Bohr and the Measurement Problem:

Moving towards Holism in Copenhagen

by

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ABSTRACT

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This thesis is an examination of the measurement problem from within the Copenhagen interpretation of quantum mechanics where I take issue with von Neumann’s theory of measurement which argues for the subjective collapse of the wave function by a conscious observer. I argue that von Neumann’s postulate of collapse has led to several intractable philosophical and conceptual problems in its account of quantum measurement. I argue that these problems arise from von Neumann’s misreading of Bohr’s complementarity regarding the relationship between subject and object as distinct metaphysical entities. Instead, I offer a new way of defining the subject-object relation based on Don Howard’s reading of Bohr’s complementarity as subject-object nonseparability (SON). I argue that the SON principle has the potential of placing Copenhagen on more solid philosophical footing by viewing the subject-object relationship not as a causal relation, but as a relation of ontological dependence to avoid the idea of collapse altogether.
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INTRODUCTION

Quantum mechanics is a physical science that studies the behaviour of matter and energy at the sub-atomic level. It describes a world that behaves quite differently from the world of classical atomic objects, and it challenges our common conceptions of the everyday things we see, like trees, the earth, and even the universe. It is a peculiar world where elementary particles behave both as waves and particles—obeying probabilistic laws, where objects can seemingly be in two places at once, and where it becomes physically impossible to know both the position and the momentum of a particle at any given time. Trying to understand quantum mechanics inevitably leads to its most peculiar aspect of all and its most central difficulty: the measurement problem (Albert, 1995 pg.73-79). The basic idea behind the measurement problem is that it is very difficult to observe the behaviour of waves and particles at the microscopic level, and since their behaviour can only be described using probabilistic laws of quantum mechanics, we cannot predict with certainty any definite outcome of a measurement as all definite outcomes breach quantum mechanics’ linear dynamics (Albert, 1995 pg.80). Unlike classical mechanics, which can determine the exact location of a particle using deterministic laws, quantum mechanics can only describe where the particle might be located. To know where a particle is, we must measure it.

One of the primary methods of describing the behaviour of the sub-atomic world is to use mathematics. Quantum mechanics uses two basic mathematical constructs: wave mechanics and operators. When talking about the probability of where a particle might be, physicists use a mathematic tool known as the wave function developed by Erwin Schrödinger to help them understand how waves and particles behave (Rae, 2004 pg.15). The central idea behind the wave
function is that it permeates all of space and evolves according to the dynamical laws laid out in Schrödinger wave mechanics. The wave function calculates all the possible locations of where a particle might be within a given region of space as well as probabilities for its momentum, energy, and other observables, which are described by operators (Hughes, pg.14). Although the wave function can predict the various outcomes of experimental observation with extreme accuracy, these predictions are only given to us as potential outcomes. The collection of potential outcomes are then said to be in superposition, which is the term physicists use to describe the way in which quantum particles appear to exist in all states simultaneously (Albert, pg.1-16). When a measurement is made, it is said to ‘collapse the wave function’ from a collection of potential outcomes into a single definite outcome.

However, this collapse of the wave function is unacceptable to most philosophers and physicists as no one is exactly sure how or when a collapse happens. So far, there is no experimental setup that can pinpoint the precise moment when the transition from a quantum description to a classical description occurs. As a result, we still have no idea how the classical world we observe and experience arises from its quantum events. In a more precise and technical way, we say that the measurement problem is the unresolved issue of our inability to observe the physical process of how (or if) observational measurement collapses the wave-function from a superposition of many states into a definite physical state. In the Copenhagen interpretation of quantum mechanics, which is the accepted orthodox version, von Neumann’s theory of measurement states that there are two fundamental laws about how the states of quantum mechanical systems evolve. The first law states that when no measurements are taking place, the physical states of unmeasured systems evolve in accordance with Schrödinger wave mechanics, and the second law states that when measurements are taking place, the physical states of
measured systems evolve in accordance to the postulate of observational collapse, and not in accordance with Schrödinger wave mechanics (Albert, pg.80).

The problem is that Schrödinger wave mechanics do not predict or describe when a measurement takes place or how the physical process of observational measurement collapses the wave function. As a result, we still do not have a working theory of measurement for Copenhagen Interpretation that answers how the classical world we observe is resultant from its underlying quantum events. The problem that remains is that the meaning of the word ‘measurement’ is not made clear in Copenhagen, nor did von Neumann clarify its meaning either, so it is not at all clear how or if a collapse is achieved. In some interpretations, like many worlds, where each state of the physical system calculated by the wave function represents an actual superposed macro world, physicists attempt to solve the measurement problem in a different manner without requiring the collapse of the wave function (Wallace, 2001 pg.16-17).

However, before any discussion on how or if collapse occurs, we will need to revisit the measurement problem from within the Copenhagen interpretation, as it is my intention to attempt to address in a unique way this unresolved lack of clarity regarding the meaning of measurement. Let me be clear here from the start and state that this thesis does not solve the measurement problem entirely. This thesis does not provide a complete theory of how and why only one of the quantum superposition states is said to be selected from the Schrödinger equation and physically manifested at the level of macroscopic reality resulting in classicality. However, it does point towards a possible way out of the measurement problem by looking at the subject–object relation in a different way than von Neumann envisioned it. When von Neumann analyzed the concept of measurement in quantum mechanics, he did not physicalize the observer. Instead, he placed the observer outside the physical system because he regarded Bohr’s complementarity thesis as
suggesting a strong separation between the subject and the object, both epistemologically and metaphysically (McEvoy, 2001 pg. 190-192).

It should be noted that Bohr’s complementarity thesis suggests that it is impossible to observe both the wave and particle aspects simultaneously in any experimental setup, but a complete knowledge of light phenomena would require both a description of wave and particle properties. Thus, the idea of complementarity is intended to provide a fuller description of particle-wave duality taken together than merely using a single aspect of particle-wave duality alone (Plotnitsky, 2013 pg. 41-45). Bohr applied this same concept of complementarity to the relationship of subject and object to provide the fullest description of a quantum system, which this thesis argues includes the entanglement and nonseparability of the subject with the object. It is this metaphysical assumption of the separation of subject and object that led von Neumann and others to analyze that the collapse of the wave function was the creation of some kind of causal interaction between the observed object and the subjective consciousness of the observer (McEvoy, 2001 pg. 88-93).

In this thesis, I argue that the von Neumann theory of subjective collapse in Copenhagen should be rejected as it is highly objectionable on philosophical grounds. Instead, what I propose is that the von Neumann observational theory of measurement should be replaced in Copenhagen by developing a different theory of measurement that is not based on reading Bohr’s complementarity thesis as suggesting a strong separation between subject and object, but rather on reading Bohr’s complementarity thesis as Don Howard reads it: as suggesting the lack of separability between subject and object (Howard, 2004 pg. 669-671). I shall call this lack of separability the nonseparability of subject and object, or SON (subject–object nonseparability). I will argue that we have good philosophical reasons and empirical evidence for the reality of
SON derived from the nature of quantum mechanics itself and that it can form the basis for a new theory of measurement in Copenhagen in an effort to solve the measurement problem by developing a non-collapse theory of measurement. In addition, I will demonstrate that a non-collapse theory of measurement is consistent with the philosophy and scientific approach of Bohr and that it neatly side steps the highly problematic criticisms of subjectivism and dualism inevitably inherited by the von Neumann theory of measurement.

