Newton's law of gravity. As such, it takes into account the disturbance that the gravity of other bodies in a system can produce on the motion of the body that will be used to obtain a time variable. Since the energy in a closed system is conserved, the total energy E of the system is constant in time. If an observer knows the values for the constants G, E, and m_i, and takes two successive measurements of the whole system, then the value for time variable δt can be determined based on displacements of the positions of all the bodies in the system. Ephemeris time was used as the standard measurement of time duration until the atomic time was introduced in 1979 (Barbour, 2008).

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[12] Ephemeris time is given by δt which is derived from the displacements and distances of the positions of celestial bodies given the constants G for gravity, E for total energy, and m_i for the mass of a body in the system.

[13] In order for this to apply, the solar system must be closed. That is, there are no external bodies that can significantly disturb its motion.

In classical mechanics, the energy of the system represented by the Hamiltonian *H*[14] is used as the generator of time translations. When the system is not affected by any time-dependent external forces, *H* is the constant *E*. This is the case with the solar system that gives ephemeris time. However, most systems are affected by external time-dependent forces. In such systems, *H* is dependent on time measure *t* (Hilgevoord, 1996). The *t* value represents an external and independent measure of time that, much like Newton's absolute time, is assumed to exist but it is unobserved. Some physicists such as Jan Hilgevoord (2002) claim that the idea that *t* represents a measure of time is a misconception. This is because *t* represents a space-time coordinate and as such, it is not a measure of physical phenomena. Instead, it is a mathematical tool used to map physical events. A measure of time can only be derived from systems containing dynamical variables. Since there is no dynamical variable for time, *t* is used to represent both the space-time coordinate and the dynamical variable. As a result, space-time coordinates are equivocated with dynamic variables for time. However, time as measured by a dynamic variable is not the same as the coordinate *t*. The use of the notation *t* to represent time obscures the fact that there are different conceptions of time.[15] This equivocation also occurs in quantum mechanics because is it modeled after classical Hamiltonian mechanics.[16]

Whereas ignoring the distinction between space-time coordinates and dynamical variables is not as problematic in classical mechanics, it is in quantum mechanics. In classical mechanics, the difference between dynamical variables such as $\boldsymbol{q}$ and the space-time coordinates such as $\boldsymbol{x}$ can be ignored because it is assumed that there is no discrepancy between the

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[14] *H* is the function of the canonical variables *p* which represents momentum and *q* which represents position.

[15] Paul Busch (1990) discusses the different conceptions of time in the article "The Time-Energy Uncertainty Relation." He distinguishes between external time, internal time, and observable time.

[16] This will be explored in greater detail in the next section of this thesis.

properties of a physical system and the properties of space-time. That is, both the dynamical variables of physical systems and the space-time coordinates have well-defined continuous measurement values ranging from $-\infty$ to $+\infty$. However, the properties of physical systems that are studied in classical mechanics are different from those studied in quantum mechanics. Whereas classical mechanics studies physical systems such as rigid bodies and point particles (Hilgevoord, 2002), quantum mechanics studies physical systems that can be described as matter waves. In 1924, Louis de Broglie proposed that subatomic entities such as an electron possess properties pertaining to both particles and wave phenomena. For example, recent experiments such as the double-slit experiment showed how the nature of electron is altered by the measuring apparatus/configuration.[17] If one slit is covered, then the electron will pass through the slit to produce a pattern that indicates particle behavior. That is, there is no interference pattern. However, if both slits are left open, the electron will pass through both of them to produce an interference pattern that indicates behavior of wave phenomena. As a result, measurements cannot always provide definite values as in classical mechanics. Instead, measurement values are given in terms of probability. That is, $|\Psi|^2$ is used to represent the probability of finding the electron in a certain position.[18] De Broglie proposed that the connection between the particle and wave nature of the electron involved Planck's constant. He found that the wavelength λ of an electron was given by Planck's constant h divided by its momentum mv (Greenstein & Zajonc, 1997). The introduction of Planck's constant as the solution to the black-body problem showed

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[17] In a double-slit experiment, an electron is shot through a wall with two slits to be captured by a screen (Auletta, 2001).

[18] Ψ represents the state of the system.

that systems can have discrete energy values.[19] The discreteness observed by Planck's solution was generalized into the Quantum Postulate which states that the total energy of quantum systems E is composed of a definite number of discrete energy packets given by the frequency value v of the system multiplied by Planck's constant ($E=hv$). This was the beginning of quantum mechanics (Auletta, 2001). The discreteness observed at the quantum level is contrary to the assumption in classical mechanics that measurement values are always continuous.