This thesis consists of four chapters. Chapter One provides a brief historical outline regarding the development of quantum theory, where I lay out some of the main physical characteristics and experimental facts that led to its discovery. In addition, I provide very basic and general introduction to the quantum formalism needed to explain quantum mechanics and its chief characteristics, which are discussed at length in Chapter Two. I acquaint the reader with the kinds of features in applied physics that classical mechanics and quantum mechanics have in common, but I also show and contrast the differences and additions in the formalism that were necessary to deal with the probabilistic nature of quantum mechanics. I introduce some notation and define some basic mathematical terms like what vectors are and what operators are and provide a simplified explanation how the Schrödinger equation works. Much of this discussion on the mathematics of quantum mechanics is based on the analysis developed in David Albert’s “Quantum Mechanics and Experience,” and it will give us the familiarity with how mathematics are applied to the study of quantum systems.

Chapter Two will show how the formalism of quantum theory connects with the actual experimental setups and thought experiments in quantum mechanics, which will reveal to us some of the basic ideas and characteristics of quantum mechanics, such as superposition, randomness, uncertainty, incompatibility, complementarity, particle-wave duality, nonlocality,
and entanglement. This chapter is essentially a nuts and bolts overview of how the characteristics of quantum mechanics radically depart from the characteristics discussed of classical mechanics. It serves as reference guide and informational component to introduce the bizarre and quirky world of quantum mechanics. It also sets the groundwork for understanding the measurement problem discussed in Chapter Three as well as helping in understanding the Howard-Bohr complementarity-inseparability issue discussed in Chapter Four. This section should prove to be more accessible and less technical than the discussion on formalism in Chapter One as it deals mainly with the conceptual aspects of quantum theory.

Chapter Three is chiefly concerned with explaining two important and central issues to the thesis: (i) explaining the measurement problem in Copenhagen and examining why it is seen as highly problematic and (ii) providing a brief introduction to Bohr’s notion of complementarity and Howard’s reading of it as a possible way towards a solution of the measurement problem. In this chapter, I give a thorough explanation of the von Neumann’s theory of measurement, and I discuss some serious philosophical objections to Copenhagen and the von Neumann theory of subjective collapse. I give a brief introduction to Bohr’s notion of complementarity and Howard’s reading of it. I discuss how Howard’s view of complementarity is vastly different than von Neumann’s view of complementarity in relation to how each philosopher defines the subject–object relation in quantum mechanics. I argue that the reason von Neumann placed the observer outside the physical system was because he believed he was following Bohr’s requirement for the strong separation of subject and object, both epistemologically and metaphysically, when analyzing Bohr’s complementarity thesis.

I maintain that von Neumann’s view on complementarity assumes a strong separation of subject and object at the quantum level. This assumption of separation between subject and
object, I argue, becomes a source of philosophical problems when trying to solve the measurement problem as it inevitably leads to the subjective causal collapse of the wave function. The idea of subjective collapse is that the individuated consciousness of the observer is somehow responsible for obtaining a definite outcome. This carries with it all the unintended consequences of dualism, subjectivism, and the problematic view that our consciousness creates reality. As a result, I discuss Howard’s interpretation of Bohr’s complementarity in opposition to the way that von Neumann is reading it and explain that rather than calling for a strong separation of subject and object from a metaphysical and epistemological viewpoint, Howard’s position is that Bohr may have actually intended that his complementarity thesis be understood as suggesting the nonseparability of subject and object (Howard, 2004 pg.669-671). I end the chapter by briefly discussing the aspects of subject–object nonseparability as Don Howard has characterized it, emphasizing that this new reading of complementarity will serve as the basis of my discussion in Chapter Four for my alternative approach to solving the measurement problem.

In Chapter Four, I discuss how my alternative approach towards a solution of the measurement problem depends on how successfully I can argue for the reality of subject–object nonseparability in quantum mechanics. This discussion will be based on the Einstein-Podolsky-Rosen (EPR) experiment, which I argue demonstrates the failure of separability of the subject and object and the genuine possibility of ontological holism. Through this discussion and the arguments contained within it, I believe I provide the necessary evidence and key arguments for the acceptance of subject–object nonseparability. Therefore, the central claim that Chapter Four makes is that quantum systems and their phenomena display certain tendencies and behaviour that allows for or possibly requires an interpretation that favours ontological holism where
subjects and objects are not separate parts of the physical system, but inseparable subject–object wholes.

I begin with the idea that the reality of SON (subject–object nonseparability) can be demonstrated by using Bohr’s response to the EPR argument when looking at the disturbance theory of measurement and questioning what was an implicit assumption (locality) about distant and classically separated systems. I conclude Chapter Four by asserting that if my arguments and claims are correct, they provide a basis for re-working Copenhagen into a more philosophically tenable position. It is a re-working that calls for the rejection of the von Neumann theory of subjective collapse and the replacement of it with a fundamentally new theory of measurement that is based on subject–object nonseparability. I believe that such a manoeuvre would lead to a non-collapse theory of measurement, and I briefly discuss what that might look like. I discuss how a non-collapse theory of measurement based on SON is actually consistent with Bohr’s overall philosophical and scientific approach.
CHAPTER ONE

One of the primary methods of describing the behaviour of quantum phenomena is the use of mathematics. Therefore, the aim of this chapter is to briefly familiarize ourselves with the mathematical notation and constructs that physicists use to describe the dynamical behaviour of quantum phenomena in order to understand how the formalism of quantum theory connects with the actual experiments. The two basic mathematical constructs of quantum mechanics I discuss are wave mechanics and operators. Getting a handle on these two constructs provides a basic layperson understanding as to how physicists understand and describe the quantum realm. As a result, I will be looking at some simplified mathematical concepts, notations, and procedures regarding the difference in formalism between classical mechanics and non-relativistic quantum mechanics.

In addition, I explain what the Schrödinger equation is and explain briefly how it is used to describe the time-evolution of a quantum system. I explain the difference between the properties of quantum systems (i.e., position, momentum, spin, etc.) that are known as ‘observables,’ and ‘operators,’ which are the mathematical representations of those properties. I explain how these observables are represented by an operator in an abstract mathematical space known as Hilbert space. I introduce terms and ideas like what vectors are, what a wave function does, and how statistical probability is applied to quantum events. I aim to keep it simple and assume no prior familiarity with the formalism of quantum mechanics. However, before I go into the mathematics, I begin with a very basic introduction on the historical origins of quantum mechanics and chronologically review some of the main physical ideas and experimental facts that led to its discovery in an effort to explain some of the problems physicists were dealing with that could not be solved classically.
1.1 The Historical Origins of Quantum Mechanics

Our understanding of physics today is generally divided into two parts: the classical period and the quantum period. The classical period of physics begins around the mid 17th century to the end of the 19th century and is largely developed around Newtonian mechanics and Maxwell’s theory of electromagnetism. In the late 17th century, Sir Isaac Newton formulated a series of equations to predict the dynamics of material bodies and the behaviour of matter in terms of particles. By the 19th century, Maxwell’s theory of electromagnetism provided a way to understand light, electricity, and magnetism by describing the behaviour of electromagnetism in terms of waves. By the end of this period, the interactions between matter and light, electricity, and magnetism were well explained by the laws of thermodynamics (Home, 1984, chapter 5). As a result, classical mechanics, the classical theory of electromagnetism, and thermodynamics generally comprised a period known as classical physics. By the end of the 19th century, these theories were so highly successful both in description and predictive power that the scientific community thought they had achieved the ultimate description of nature as it seemed all known physical phenomena could be explained and determined within the general framework of the theories of matter and light, electricity, and magnetism (Home, 1984, chapter 5).