Due to the nature of subatomic entities, ignoring the distinction between space-time coordinates and dynamic variables contributes to the problem of time in quantum mechanics. In quantum mechanics, dynamical variables are represented by operators. However, if time t is expected to be external and independent of physical systems and is expected to have continuous values that range from $-\infty$ to $+\infty$ like space-time coordinates do, then there is no self-adjoint operator that can represent time as an observable.[20] As a result, time has to be represented by the

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[19] A black body is a hollow object built of a material that keeps its internal temperature constant and uniform. These two properties of its temperature cause the electrical charges to also move in a continuous manner. This continuous movement produces electromagnetic waves. Since the movement is always occurring, the electromagnetic waves are always produced. Because of its nature, it is mathematically hypothesized that the intensity of the radiation emitted by the black body would increase infinitely. This would result in an explosion called an ultraviolet catastrophe. However, this is not what is experimentally observed. Instead, after the radiation reaches a certain level, the emission and absorption of waves reaches a level of stability. After this, the amount of radiation emitted tappers off until it stops. The discrepancy between mathematical models and experimental observations is called the black-body problem. Planck, however, solved this by introducing the idea that energy for physical systems such as black bodies is discrete. He proposed that the energy of black bodies is composed of a definite number of energy elements having 6.55×10^{-27} erg/s. This number is known as Plack's constant h (Auletta, 2001).

[20] An observable is property that can be measured like a system's position, momentum, angle, spin, etc. It is a dynamical variable.

parameter *t*. If time cannot be represented by an operator like the spatial coordinates, then the close connection between *x, y, z* and *t* established by Einstein using the Lorentz transformations in the theory of relativity cannot be mirrored in quantum mechanics.[21] Thus, time is treated independently from space in standard quantum mechanics (Hilgevoord, 2002). Standard quantum mechanics assumes a Newtonian conception of time and space despite the fact that the theory of relativity proves that this should not be done.

Given the problems with time in quantum mechanics, the purpose of my thesis is to explore its role. I aim to gain a better understanding of the nature of time and the nature of the problems associated with time. For example, I aim to explore the problem associated with the energy-time uncertainty relation due to the lack of a universal operator for time. Using Hilgevoord's work, I will explore the idea that if a measure of time is to be obtained in quantum mechanics, then time has to be a property of physical systems that can only be measured in relation to other systems. As such, time cannot be independent of physical systems. This implies that there cannot be time without physical systems. As a result, I will show how the philosophical position of "Relationism with Respect to Time" provides an accurate account of the nature of time that is consistent with observations made in physics. In order to achieve this, I will: 1) present Hilgevoord's argument about the problems of time in quantum mechanics; 2) provide an account of the ontology of time based on Hilgevoord's work; and 3) provide an analysis of the implications of what I am proposing in connection to Einstein's theory of special and general relativity in hopes of showing that his insights can and should be applied to quantum mechanics.

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[21] This will be explored in greater detail in the next section of this thesis.

Hilgevoord's Exposition of the Problem of Time in Quantum Mechanics

In his article "Time in Quantum Mechanics," Jan Hilgevoord (2002) claims that the "root of the problem of time in quantum mechanics" has its origins in a conceptual error that has been carried from classical mechanics (p. 301). This is due to the fact that classical Hamiltonian mechanics serves as a model for quantum mechanics. Hilgevoord explains how in Hamiltonian mechanics, Q_k and II_k represent any generalized canonical conjugate variables that describe a physical system. Conjugate variables are a pair of variables that have a relationship such that any change in one variable will reflect in the other variable. For example, position $\boldsymbol{q}$ and momentum $\boldsymbol{p}$ are conjugate variables. Any change in the position of a system will reflect a change in the momentum of a system. If Q_k and II_k are used to describe a system that constitutes a collection of point particles, these variables can be represented by the pair of conjugate variables describing the positions $\boldsymbol{q}_n$ and momenta $\boldsymbol{p}_n$ of the particles in that system. He also explains how in physics (except for general relativity), it is assumed that these physical systems are situated in a Euclidean space which is both continuous and independent from the physical systems that are being described.[22] The points constituting this Euclidean space are given by the Cartesian coordinates x, y, z and a time parameter t. As Hilgevoord states, "Together with the time parameter t, the [Cartesian coordinates $\boldsymbol{x}=(x, y, z)$] form the coordinates of a continuous, independently given, space-time background" (p.301). Hilgevoord states that although there is a numerical identity relation $q_x=x, q_y=y, q_z=z$ between the dynamical variable of a point particle $\boldsymbol{q}$

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[22] It is important to note that physical systems in special relativity are not situated in Euclidean space. Instead, they are situated in Minkowskian space-time which is also independent from the physical systems that occupy it. This view of space-time is not assumed in general relativity.

and the space-time coordinates $\boldsymbol{x}$, the dynamical variables (Q_k, II_k) of a system in space-time must be "sharply distinguished" from the space-time coordinates ($\boldsymbol{x}$, t).[23]

Hilgevoord states that making this distinction, although seemingly obvious, is important because dynamical variables and coordinates have different properties. Whereas the variables represent point particles that have mass, position, velocity, and acceleration, space-time coordinates do not have any of the properties listed above. Like the Cartesian coordinate system used to map physical systems, space-time is assumed to be a fixed, independent, continuous background that extends linearly with its values ranging from $-\infty$ to $+\infty$ where each space-time interval is determined by a unit vector. Just like dynamical variables and coordinates represent different concepts, so do physical systems and space-time. The properties of space-time do not have to be the same as the properties of physical systems. For example, whereas space is supposed to possess both translational and rotational symmetry and time is supposed to possess translational symmetry, physical systems do not. Hilgevoord states that it is the assumed symmetry of space and time that allows for the three spatial coordinates $\boldsymbol{x}$ and the time coordinate t to be joined together via Lorentz transformations to form the four components in a four-vector. That is, the four space-time coordinates can be treated as a single vector. However, based on the distinction mentioned above, the dynamical variables representing physical systems cannot be components of a single four-vector with the position dynamical variable $\boldsymbol{q}_n$ combined with time coordinate t. This is because since $\boldsymbol{q}$ represents a dynamical variable of a physical system and t represents a space-time coordinate—i.e. they represent different concepts with

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[23] Since time as a parameter t and time as a dynamical variable have very different properties, Hilgevoord's distinction provides more than just another name for time. That is, this is not an issue of nomenclature. He is stating that the word "time" is used to refer to different concepts. As such, he is implying that at the root of the problem of time is the failure to recognize the many types of time that exist.

different properties. As a result, t and $\boldsymbol{q}$ should not be combined to mirror the close connection between x, y, z and t established by Lorentz transformations.

In quantum mechanics, space-time and physical systems also have different properties. Whereas space-time is fixed and unquantized (continuous), the dynamical variables of physical systems are quantized. In quantum mechanics, space-time points are represented by c-number coordinates $\boldsymbol{x}$, t and dynamical variables are represented by operators. For example, the dynamical variable for position $\boldsymbol{q}$ is represented by the multiplication operator and the dynamical variable for momentum $\boldsymbol{p}$ is represented by the differential operator. Like in classical mechanics, coordinates should not be equivocated with dynamical variables because they have different properties (Hilgevoord, 2002). The problems that result from not making this distinction can be demonstrated by describing the effects it would have on uncertainty relations. If we treat $\boldsymbol{x}$ as a dynamical variable in a physical system, then $\boldsymbol{x}$ will have the property of being a fixed point in space. Furthermore, if $\boldsymbol{x} = \boldsymbol{q}$, then $\boldsymbol{x}$ will also be the conjugate variable of momentum $\boldsymbol{p}$. As such, $\boldsymbol{x}$ will also be part of the uncertainty relation $\Delta\boldsymbol{x}\Delta\boldsymbol{p} \geq -\boldsymbol{i\hbar}$. However, if $\boldsymbol{x}$ is a fixed point, then the system's momentum $\boldsymbol{p}$ will tend towards infinity. This implies that a measure of system's momentum cannot be obtained. If this situation is to be avoided, then $\boldsymbol{x}$ should be distinguished from $\boldsymbol{q}$. It should be noted that such a situation does not occur with $\boldsymbol{q}$ because it is not a fixed point in space. This shows how the different properties of $\boldsymbol{x}$ and $\boldsymbol{q}$ have will affect systems in different ways.

Such problems also occur with the energy-time uncertainty relation. In quantum mechanics, the time-value of a particle system is denoted by the parameter t instead of by the dynamical variable that represents time. An example of the lack of a dynamical variable for time is found in the time dependent wave function $\Psi(\boldsymbol{x}, t)$. Hilgevoord states, "the notation suggest that ***x*** and *t* are quantities of the same type and leads to the question why *t*, the universal time coordinate, is not an operator like ***x*****"** (p. 303). If the parameter *t* is equivocated with the dynamical variable for time, then there is no operator for time. In quantum mechanics, the parameter *t* is used to represents the canonical conjugate variable to the Hamiltonian *H*. As such, *t* is expected to satisfy the commutation relation $[t, H]=i\hbar$ (Auletta, 2001). This expectation leads to a problem because if *t* is to represent the universal operator for time, then its eigenvalues in any system should be continuous and include every number from $-\infty$ to $+\infty$.[24] This is because although *t* is used to represent a dynamical variable, its properties are assumed to be those of a coordinate number. That is, *t* represents fixed points in space-time that are independent, continuous, and extends linearly with values ranging from $-\infty$ to $+\infty$. Since *H* is the conjugate variable of *t*, this implies that every eigenvalue of any *H* should also have the same properties as the eigenvalues of *t*. For example, as the conjugate variable of *t*, *H* is also supposed to have eigenvalues that are continuous and that range from $-\infty$ to $+\infty$. However, Wolfgang Pauli showed that there is no operator for time that will satisfy this relation. When the operator representing the Hamiltonian does not have continuous eigenvalues ranging from $-\infty$ to $+\infty$, there cannot be an operator for time because it would result in negative energy values (Pauli, 1980). The Hamiltonian must be bounded from below in order to obtain positive energy values and the ground state of the energy of a system (Auletta, 2001). Thus, there cannot be a universal operator for time that has the properties of the coordinate *t*. As a result, time has to be treated as a parameter *t*. This is the main problem with time in quantum mechanics.