The historical origins of quantum mechanics begins at the start of the 20th century when our understanding of physics revealed that there were a number of microscopic phenomena that resisted a classical description and explanation, such as blackbody radiation, the photoelectric effect and atomic stability, (Schwab, 2007 pg1-6). At the beginning of the 20th century, Max Planck provided a new insight and understanding on blackbody radiation when he first introduced the concept of the quantum of energy. Blackbody radiation is radiation that is produced when objects are heated. It occurs with specific kinds of objects that absorb all types of
radiation (i.e., visible light, infrared, UV, etc.) that fall on it and also radiates at all the frequencies that heat energy produces in it. Planck theorized that the energy exchange between radiation and its environment takes place in discrete or quantized amounts of energy, which eventually were called quanta by later physicists. Experimental evidence confirming Planck’s notion of quanta soon followed, giving us for the first time an accurate description of blackbody radiation. Planck’s contribution eventually led to other new discoveries and to new solutions to other problems in classical physics that were previously resisting classical explanation. Consequently, it was Planck’s notion of quantized amounts of energy now known as quanta that began what was arguably physicists’ first descent into the quantum world (Mehra, 1982, pg 23-44).

The second step happened in 1905, when Einstein postulated that Planck’s notion of the quantization of electromagnetic waves could also apply to light (although the latter is a special case of the former). This further reinforced Planck’s notion of quantized amounts of energy because it was Einstein who theorized that light itself must also be made of these discrete bits of quanta energy, or tiny particles that were eventually called photons by Gilbert Lewis in 1926 (Mehra, 1982, pg 59-83). This conceptual move from quanta to photons allowed Einstein to give a proper scientific explanation of the photoelectric effect, which also had been resisting classical explanation and a solution ever since it was first experimentally discovered by Hertz in 1887. Following Rutherford’s experimental discovery of the atomic nucleus and the Rutherford atomic model in 1911 (Mehra, 1982, pg 96-98), along with Planck’s notion of quantized amounts of energy and Einstein’s photons, the Danish physicist Niels Bohr made a further contribution to understanding the sub-atomic world when he came up with the model of the hydrogen atom around 1913. From this model, Bohr postulated that the interactions of atoms with light,
electricity, and magnetism, interactions that emit and absorb radiation, could only take place in
discrete amounts of energy resulting from the atom’s transition from different energy levels.
Bohr’s discovery soon led to the resolution of several otherwise intractable problems, such as
atomic stability (Hund, 1974 pg. 53-77).

As a result of Planck, Einstein, and Bohr’s scientific endeavours, much of the theoretical
foundations and conclusive experimental confirmation for the particle aspect of waves started to
become established and experimentally grounded. Physicists now had a new way of seeing and
understanding light as they began to realize that waves exhibit particle behaviour at the
microscopic scale, which did not fit with their previous classical concept of waves. As a result,
the classical picture was being theoretically challenged by these new discoveries and ideas on the
nature of matter and energy, which did not conform with the classical picture very well. The
theoretical situation for classical physics was challenged again in 1924, when de Broglie
introduced a paradigm shifting concept regarding the behaviour of particles that simply could not
be reconciled with the classical picture of particles solely as discrete bits of matter occupying
space-time points (Hund, 1974 pg. 143-146). He postulated that just as radiation waves exhibit
particle-like behaviour, material particles themselves display wave-like behaviour. Davisson and
Germer confirmed his theory experimentally in 1927, which showed how to produce interference
patterns that were normally thought of as a property of waves with material particles such as
electrons.

One of the main criticisms surrounding the theories and findings of Planck, Einstein, and
Bohr was that the study of the dynamics of matter at the microscopic scale seemed to be quite
arbitrary and did not follow from the first principles of quantum theory. Two of the founding
physicists of quantum mechanics, Heisenberg and Schrödinger, were not satisfied with what they
saw as the arbitrary nature of the new physics and argued that its postulates and findings needed to be grounded within the context of a consistent physical theory. As a result, Heisenberg and Schrödinger both sought to find a proper theoretical foundation for the quantum mechanics underlying the concepts and principles of this new physics. From 1923 to 1925, Heisenberg and Schrödinger worked independently to produce two mathematical and theoretical approaches to quantum mechanics. These two approaches, known as Schrödinger wave mechanics and Heisenberg matrix mechanics (Griffiths, 2005 pg.1-5,441), were developed to combine the various experimental findings of Planck, Einstein, and Bohr into a more internally self-consistent system. It was determined that Heisenberg’s matrix mechanics and Schrödinger wave mechanics not only provided an accurate reproduction of the existing experimental data, but also provided extremely reliable predictive power as well as explanatory force.

Heisenberg and Schrödinger separately derived independent formulations of quantum mechanics. Heisenberg’s matrix mechanics was developed to describe the atomic structure that had been observed in Bohr’s model of the hydrogen atom and from Planck’s notion of the quantization of waves. Heisenberg founded matrix mechanics on the idea that the only allowed values of energy exchange between microphysical systems are those that are discrete. By expressing the properties of physical objects, such as energy, position, momentum, and angular momentum in terms of matrices, Heisenberg obtained a mathematical description that describes the dynamics of microscopic systems (Griffiths, 2005 pg.441). I will not delve into the formalism of Heisenberg’s matrix mechanics or give a more detailed explanation, but only convey that this matrix formulation was very successful in accounting for the discrete quanta of light emitted and absorbed by atoms. Although useful, Heisenberg’s matrix mechanics is preferred only for some mathematical and conceptual purposes in quantum mechanics. For other
mathematical and conceptual reasons, Schrödinger’s wave mechanics became much more popular, and it is Schrödinger’s wave mechanics that will be the focus of the discussion of formalism in the next sections.

In 1923, Erwin Schrödinger developed the second formulation of quantum mechanics, which we now know as wave mechanics. Wave mechanics is the generalization of the de Broglie postulate of the dual wave-particle behaviour of matter, and it describes the dynamics of microscopic matter by way of their wave-function, called the Schrödinger equation (Albert, 1992 pg.34). Rather than describing the dynamics of matter by generating matrix values like Heisenberg, Schrödinger obtained a differential equation for which values can be calculated and solved. The solutions of this equation describe the various values of the energy spectrum as well as other observable properties, such as location, momentum, etc., regarding the quantum system under consideration (Hughes, 1989 pg 57-70 Chapter 2). Now, when we talk of quantum mechanics and the measurement problem, we often refer to the ‘collapse of the wave’ or the ‘reduction of the wave-packet’ which strictly involves the Schrödinger equation and not Heisenberg’s matrix mechanics. For this reason, we will not be looking at Heisenberg’s matrices, and my discussion on the formalism of quantum mechanics will focus on the wave mechanics of Schrödinger as the mathematical foundation of quantum mechanics.

1.2 The Formalism of Quantum Mechanics

The approach to the study of classical physics is comprised of two distinct but interrelated components: mathematical formalism and the corresponding physical interpretation. Quantum mechanics is no different. On one side, the mathematical formalism of quantum mechanics is an algorithmic structure consisting of equations and calculational procedures. On
the other side, we have the physical interpretation of theory that attempts to connect and correlate calculated values supplied by the formalism with empirical observations gathered from the actual experiments. The two basic mathematical constructs of quantum mechanics I will discuss in this chapter are wave mechanics and operators. Once these are introduced and explained, we will be better equipped with a basic understanding as to how physicists understand and describe the quantum realm. In addition, I will be looking at some of the simplified mathematical concepts, notations, and procedures regarding the difference in formalism between classical mechanics and non-relativistic quantum mechanics. This requires that we first acquaint ourselves with a number of aspects that both classical mechanics and quantum mechanics share in common.

First, I want to introduce two terms: kinematics and dynamics. Kinematics is the theory of the motion of bodies. Kinematics deals with the mathematical description of motion without considering the applied forces. The observable quantities of position, path, time, velocity, and acceleration are mathematical entities and are central to kinematics’ study (Benenson et al, 2002 pg. 3). Dynamics is the theory of motion caused by applied forces. Dynamics describes how bodies move under the action of external forces. Unlike kinematics, it is concerned with the causes of the motion on a body. The concepts of mass and force are introduced for the description of the dynamics of motion (Benenson et al, 2002, pg 37). Newton’s great achievement was to show that forces are the cause of change in the state of motion of bodies. Newton’s dynamical laws along with his three laws of motion established and demonstrated a relation between the applied forces and the kinematical quantities of velocity and acceleration in macroscopic objects. Quantum mechanics also use the kinematical quantities of velocity and acceleration, but on subatomic bodies.
Second, we need to provide a conceptual reference system regarding how we describe how bodies move through space. Motion is defined as the change of position of a body during a time interval (Benenson et al, 2002, pg 14). When we describe a motion of a body, we assign numerical values (i.e., coordinates) to the position of the body in a two-dimensional Cartesian coordinate system. The time variation of the coordinates characterizes its motion. When we are trying to determine the position of the body in space, we assign a number along an axis to explain the body’s movement though all areas of that space. For instance, a straight line is one-dimensional, since one numerical value is needed to fix the position. For example, the motion of a train is fixed along a rail and is one-dimensional (1-axis (x-value)) with one degree of freedom—the movement of left or right. An area is two-dimensional with two numerical values. An example is the motion of a car (2-axis (x, y)), which has two degrees of freedom—movement of left or right, and forwards or backwards.

However, ordinary space is three-dimensional, and three numerical values—x, y, z—are needed to fix position in that space. Spatial movement has up and down, left and right, and forwards and backwards. For example, the space in which a helicopter moves is three-dimensional: 3-axis (x, y, z) with movement of left or right, forwards or backwards, and up or down. Thus, coordinate systems are used for the mathematical description of motion. They provide numerical values to the index positions of a body within Cartesian three-dimensional space (Benenson et al, 2002, pg 3-5). A motion can thereby be described as a mathematical function that gives the space coordinates of the body at any time. These kinds of characterizations of space are known as ‘Euclidean space’ and it is based on typical Euclidean geometry. This is most commonly known as the 3-axis coordinate system within the Cartesian system consisting of perpendicular straight coordinate axes (x, y, z). The coordinates (x, y, z) of
the space point O are the orthogonal projections on the position of O onto these axes (see Fig. A.1 below).

In addition, there are other generalizations concerning the idea of the dimensions of space. For instance, Minkowski space is a four-dimensional space–time continuum, the coordinates of which are the three space coordinates and one time coordinate. Another kind of space that will figure prominently in the discussion on the formalism of quantum mechanics is the notion of a Hilbert space. A Hilbert space is a vector space or mathematical entity that does not describe an actual physical space, but instead helps generalizes the notion of Euclidean space (Griffiths, 2005 pg. 93-96). What a Hilbert space enables us to do is to expand the methods of vector algebra and calculus from two-dimensional Euclidean space and three-dimensional spaces to spaces with any finite or infinite number of dimensions. Further on, we will see that a Hilbert space is an ‘abstract vector space’ that possesses the structure of an inner product, which allows length and angle to be measured (Clifton 1996, Chapters 1&2). Please see Fig.A.2

Figure A.1 (Image from Google)

The Cartesian coordinate system is a coordinate system that specifies each point on a plane by a pair of numerical coordinates. The pair of numerical coordinates signifies the distance from the point or origin to two fixed perpendicular lines of the same length. In three dimensions, we need to specify the origin and the orientation of the x-axis and the y-axis.
The formalism of quantum mechanics is essentially based on two constructs: Schrödinger wave mechanics and operators. The physical state of the quantum system is represented by its wave function, and the operators mathematically represent the quantum observables (Hughes, 1992 pg.42-43). It is important to note that the term ‘observable’ should be distinguished in a mathematical sense and in a physical sense. In a physical sense, an observable is some property of a physical object (i.e., its position, momentum, angular spin, etc.) of the physical system or some object itself under consideration that can be ascertained by some sequence of physical operations or experimentation. In a mathematical sense, an observable is represented by an operator, which is a mathematical entity that represents some property of physical objects (Albert, 1992 pg.30-33). The physical state of the system basically refers to the portion of the physical world under analysis or sometimes refers to the state of a specific object under consideration. The state of the physical system includes all the physical processes and all events, dynamics, state of affairs, or situations that we are interested in observing in an isolated system.

To give a complete description of the state of the physical system, physicists need to be able to both describe the observable properties of physical systems that remain unchanged with respect to time and also describe those observable properties that change with respect to time. When physicists talk about the dynamics or the movement of physical objects through space-time, the complexity requires them to speak mathematically. Quantum physicists use a number of mathematical tools such as the abstract vectors of Hilbert space, operators, wave functions, and linear transformations to describe the dynamics of matter. These vectors are especially useful mathematical tools that help represent the physical state of the system vector. More specifically, a vector is a mathematical and geometric entity that has both length and direction (sometimes called magnitude) (Hughes 1992, pg.12-56). Such vectors are usually represented by line
segments with a definite direction represented graphically as an arrow that connects some starting point, in this case A, to some terminal point B (see Fig. A.2). Thus, the vector denoted here is \( \mathbf{AB} \), and it exists within the Cartesian two-dimensional \((x, y)\) coordinate plane of real space.

![Diagram of vector AB](Image from Google)

The notation for a vector in quantum mechanics is Dirac Notation, using the symbols \(| \rangle \) around some expression. This indicates the name of the vector.

The vector here is \(| \mathbf{AB} \rangle\) and denotes the vector called \( \mathbf{AB} \).

Starting point is A with a \((x, y)\) coordinate and its terminal point is B also with a \((x, y)\) coordinate

The vector \( \mathbf{AB} \)—written ‘\(| \mathbf{AB} \rangle\)’—is a mathematical object characterized by a length, \(| \mathbf{AB} |\), and a direction. Any normalized vector is a vector of length 1; i.e., \(| \mathbf{AB} | = 1\) (see Fig. A.3). Vectors can be added together using an addition rule called the parallelogram law. When you add vectors together, the addition maps any pair of vectors onto another vector so that the new vector is obtained by moving the second vector where its tail coincides with the tip of the first, without altering the length or direction of either, and then joining the tail of the first to the tip of the second (Albert, 1992 pg. 21-22). For instance, adding vectors \(| \mathbf{A} \rangle\) and \(| \mathbf{B} \rangle\) yields vector \(| \mathbf{C} \rangle = | \mathbf{A} \rangle + | \mathbf{B} \rangle\), as in Figure A.4

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Vectors can be multiplied as well. The multiplication of a vector by a vector is the inner product, which results in a coefficient/number and not another vector. The inner product is an additional structure to an inner product space normally known as a vectors space.