However, Hilgevoord (2002) notes that the lack of a universal operator is only a problem if the properties of *all* physical systems are expected to be the same as the properties of the

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[24] It should cover the entire real number spectrum.

space-time continuum. Yet not all systems have such properties. Thus, Pauli's theorem is a genuine concern for only *some* systems. For example, Pauli showed that a universal operator cannot represent systems with discrete energy eigenvalues, but not all systems are discrete. Some systems do have continuous energy eigenvalues. For such systems, there can be an operator that functions in the same way that a universal operator should function. This is because the system has the same properties as the space-time coordinates. That is, the system is fixed and unquantized with eigenvalues that range from $-\infty$ to $+\infty$. According to Hilgevoord, Pauli's theorem does not apply to such systems.[25] However, the problem still remains for systems that don't share the same properties as the space-time coordinates such as systems with discrete energy eigenvalues or systems that are bounded from below. For this reason, an operator has to be established that can adequately measure and account for the particular nature of the physical system that is being measured. In order to find an operator for time, Hilgevoord proposes that a dynamical variable for time should be established. The time variable for time should have the same type of relation to the coordinate t as the dynamical position variable $\boldsymbol{q}$ has to the coordinates $\boldsymbol{x}$. As Hilgevoord states, "Just as a position variable indicates the position of a system in space, a clock variable indicates the position of a system in time" (p.302). This dynamical time variable will be found in a particular type of physical system—i.e. clocks. Hilgevoord defines a clock as any physical system that can be described by a dynamical variable

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[25] A physical system that has these properties is said to be an open system. The energy in such systems is unbounded. However, in order for a system to be stable, its Hamiltonian must be bounded from below. As a result, there cannot be an operator that has negative eigenvalues. Pauli's objection to a universal operator still applies to these systems. Nevertheless, Hilgevoord states that the demand for a lower bound to the Hamiltonian values does not apply for isolated systems. This implies that the only systems that bypass Pauli's argument are isolated continuous systems.

that mirrors the behavior of the t coordinate under time translation. For example, a dynamical time variable can be a pointer position, an angle, or a momentum.[26] The corresponding operator for a dynamical time variable can also be represented by different functions. The type of functions that will define the time operator will depend on the dynamical time variable used to describe the physical system that will serve as a clock. Each physical system/clock will have a unique time operator. Some dynamical physical systems will have discrete time variables, others will have continuous time variables, and others will not have time variables. As Hilgevoord states:

> "If we are to look for a time operator in quantum mechanics, we should not try to quantize the universal time coordinate but consider timelike (in the literal sense) dynamical variables of specific physical systems, that is, clocks. Because a clock variable is an ordinary dynamical variable, quantization should not, in principle, be especially problematic." (p.303)

Hilgevoord shows how ordinary operators can be used to represent time variables in three different types of physical systems—i.e. linear quantum clocks, continuous cyclic quantum clocks, and discrete cyclic quantum clocks. It must be remembered that whatever operator is used to represent the dynamical time variable, it has to satisfy the conjugate commutation relation for the time and energy $[\eta, H]=0$, $[\theta, H]=i\hbar$. It is important to note that although this is also a conjugate commutation relation for time and energy, it is not the same as the conjugate commutation relation $[t, H]=i\hbar$. Whereas the former is a relation for time and energy operators, the latter is for time as a parameter t and a Hamiltonian operator. This distinction is important

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[26] E.P. Wigner (1957) introduced the notion of a quantum clock. Others that discuss the nature of quantum clocks include A. Peres (1980) and C. Rovelli (1991).

because it takes into account Pauli's argument. Whereas the $[t, H]=i\hbar$ conjugate commutation relation is not possible, the $[\eta, H]=0$, $[\theta, H]=i\hbar$ conjugate commutation relations is possible. Hilgevoord notes how in the case of a linear quantum clock, the conjugate commutation relation for time and energy is satisfied under the following conditions:

1) θ is the multiplication operator.
2) $\eta= - i\hbar d/d\theta$.
3) $H= \eta$.
4) θ and η are operators that satisfy the relation $[\theta, \eta]=i\hbar$.
5) $\theta, \eta,$ and H have eigenvalues that span over the entire real axis.

In the linear quantum clock, the Hamiltonian has continuous eigenvalues. Furthermore, the operator θ has the similar functions as the universal time parameter t. This is because both have continuous eigenvalues ranging from $-\infty$ to $+\infty$. The continuous cyclic quantum clock works similarly to linear quantum clock. The difference is that the intervals that define the function for the time operator are finite. For the continuous quantum clock, the energy is unbounded yet it has discrete energy eigenvalues. To illustrate the nature of a continuous quantum clock, Hilgevoord uses the following analogy: "[this] is precisely the behavior we expect of the hand of a clock: it rotates at constant angular velocity and after an arbitrarily short time, an eigenstate $|\varphi>$ of the hand position goes to an orthogonal state" (p. 304). Like the continuous quantum clock, the discrete quantum clock has discrete energy eigenvalues. The difference is that the discrete quantum clock's time translations are also discrete. To illustrate the nature of the discrete quantum clock, Hilgevoord uses the following analogy: "this behavior brings to mind the famous clock in the railway station that can only show discrete times" (p. 305). By considering different physical systems such as clocks, Hilgevoord is able to show how depending on the system, dynamical variables can be established and represented by "well behaved" ordinary operators. According to Hilgevoord, Pauli's argument only applies if we expect the time operator to be universal and behave exactly as the c-number t. This expectation is a result of not acknowledging the differences between dynamical variables and space-time coordinates.

Although Hilgevoord argues in "Time and Quantum Mechanics" that any physical system that qualifies as a clock can yield a specific time operator that will satisfy the energy-time uncertainty relation, he does not provide a general formula for the energy-time uncertainty relation that can apply to all types of clocks. However, he does so in his article "The Uncertainty Principle for Energy and Time" (Hilgevood, 2006). Instead of focusing on finding clock and energy variables that can be represented by operators, Hilgevoord uses the lifetime and the energy width of a quantum state to show how operators can be used to satisfy a version of the time-energy uncertainty relation that can apply to any system. He states that in an arbitrary closed system, its lifetime and energy width can be derived from the equation $<\Psi|\mathbf{U}(a)|\Psi>=\int e^{iaE}|<E|\Psi>|^2\, dE$ where $<\Psi|\mathbf{U}(a)|\Psi>$ is the transition or survival amplitude of the state of the system $|\Psi>$ and the square of its absolute value $|<\Psi|\mathbf{U}(a)|\Psi>|^2$ is the probability of finding the state of the system $|\Psi>$ in its initial state after an interval of time a has passed. The lifetime of a physical system β can be defined in terms of the equation $<\Psi|\mathbf{U}(\tau_\beta)|\Psi>= \beta \quad (\beta<1)$ where τ_β is the smallest time interval that satisfies this equation. For example, for the half-life of a system, β will equal $\sqrt{1/2}$ and $\tau_{\sqrt{1/2}}$ will the smallest time interval in which there is a 50% probability of finding the system in its initial state. The energy width of a physical system W can be defined in terms of the equation $\int_{W\alpha}|<E|\Psi>|^2\, \mathrm{dE}=\alpha \quad (\alpha<1)$ where W_α is the smallest energy interval that satisfies this equation. For example, when $\alpha=0.9$, W_α will be the smallest energy interval that can contain 90% of the energy distribution of a system. From the latter three equations, the energy-time uncertainty relation $\tau_\beta W_\alpha \geq 2\hbar \arccos((\beta+1-\alpha)/\alpha)$, $(\beta \leq 2\alpha - 1)$ can be established which is valid for all states $|\Psi>$. For the examples given above, this relation would be $\tau_{\surd 1/2} W_{0.9} \geq 0.9\hbar$ (p.1455).

Exposition of the Ontology of Time Unaddressed by Hilgevoord

Although Hilgevoord addresses how time as an operator should be dealt with in quantum mechanics, he does not address what his approach says about the ontology of time. Hilgevoord argues that if time is to be dealt with properly in quantum mechanics, it should not be equated with the time coordinate *t*. In fact, Pauli showed that such a conception of time is problematic because time as a parameter is not an observable (dynamical variable) and as such, it cannot be represented by an operator. Hilgevoord shows that Pauli's argument applies only if time is represented by a *universal* operator. However, instead of accepting that time cannot exist as an observable and confining it to a parameter, time can be seen as an observable that is dependent on physical systems. If time is measured in terms of observables such clock variables, time variables, or the lifetime of a system, an ordinary operator for time can be determined. Furthermore, he shows that the measure of time as an observable will vary from system to system. This implies that time is not an independent observable that is extrinsic to a physical system. Instead, time is internal to the physical system being measured. In this sense, time is derived from physical systems. However, this is a claim about the ontology of time that Hilgevoord does not quite address. Instead, he just makes claims about the impact his approach has on the epistemological accounts of time. He states:

> "It seems plausible that the notions of space and time are derived from the properties of material bodies. The *q*'s and *w*'s would then correspond to more primitive notions of space and time than the *x*'s and *t*, the latter being abstractions from the former. We may speculate that the concrete notions of time as they are connected with periodic changes would have led to the abstract notion of a single linear time extending from minus to plus infinity. Similarly, the local notions of space as derived from the behavior of material

> bodies would have led to the abstract notion of an infinitely extended linear space. Thus there would have originated the idea of an empty, infinitely extended linear space time, the stage on which the drama of nature unfolds and the starting point of most considerations in theoretical physics since Newton" (Hilgevoord, 1996, p. 1454).