(1) vectors + vectors = vectors

(2) vectors x numbers = vectors

(3) vectors x vectors = inner product

In addition to adding and multiplying vectors together, another important feature of vector spaces is scaling. Scaling is when you multiply a vector by a number. By multiplying the vector by some coefficient or constant, it can either lengthen or shorten the vector, and if the
multiplier is negative, it changes the direction of the vector by reversing it (Albert 1992, pg.20-21). Multiplying a vector \(|A>|\) by \(n\), where \(n\) is a constant, gives a vector which is the same direction as \(|A>|\) but whose length is \(n\) times \(|A>|\)'s length. By multiplying a pair of coordinates \((x,y)\) by a number (coefficient) \(C\) yields \((Cx,Cy)\). In Dirac notation, the vector \(5|A>|\) is defined to be the vector direction \(5\) times the length of \(|A>|\). It is written as \(5|A>| = |A>| + |A>| + |A>| + |A>| + |A>|\). So generally speaking, multiplying an ‘\(n\)’-ordered list of elements \((A1,A2,A3…An)\) by some coefficient \(c\) yields \(c(A1,A2,A3…An) = (cA1,cA2,cA3…cAn)\).

When we have a collection of vectors, we can call that collection of vectors a vector space. Also, when we add two vectors together in the collection, we yield a number, and their sum is also a vector in that collection, but only in some vector spaces like Hilbert spaces. In addition, any vector in the collection times any real number (scaling) is also a vector in the collection. We should see that such collections clearly have to be infinite. Now when multiplying two vectors in a vector space, \(|A>|\) times \(|B>|\) (written \(<A|B>|\)) is defined to be the number: the length of \(|A>|\) times the length of \(|B>|\) times the cosine of the angle, \(\theta\), between \(|A>|\) and \(|B>|\). Thus, for a real vector space, any inner product of a pair of vectors \(|A>|\) and \(|B>|\), written ‘\(<A|B>|\)’ is a scalar equal to the product of their lengths (or ‘norms’) times the cosine of the angle, \(\theta\), between them, written as \(<A|B>| = |A>| |B>| \cos \theta\). The length of \(|A>|\), also called the norm of \(|A>|\), written \(|A>|\), is equal to the square root of the number \(<A|A>|\) because the cosine of zero degrees is the angle between \(|A>|\) and itself is equal to 1. Two vectors are then said to be ‘orthogonal’ or perpendicular if the angle between \(|A>|\) and \(|B>|\) is 90 degrees since the cosine of 90 degrees is 0 (Albert 1992, pg.20-21).

Now the dimension of a vector space is equal by definition to the maximum number (\(n\)) of vectors \(|A1>|,|A2>|,|A3>|,…|An>|\) that can be chosen in that space such that for all values of \(i\)
and \( j \) from 1 through to \( n \) such that \( i \) cannot equal \( j \) is \( \langle A | A \rangle = 0 \). This means that the dimensions of the spaces include the number of mutually perpendicular or orthogonal directions in which vectors within that vector space can point. Obviously, there are many directions in which vectors within that vector space can point given some \( n \)-dimensional space. So, finding a set of \( n-1 \) vectors in the vector space orthogonal to the original vector will always be obtainable. Such a set of vectors is said to form an orthonormal basis of that \( n \)-dimensional space. The ‘ortho’ is for orthogonal, and the ‘normal’ is for vectors whose norm length is 1 (Albert 1992, pg.20-21).

For instance, let \( |A_1> \) and \( |A_2> \) be vectors of norm length 1 (‘unit vectors’) such that \( \langle A_1 | A_2 \rangle = 0 \) such that the angle between these two unit vectors must be 90 degrees. We represent an arbitrary vector \( |B> \) in terms of our unit vectors as follows:

\[
|B> = b_1|A_1> + b_2|A_2>
\]

A graph showing how \( |B> \) can be represented as the sum of the two unit vectors \( |A_1> \) and \( |A_2> \) looks like this

(see Fig. A.5 on next page)
The set of vectors \(|A_1>, |A_2>, |A_3>, \ldots |A_n>\) thus forms an orthogonal basis of the \(n\)-dimensional vector space, and every vector in that space is expressed by the sum \(|B> = b_1|A_1> + b_2|A_2> + \ldots + b_n|A_n>\) where \(b_i = <B|A_i>\). The \(b_i\)'s here are known as B’s **expansion coefficients** in the A-basis.

This reveals how any vector (e.g., \(|B>\)) in a vector space can be constructed out of the elements (e.g., \(|A_1>\) and \(|A_2>\)) of any basis of that space (Albert 1992, pg.23).

Vectors can also be expressed by writing their expansion coefficients, relative to a given basis, in a column as: 
\[
|Q> = \begin{bmatrix} q_1 \\ q_2 \end{bmatrix}
\]
where \(q_i = <Q|A_i>\) and the \(A_i\) is the chosen basis vectors. Since vector spaces can be of an infinite dimension as discussed, it would be impossible to write out the whole column of expansion coefficients required to pick out a vector. Such a column would be infinitely long. Since we cannot write out the entire column expansion coefficients, our physicists replace the column with a wave function for \(Q\), represented as a function \(\psi (i)\), which has those coefficients as values. The wave-function is written as \(\psi (i) = q_i = <Q|A_i>\). This
means that, for any vector in a vector space, and for any basis in that vector space, we can obtain a wave function of the vector in that basis. Also, when we have some wave function for a vector, in a particular basis, we are able to devise the vector for whose wave function it is. We now have enough basic knowledge on vectors to eventually see how to connect and apply the formalism to actual experimental results. What remains is some explanation of how operators are used and how they function in conjunction with vectors within the formalism.

Operators are mathematical entities that represent the properties of observables. These mathematical entities are functions that act on the spaces of physical states for making new vectors from previous ones. When an operator is applied to some physical state, another physical state is obtained (Hughes, 1989 pg.14-15). Thus, loosely speaking, an operator is a map of a vector space that maps onto itself. What an operator does is it that it provides a definite prescription for transforming every vector in that vector space onto some other vector. So it takes any vector, say \(|B>|\) in a space onto another vector \(|B'>|\) also in that space, written as \(O|B>=|B'>|\).

Examples of operators are ‘unit operators’ that tell us to multiply every vector in that space by the number 1, such as written as \(O|B>=|B>|\), and rotational operators, which can rotate vectors by degrees if say \(O\) is 90 degrees, which transforms \(|A>+|B>|\) to \(O|A>+O|B>|\). But the kind of operator that is of particular interest to quantum algorithms are linear operators (Albert 1992, pg.25-30). These operators have the following properties:

1. \(O(|A>+|B>) = O|A>+O|B>\)

(1) States that if we take that vector which is the sum of two vectors \(|A>|\) and \(|B>|\), and operate on that sum, the new vector will be that vector which is the sum of the new vector produced by operating on \(|A>|\) with \(O\) and the new vector produced by operating on \(|B>|\) with \(O\).
2. $O(c|A\rangle) = c(O|A\rangle)$  

(2) States that the vector produced by operating on $c \times |A\rangle$ with $O$ is the same as $c$ times the vector produced by operating on $|A\rangle$ itself with $O$, for any number $c$.

In finite-dimensional vector spaces, linear operators are also easily represented by arrays of numbers similar to how a column of $N$ numbers can represent any vector in an $N$-dimensional space relative to a choice of basis for the space. Here, the linear operator on the $N$-dimensional space is represented in a column notation by $N^2$ numbers, but the difference in the column is arranged in a matrix as follows: $O = \begin{bmatrix} O_{11} & O_{12} \\ O_{21} & O_{22} \end{bmatrix}$ where $O_{ij} = \langle A_i | O | A_j \rangle$ and the $|A_N\rangle$ are the basis vectors of the space. The result of the linear operator $O$ on the vector $B$ is determined as follows:

$$O|B\rangle = \begin{bmatrix} O_{11} & O_{12} \\ O_{21} & O_{22} \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} O_{11}b_1 + O_{12}b_2 \\ O_{21}b_1 + O_{22}b_2 \end{bmatrix} = |B'\rangle$$

What this shows is that we can calculate the operator $O$ effect ($O$ is some number) on any vector $|B\rangle$ by multiplying the $O$-matrix by the $|B\rangle$ vector column. Observables are represented by what is called Hermitian linear operators (Griffiths 2005, pg.100-101). The operator $\hat{O}$ can be thought of as something that operates on a function to produce another function—for example, $O f(x) = g(x)$. Usually, the operators of quantum mechanics are linear as long as they possess properties. For instance, $O [f(x) + g(x)] = O f(x) + O g(x) = O c f(x) = O c g(x)$ where $c$ is a constant for any
functions \( f \) and \( g \) and for any complex numbers \( a \) and \( b \). These perform and constitute linear transformations on the space of all functions. What we need to know is that operators mathematically represent observables and help carry out calculations to determine various numerical values of the properties of those observables.

Our last bit of terminology concerns that of an eigenvector. If the operator \( \hat{O} \) is operating on \(|B\rangle\), written \( \hat{O}|B\rangle \), and generates a new vector \( \hat{O}|B\rangle \) (where \( i \) is some number) that is pointing in the same direction as \(|B\rangle\), then \(|B\rangle \) is called an eigenvector of \( \hat{O} \) and has an eigenvalue \( i \) that is the length of that new vector relative to the length of \(|B\rangle\). Thus, \(|B\rangle \) is an eigenvector of \( \hat{O} \) with eigenvalue \( i \) if, and only if, \( \hat{O}|B\rangle = i|B\rangle \). The eigenvector/operator relation stays the same under a change of basis. This means that different operators can have different eigenvectors, but the eigenvector/operator relation depends only on the operator and vectors you are using, and not on the particular basis in which they are expressed. Expressed another way, if the eigenvector/operator relation obtains between the vector column and the operator matrix of a certain vector and a certain operator in some particular basis, then it can be shown that the same relation, with the same eigenvalue, will obtain between the vector column and the operator matrix for any basis in whatever space (Albert, 1992 pg.28-29). Note that an eigenstate is the measured state of the object in question represented by a vector possessing some quantifiable attribute like position and momentum (etc.) and the eigenvalue is the known value of whatever attribute is being measured.

Earlier, I stated that the mathematical formalism of quantum mechanics is an algorithmic structure consisting of equations and calculational procedures. The ideas discussed so far on vectors and operators are some of the fundamentals that go into the algorithmic formulation of a
quantum mechanical representation of a basic physical system. However, we also need to look at
the how motion and change are expressed in quantum mechanics. Given some moment in time,
there is a vector that represents the state of the system at that time. At a future moment in time,
there is also a vector that represents the state of the system at that time. In quantum mechanics,
the dynamics of the state vector evolve into the future and changes according to its initial
conditions, applied forces, constraints, and deterministic laws that are in the form of an equation
of motion. In non-relativistic systems, the deterministic equation of motion is known as the
Schrödinger equation, which I will explain in the coming sections. As all state vectors are a
vector length of 1, any changes in state vectors prescribed by the dynamical laws of motion are
always changes in direction and never in length (Albert, 1992, pg 30-34).

The important property of quantum mechanical dynamical laws is linearity. For instance,
if we observe a certain system at a certain time of $t_1$, whose state vector at $t_1$ is $|A>$, it evolves
according to the dynamical laws at $t_2$ into $|A^1>$. Take that same system at time $t_1$, whose state
vector at $t_1$ is $|B>$: it evolves according to the dynamical laws at $t_2$ into $|B^1>$. Given that this is
the same system and that it is subject to the same applied forces and constraints, the dynamical
laws prescribe that if the system were in a state of $\alpha|A> + \alpha|B>$ at time $t_1$, then its state at $t_2$ will
be $\alpha|A^1> + \alpha|B^1>$. Using the formalism here, not only can we describe mathematically how
different states of affairs and physical situations change throughout time, but we can also
describe and predict with a good deal of certainty what changes will occur in the system by
picking out their associated state vector with respect to some specified time length. Of course,
this does not predict which definite outcome will be obtained as the dynamics of what takes
place during a measurement is nonlinear and probabilistic (Albert, 1992, pg 34-35).
In addition, every vector assigned in the algorithm represents a possible physical state in that the system’s associated space, i.e., the state vector. Since the dynamical laws evolve deterministically, we can predict many possible states at many possible times—if not infinitely many. The advantage here is that one can represent multiple physical states in the system with multiple vectors all with respect to different times. More importantly, it allows for the possibility of superposing two physical states over one another to form another. This superposing is reflected in the algorithm by the possibility of adding and subtracting two vectors to form another vector. This idea of super-positioning will be further discussed in Chapter 2 when I explain the double-slit experiment and Schrödinger’s cat.

Lastly, the measurable properties or observables of physical systems are represented in the algorithm by linear operators on the vector spaces associated with those systems. The way we connect operators and vectors is by seeing if the vector associated with a particular state is also an eigenvector with some eigenvalue ‘a’ of an operator associated with some particular measurable property of that system. If it is, then that state possesses the value ‘a’ of that particular measurable property. There is more on operators, vectors, and dynamics than what I have discussed here, but this is enough of an introduction to understand my example in Chapter Two. In Chapter Two, I give an experimental example of how the formalism connects with an actual experiment to help demonstrate how operators function and how they represent the behaviour of quantum objects. It is hoped that the example in Chapter Two helps solidify some of the formalism discussed here. Chapter Two should also help describe and illustrate that the ideas of superposition, incompatibility (these are pairs of observables whose operators do not commute), probability, and indeterminism that we have learned here in Chapter One can be accounted for and expressed by vectors and operators in quantum mechanics. Chapter Two’s
Albert’s colour box example should help concretize our basic understanding of the formalism discussed here in terms of how it works to describe physical systems.