In this quote, Hilgevood is only making claims about the way that time is *perceived* to be based on observations of physical systems. He does not explicitly state time itself depends on physical systems. To him, what depend on physical systems are the claims that we can make about time. The fact that Hilgevoord is hesitant about making claims about the ontology of time can be seen in both articles. For example, although Hilgevoord (1996) shows that time can be represented by dynamical variables and operators, he claims that such observables pertain to "'*timelike*' canonical variables" (p.1451). That is, instead of claiming that these observables are measuring time, he claims that they are measuring something that is *similar* to time. Although Hilgevoord does not explicitly state what these timelike variables are measuring, it is can be inferred from the formulas he is using that they are measuring the amount of change that a system undergoes. If the "Relationism with Respect to Time" or the "Reductionism with Respect to Time" approach in philosophy is taken, then these timelike variables are precisely measuring time. As a consequence, the "Absolutism with Respect to Time" or the "Substantivalism with Respect to Time" approach in philosophy cannot be valid.

Furthermore, Hilgevoord's (2002) hesitation is displayed when he separates space-time from physicals systems. For example, his analysis of the problem of time assumes that physical systems are independent from a continuous space-time background. Although he acknowledges that this assumption is an important issue, he is not willing to consider any other alternatives. He states, "How the existence of this space and time background is to be justified is an important and difficult question into which I will not enter" (p.301). Another example of Hilgevoord's separation of space-time from physical systems is found in his claim that they do not need to have the same properties. Whereas space is supposed to possess both translational and rotational symmetry and time is supposed to possess translational symmetry, physical systems do not. As Hilgevoord states, "it is important to note that individual physical systems in space-time need not show these symmetries" (p.301). The separation of space-time from physical systems shows how Hilgevoord remains largely unconcerned with the implications of not providing an accurate account of the nature of time using formalism/mathematical tools that assume that time can be represented as being continuous, independent, and absolute.

However, I am proposing that the ontological implications of Hilgevoord's work should be taken into account when describing the nature of time.[27] If this is done, then time itself is dependent on physical systems. As a result, time as an observable cannot exist if there are no physical systems. This implies that time cannot be an independent substance or background where physical systems are contained. The account of the ontology of time I am proposing suggests that time is an internal property of physical systems themselves.[28] Thus, accounts in standard quantum mechanics and in philosophy that claiming that time is an independent background does not address the nature of time appropriately. If this is the case, then the formalism/mathematical tools used in quantum mechanics suggesting that time is independent from physical systems should be not be used. For example, since the parameter *t* does not adequately represent the nature of physical systems, it should not be used as a mathematical tool

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[27] Due to the interconnection between space and time that was demonstrated by Einstein's theory of relativity, the claims made about time can also apply to space. However, since the focus of this thesis is time, I do not address how such claims also apply to space. For this reason, I limit myself to only making claims about the nature of time.

[28] This will be explored in greater detail in the next section of this thesis.

to account for the succession of events (time). Just as Einstein replaced the Cartesian coordinate system for the Gaussian coordinate system in order to account for the effects of gravity on space-time (Einstein, 2005),[29] the parameter *t* should be replaced by operators like those use by Hilgevoord that indicate change. Doing so will help address the problems of time in quantum mechanics more effectively.

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[29] This will be explored in greater detail in the next section of this thesis.

Implications of an Ontological Account of Time

A consequence of claiming that time is an intrinsic property of physical systems is that every physical system has its own measure of time and that these time measurements are defined in relation to the physical system being measured and to those doing the measuring. Another consequence of this approach to time is that time cannot be independent from physical/material systems. As a result, time cannot have the same properties throughout an independently existing background or stage where physical systems are placed. If these ontological implications of Hilgevoord's work are taken into account, then the picture of time that arise in quantum mechanics is analogous to the one proposed by Einstein in the theory of special[30] and general relativity.[31]

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[30] In the theory of special relativity, Einstein (2005) proves how space and time are dependent on each other. He also proves how time and space are not containers that have absolute values that are independent of the reference frame used to measure the motion of objects. He does this by showing that there cannot be an absolute measure of simultaneity through a simple thought experiment. The distance from point *A* to point *B* is measured with an observer placed at midpoint *M*. Lightning strikes at both points A and B. If the lightning strikes at both point *A* and point *B* at the same time, then these events are simultaneous. However, the law of propagation of light in electromagnetism states that the fastest light can travel in vacuum is *c*=300,00km/sec. Due to this limit, the information received at midpoint M will depend on the distance that light has to travel from point *A* to point *M* and from point *B* to point *M*. If the distances that light traverses are equal, then simultaneity can be claimed. A consequence of this is that it can no longer be concluded that absolute simultaneity is possible. Furthermore, since distance is a measure of space, and simultaneity is a measure of time, and since simultaneity is dependent on the distance light travels, then time is dependent on space. However, the special theory of relativity is limited because it assumes that space-time can be adequately represented by the rigid, uniform reference frames that make up Minkowskian spacetime. However, Einstein showed in the general theory of relativity that this assumption was wrong by showing that space-time is affected by the motion of objects. Thus, the theory of special relativity does not provide an adequate method for measuring the motion of objects. In order for the laws of nature to apply to all

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reference frames in an equal manner, the general theory of relativity had to take into account the uniqueness of each reference frame and the physical nature of space-time.