1.3 The Schrödinger Equation

In the Copenhagen interpretation, the Schrödinger equation is an equation that calculates the changes in state vectors with respect to a given time under initial conditions. It represents the most complete description that can be given to the evolution of any physical system that is microscopic (molecular, atomic, or sub-atomic) (Hughes, 1989 pg.113-118). Since the Schrödinger equation is non-relativistic, that is, it describes time in a way that is not conducive for relativistic theories, its basic form is the ‘time-dependent’ formulation, which describes the state of the physical systems as it evolves according to the system’s dynamical laws, initial conditions, and boundaries. (There is a time-independent formulation, but it will not concern us here.) The ‘time-dependent’ formulation of the Schrödinger equation is as follows:

\[ i\hbar \frac{\partial}{\partial t} \Psi = \hat{H} \Psi \]

Where \( \Psi \) is the wave function or state vector. Where \( i\hbar \frac{\partial}{\partial t} \Psi \) is the energy operator (\( i \) is the imaginary unit) and \( \hbar \) is the reduced Planck constant

\( \hat{H} \) is the Hamiltonian operator, which is the state of definite total energy of kinetic and potential energy.

To help demonstrate the function and role of the ‘time-dependent’ formulation of the Schrödinger equation, consider the following illustration in Figure A.6. Figure A.6 depicts some classical particle of mass \( m \) in motion constrained on a one-dimensional path of an x-axis.
In classical mechanics, to calculate the position of particle $m$ at some given time $x(t)$, we apply Newton’s second law: $F = ma$. If a force acting on an object is a function of position only, it is said to be a conservative force, and it can be represented by a potential energy function, which for a one-dimensional case satisfies the following derivative condition. The force here can be expressed as a derivative of a potential energy function: $F = -\frac{dV}{dx}$. Rewriting the equation, we have $-\frac{dV}{dx} = m\frac{d^2x}{dt^2}$. From this, along with the appropriate initial conditions of position and velocity at $t=0$, we can determine $x(t)$. Once $x(t)$ is determined, we can calculate the velocity: $v=dx/dt$, the momentum: $p=mv$, the kinetic energy: $T = \frac{1}{2}mv^2$, and other dynamical variables we are seeking to obtain. Thus, contrary to the indeterministic laws of quantum mechanics, we can see that classical physics is solely deterministic (Griffiths, 2005, pg. 1-2).

In quantum mechanics, the Schrödinger equation functions in an analogous way to Newton’s second law, but instead of determining $x(t)$ or the particle’s location for all times, the Schrödinger equation determines $\Psi(x,t)$ or the particle’s wave function for all times given the appropriate initial conditions and boundaries.
We obtain these results by solving the Schrödinger equation:

\[
\frac{i\hbar}{\partial t} \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + V\psi
\]

Here \(i\) is the square root of \(-1\) and \(\hbar\) is Planck’s constant, i.e. the original constant (\(h\)) divided by \(2\pi\).

It should be noted that when discussing the application of Newton’s second law to solve for \(x(t)\), we were obtaining results for the particle by way of space–time points since classically described, a particle, by nature, is a localized point. However, in quantum mechanics, the wave function \(\psi(x,t)\) describes the state of the particle as ‘spread out in space’ as it is a function of \(x\) for any time \(t\). This means that particle is not represented solely by any one specific localized point but is instead represented as a collection of possible localized space–time points. Thus, with respect to the position basis, the state vector describes this collection of possible locations as a superposition of definite position values (Griffiths, 2005, pg. 1-3). Here we can begin to see how the formalism takes shape and why vectors and operators are very useful in describing the physical system since there is more than one state to represent and more than one value for the position basis.

However, it may seem awkward to represent the state of the particle as spread out as a wave of possible localized space–time points when the classical nature of talking about a particle naturally refers to a single location in space–time. As a result, Born’s statistical interpretation of the wave function \(\psi(x,t)\) squares the wave function in order to provide a probability distribution of where the particle is most likely to be. Born’s statistical interpretation of the wave function, which says that \(|\psi(x,t)|^2\), gives us the probability of finding the particle at point \(x\), at some time \(t\), which is written as the following:

\[
\int_a^b |\psi(x,t)|^2 \, dx
\]

This means that we can obtain the
probability of finding the particle between $a$ and $b$, at time $t$ (Griffiths, 2005, pg. 1-3). Consider Figure A.7.

Figure A.7

The wave function $|\psi(x,t)|^2$. The shaded area gives us the probability of finding the particle between $a$ and $b$. It illustrates that the particle is most likely to be found near $A$ and most unlikely to be found near $B$. (Diagram from David Griffiths Introduction to Quantum Mechanics)

What happens is that this statistical interpretation of the wave function introduced by Born brings in a level of indeterminacy into quantum mechanics as we cannot predict with absolute certainty exactly where the particle will be located despite the wave function having calculated all the most possible outcomes. Much to the disappointment of Einstein, all quantum mechanics can offer us is statistical information about possible results. Only until a measurement is made do we actually obtain a definite result. The issues of indeterminacy, probability, the measurement problem, and other bizarre peculiarities of quantum mechanics have been absolutely perplexing to physicists and to philosophers, to say the least. There is much more to say about the formalism of quantum mechanics that what I have done justice to here. I continue on in Chapter Two, taking up the issues of indeterminacy, probability, and nonlocality. It is hoped that the examples in Chapter Two not only will show how the formalism links up with actual experiments, but also how the formalism reflects the indeterminacy and probability and other characteristics of quantum mechanics.
CHAPTER TWO

In this chapter, I use some well known quantum thought experiments and physical setups to lay out the main characteristics of quantum mechanics. I use David Albert’s colour boxes example to show how the formalism of quantum mechanics discussed in Chapter One actually connects with experimental setups to help us understand and describe quantum phenomena. The main characteristics and ideas I will touch upon here in Chapter Two are superposition, randomness, uncertainty, incompatibility, particle-wave duality, complementarity, nonlocality, and entanglement. A discussion of these characteristics will be central in supporting subject–object nonseparability for the latter chapters, especially the characteristics of entanglement, complementarity, incompatibility, and nonlocality, as a study of these characteristics figures prominently in the EPR debate for developing an argument for the reality of SON discussed in Chapter Four. So, although the main focus of this chapter is to provide us with a general understanding of the main characteristics of quantum mechanics and how the formalism of Chapter One describes and predicts it, much of the rest of the discussion sets the philosophical groundwork for understanding the problem of measurement, which will be our main topic of discussion in chapters three and four.

In Section 2.1, I discuss and explain some thought experiments and other physical experimental setups that will help us understand the ideas of quantum superposition, incompatibility, uncertainty, and other notable quantum features. The main example I use is Albert’s black box example. In Section 2.2, I discuss the double slit experiment to demonstrate the particle-wave duality of light. The double slit experiment is highly significant as it is said to contain all the mysteries of quantum mechanics and is the chief reason Bohr developed his notion of complementarity as the double slit experiment is impossible to explain in any classical
way. I believe these examples are good starting points for helping us understand the peculiarities of quantum phenomena as well as setting us on the path to understanding Bohr’s complementarity.

What we will see is that all of the discussion and examples used here in Chapter Two converge towards the problem of understanding the issue of measurement in quantum mechanics. Each characteristic I discuss, from superposition to entanglement, reveals the difficulty of explaining how classicality arises from the quantum domain. At the heart of the matter is how to reconcile the microscopic indeterminate events of quantum mechanics described by probabilities with our world of everyday deterministic macroscopic experience. Chapter One’s short introduction on the historical development of quantum mechanics revealed that the current science and underlying philosophy in classical physics was inadequate in the face of new discoveries being made in quantum physics because the language and conceptual framework of classical physics was ill-equipped to explain the strange characteristics of quantum mechanics. As a result, a new formalism had to be developed to deal with the indeterminism and probabilistic nature of quantum formalism as well as its other strange characteristics.