[31] In the general theory of relativity, Einstein (2005) demonstrated that the nature of space-time is affected by material objects because they produce gravitational fields. By using a thought experiment that showed the validity of the equivalence principle, Einstein demonstrated how both acceleration and gravity will have the same affect on an object. He does this by constructing a scenario where a chest is suspended in a region of empty space. Inside this chest is an observer equipped with a measuring apparatus. A rope is attached to a hook placed in the middle of the lid of this chest. If the rope is pulled with a constant force, then chest will move up at a uniform accelerated velocity. The standing observer will feel the pressure produced by the acceleration. If the observer compares his experiences inside the chest to his experiences on the Earth, and the observer has knowledge of gravitational fields, then the observer will conclude that the chest is being affected by a gravitational field. If the observer hangs an object from the rope, the rope will stretch downwards. As a result, the rope experiences a tension. The observer explains that since the rope is attached to the chest, the accelerated motion experience by the chest is transmitted to the rope. Thus, the observer concludes that the inertial mass of the object is determining the amount of the tension experienced by the rope. Now, the same chest is placed on earth. The rope also stretches downward. However, the observer provides a different explanation of why this occurs. He concludes that the gravitational mass of the object is determining the amount of tension experienced by the rope. Since the amount of tension on the rope is the same in both scenarios, the equality of inertial mass and gravitational mass is confirmed. A consequence of this is that any physical object that has acceleration will have a corresponding gravitational field. Since gravitational fields influence the trajectory of objects, a theory about the nature of the space-time continuum needs to take into consideration the effects of gravity. Such a theory must also show how space-time is affected by the motion of objects. This is because gravity fields will curve space-time. In Appendix V of *Relativity*, Einstein explains how in general relativity space-time does not have a separate existence from gravitational fields. As Einstein states, "There is no such thing as an empty space, i.e. a space without field. Space-time does not claim existence on its own, but only as a structural quality of the field" (p.176). This implies that views which treat space-time as independent of matter cannot be correct. Einstein states, "According to the general theory of relativity, the geometrical properties of space-time are not independent, but they are determined by matter" (p.143).

In SR, Einstein (2005) demonstrated how measures of time and space are established by physical events. That is, time-values and space-values[32] are dependent on the physical phenomenon that is being measured from arbitrarily established reference frames.[33] For example, if a time-value is to be obtained, then it can be establish by using a clock. Einstein showed how a clock can be constructed out of any physical system that is arbitrarily established. The physical system that Einstein chose to prove that there is no absolute measure of simultaneity included two lightning strikes, a train, and an embankment. I am proposing that a similar approach to time should be followed in quantum mechanics. Hilgevoord showed how measures of time are dependent on physical systems. The dynamic variables used to represent time are arbitrarily chosen. For example, time can be represented by momentum variables, lifetime variables, angle variables, etc. Regardless of the variable chosen, such variable is an intrinsic property[34] of the

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[32] Although I am arguing that time is dependent, I will not address the dependence time has on space since the focus of my thesis is on time. Although this approach to time facilitates the merging of space and time because now they can both be represented by operators that can be combined into components of a four vector, doing so is beyond the scope of this thesis. Nevertheless, this approach is compatible with relativistic quantum mechanics. Hilgevoord (1996) states, "Evidently, these [uncertainty] relations fit easily in a relativistic formulation of quantum mechanics. Space and time then merge into space-time and $\mathbf{P}_k$ and $\mathbf{H}$ become the components of a four vector" (p.1455). The work being done in relativistic quantum mechanics can address these issues more adequately.

[33] Both Einstein and I are proposing a "Reductionist with Respect to Time" philosophical approach.

[34] The claim that time is an intrinsic property of physical systems or objects has spurred a philosophical debate on the role of time on identity between perdurance and endurance theorists. Perdurance theorists claim that objects are composed of temporal parts or stages. Each part is only present at a particular point in time. It is the summation of all these parts that gives an object its complete identity. Endurance theorists claim that objects have spatial parts, but no temporal parts. The complete object exists at every point in time. Under this view, the identity of an object is what endures through time (Noonan, 2006).

physical system that is being measured much in the same way that the lightning strike is a physical system and its velocity *c* is an intrinsic property of light. Furthermore, just like values for the same physical phenomenon are different depending on the reference frame that is used to measure them in the theory of relativity, so should they be in quantum mechanics. That is, time is relative. In relativity, every reference frame is stationary in relation to itself. If any measure of change is to be observed, then another reference must be established. Only then can a measurement value be obtained for intrinsic properties/dynamical variables. For example, a car moving at 60 miles per hour from the reference frame of the Earth is stationary from its own reference frame. If the reference frame provided by the Earth is not used, then the value of 60 miles per hour cannot be obtained. If only the reference frame of the car is used, then no measurement value can be obtained because the car is not in motion in relation to itself. In a similar manner, I am proposing that if a measurement value for any physical systems is to be obtained, then there needs to be another physical system that is doing the measuring. This implies that it is not just because of the chosen reference frame that values for time will be different. The time-values are different because the physical systems that are both measuring and being measured are different from other systems. For example, if a time value is to be derived from the lifetime of the physical system A, another physical system B that has its own internal clock is needed to measure the lifetime of physical system A. Thus, time is a property of physical system A as measured by physical system B. The time value for system A will be different if measured by another physical system C. In this sense, time is dependent on both the physical system that is being measured and relative to the physical system that is doing the measurement. The approach I am suggesting coincides with Barbour's (2008) approach to time in "The Nature of Time" where he claims that "it is not a clock that we must define but clocks and the correlations between them" (p.7). Since different systems will have different types of clocks, the dynamical evolution of a system will be established by a comparison between these different types of clocks.

In GR, Einstein (2005) demonstrated how physical objects distort space-time due to gravity. This showed that the account of space-time as an entity that is independent and unaffected by physical objects is inaccurate. Furthermore, this implies that an accurate measure of time will have to include the effects of gravity.[35] If physical systems are used to measure time, and dynamical variables of physical systems are affected by the gravitational fields of other physical systems, then the effects of gravity and the interaction between physical systems should be taken into account when obtaining a measurement value for time. This is especially the case in quantum mechanics since the interaction between physical systems affects the properties of these systems. For example, the double-slit experiment shows how the electron can display particle and wave behavior depending on the interaction between the electron and the measuring apparatus. If the physical system used as a clock is an electron and the dynamical variable used as a measure of time is the electron's momentum, then the interaction between the apparatus and the electron must be taken into account because of the uncertainty relation between momentum and position. In quantum mechanics, the interaction and the relation between different physical systems do more than just distort space-time like Einstein had claimed. This interaction changes the nature of physical systems and as a result, it both changes and creates the properties time. If Hilgevoord's work accurately describes the nature of time as dependent on physical systems, then physical systems (including gravity fields) cannot exist without time and time cannot exist without physical systems. To Einstein, there cannot be space-time without physical objects to

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[35] Ephemeris time includes gravitational effects.

produce gravitational fields. It is not so much the physical objects themselves, but the fields they create that distort space-time. However, I am proposing that it is the physical systems themselves and the relation/interaction between them that gives rise to time.[36]

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[36] Since gravity is part of physical systems, any accurate measure of time must include the effects of gravity. However, exploring such effects is beyond the scope of this thesis. Work in quantum field theory and quantum gravity can address this issue more adequately.

Conclusion

The purpose of my thesis was to gain a better understanding about the problem of time in quantum mechanics. I aimed to explore the role that time plays in quantum mechanics and why it cannot be represented by a canonical operator. The research I have done suggests that time cannot be an operator because it is treated as a parameter instead of as a dynamical variable. As Hilgevoord claims, if this distinction is acknowledged, it becomes possible to find an operator for time. A consequence of taking this approach is that time becomes a property of physical systems. As such, time cannot be an independent background that physical systems occupy. In order to show how this is the case, my thesis focused on: 1) presenting Hilgevoord's argument about the problems of time in quantum mechanics; 2) providing an account of the ontology of time based on Hilgevoord's work; and 3) providing an analysis of the implications of what I am proposing in connection to Einstein's insights in special and general relativity. However, there are still many issues with time that could not be discussed here. In order to have a better understanding of the role of time in quantum mechanics and the problems it presents, the interdependence between time and space must be explored. Furthermore, a better understanding of the relation between time and gravity also has to be explored. These are topics that can be better addressed by research being done in areas such as relativistic quantum mechanics, quantum field theory, and quantum gravity.

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Curriculum Vita

After graduating from Bel Air High School, El Paso, Texas, in the spring of 1998, Crisol Escobedo continued her education at El Paso Community College where she received her associate's degree in psychology in the fall of 2001. She entered The University of Texas at El Paso in the fall of 2003 to pursue a bachelor's degree in both psychology and philosophy. In 2004, she received the Career Opportunities in Research Fellowship funded by NIMH for two years. Under the mentorship of Dr. Art Blume and Dr. Lawrence Cohn, she participated in various psychology research projects at The University of Texas at El Paso. In the summer of 2005, she was granted an internship at the Behavior and Research Therapy Clinic in The University of Washington, Seattle conducting research on borderline personality disorder under the mentorship of Dr. Marsha Linehan. In the spring of 2005, she presented her summer research project on borderline personality disorder titled *Neuropsychological Effects of Treatment on Borderline Personality Disorder Patients* at the national Career Opportunites in Research Conference in Atlanta, Georgia. In the spring of 2007, she presented a research project on the Maya titled *The Significance of Death for the Maya* at the in El Paso, Texas. She received her bachelor's degree in both psychology and philosophy from The University of Texas at El Paso on May, 2007. In the fall of 2007, she began her graduate work in philosophy while pursuing her master's degree in interdisciplinary studies (MAIS). When the philosophy department at The University of Texas at El Paso initiated their master's program, Ms. Escobedo began pursuing her master's degree in philosophy. In the fall of 2009, she completed her master's thesis titled *The Problem of Time in Quantum Mechanics*.