2.1 The Characteristics of Quantum Mechanics

We briefly encountered one of the main characteristics of quantum mechanics—the idea of superposition—when I discussed in Chapter One how vectors can be added together and how they can represent multiple physical states and affairs at a single time. To bring out the idea of quantum superposition (as well as other characteristics) in full, I will be discussing a number of well known quantum thought experiments and physical setups. I start with Albert’s black box example, the double slit experiment, and a few others, to demonstrate some of the other bizarre characteristics of quantum mechanics, namely those of randomness, incompatibility, and
uncertainty. In Albert’s black box example, we are told to consider two made-up physical properties of electrons: hardness and colour (this example is really an analogue of spin $x$ and spin $y$ that I discuss later in this chapter). Albert’s black box is an apparatus for measuring colour and also hardness (a black box is a metaphor for any device whose workings are not understood by or accessible to its user). To help illustrate quantum mechanics’ characteristics of incompatibility, uncertainty, and randomness, Albert mentions that it is an empirical fact that the colour of an electron can take on only two possible values: white or black. No other colours have ever been seen or recorded. This is the same for hardness; only hard and soft electrons are possible. In the example, a black box is constructed to measure whether electrons are hard or soft, white or black. There is one box built for measuring colour, one for measuring hardness, and one for measuring both hardness and colour, one after the other, but never together (Albert, 1992 pg.1-15).

When electrons are fed through the box for measuring colour, there are two possible exits: an aperture marked $B$ where black electrons come out and an aperture marked $W$ where white electrons come out. For every black electron that enters the colour box, it exits $B$, and for every white electron, it exits $W$. Thus, the colour of every electron can be inferred from what aperture it exits, either $B$ or $W$. By definition, if a certain electron is measured to be black, it has exited aperture $B$, and if that same electron was fed through another colour box, then that electron will with certainty also emerge from the second colour box through aperture $B$. The same goes for the hardness box

(See Fig. A.8 on next page. Diagrams from Albert’s Quantum Mechanics and Experience).
Questions arise whether there is a possibility that the properties of colour and hardness of an electron might be correlated. Albert tells us that the black box setup can easily test for such correlations but goes on to mention that when tested out on a sample of white electrons, precisely half emerge from the hardness aperture and half emerge from the softness aperture. Thus, it appears that there is no correlation between the two properties of hardness and colour for the electron. Instead, the colour/hardness of an electron is purely a function of the indeterminism of quantum probability since there is only a 50/50 chance about the hardness/colour of an electron (Albert 1992, pg.1-15).

As our experiment continues, a series of three boxes are constructed in a row: a colour box, then a hardness box, and then another colour box. Once again, a single electron enters the aperture of the first colour box that exits the white aperture, and then it continues and enters into the hardness box where it emerges from the soft aperture. The same electron, now observed to be white and soft, enters the third colour box. No tampering or altering has occurred between or with any of the boxes linked in this experiment. Most likely, we would expect that electron to emerge again from the white aperture, thus confirming the observation of the first colour box and our knowledge that the electron we initially measured is indeed still white. However, we receive unexpected results. It is black. Once a sample of electrons has been fired into the series of linked
boxes, the results obtained are that exactly half the electrons emerge out of the third box from the white aperture and half from the black aperture—a 50/50 split. In fact, this same 50/50 split is obtained even if we had two hardness boxes and one colour box (hardness box + colour box + hardness box). Half are soft, the other half, hard (Albert, 1992 pg.1-15).

Albert raises the question whether it is something in the construction of the hardness box that, while in the process of measuring very accurately the hardness of the electron, it somehow also disrupts its colour, and if this is the case, what it is that exactly determines which electrons have their colours changed (or hardness) and which do not. As the story turns out, there is nothing in the construction of the boxes such that if the boxes were built in a manner that would minimize or eliminate entirely the amount of disruption to colour, it would not change the results even one millionth of one percentage point away from our 50/50 split of white to black, regardless of how the boxes are constructed. As long as any and every box constructed is built to measure the colour of the electron, repeatedly the colour probability distribution has always been 50/50. What this illustrates is that one of the chief characteristics of quantum mechanics is that although it generates statistical probabilities that we can predict with exact precision, there is an element of randomization that cannot be attributed to any experimental setup nor can it be deterministically accounted for as white electrons seemingly enter the third colour box only to randomly emerge out of the black aperture where they are indeed measured to be black in a simplified thought experiment. Thus, one of the main characteristics of quantum mechanics is its indeterminacy and randomness (Albert, 1992 pg.1-15).

In fact, even if we were to observe and record all the measurable properties of the electrons that enter the first colour box and make certain that the experimental setup remains constant, fixed, and unaltered, and then try to find out if any correlations exist where the
hardness/softness affected the colour of an electron, we find that no such correlations have ever been measured and recorded to exist. Again, the statistical outcome remains exactly as before—a 50/50 split. What this means is that as far as our knowledge permits, we are completely unable to determine what accounts for why some electrons have their colours changed (or hardness) and why others do not. Moreover, a further refinement is added to this experimental setup by constructing a single box, a colour and hardness box. Such a box would require five apertures: an entry, a white-hard aperture, a white-soft aperture, a black-hard aperture, and a black-soft aperture (see Fig. A.9), which would measure and record both the colour and hardness of electrons. So the electrons that emerge from the apertures would consist of a set of electrons that were (1) white-hard, (2) white-soft, (3) black-hard, and (4) black-soft. However, such a box would be impossible to build as we can only end up with reliable information regarding the colour or hardness depending on which box is placed first (Albert, 1992 pg.1-15). So it is not the experimental setup that is preventing us from knowing with certainty the colour or hardness of an electron; it is a peculiarity of the quantum world known as Heisenberg’s uncertainty principle.

(Figures from Albert’s Quantum Mechanics and Experience)
Just as it is impossible to know the hardness and colour of an electron at the same time, it is similarly impossible to know both an electron’s position and momentum at the same time. I discuss Heisenberg’s uncertainty principle in much greater detail later on in Chapter Three in a discussion about the measurement problem.

The construction of a colour and hardness box is essentially built out of the two boxes: one hard and one colour (the best way to visualize this is to see both boxes super imposed on each other), and it is impossible to construct a box that could simultaneously measure both the hardness and colour of an electron. However, if electrons first pass through the hardness box, their hardness could change by passing through the colour box, and we would obtain consistent information about only the colour of the emerging electrons. If electrons first pass through the colour box, their colour could changed by passing through the hardness box, and we would obtain consistent information about only the hardness of the emerging electrons. It becomes evident, then, that no matter how we try, the ability to ascertain simultaneously both the hardness and colour of electrons is something that is epistemically restricted for us (Albert, 1992 pg.1-15).

This is an example of the characteristics of uncertainty and incompatibility in quantum mechanics that, if we obtain knowledge about one property of an electron, like hypothetical white colour, then we cannot obtain certain knowledge of whether that same electron is hard or soft. And if we obtain knowledge that the electron is hard, we cannot obtain certain knowledge of whether that same electron is white or black. Knowledge of these two properties are said to be incompatible—that is, we can never know both properties, colour and hardness, simultaneously. This is actually an example of Heisenberg’s principle of uncertainty ($\Delta x \Delta p \geq \hbar$) which refers to a fundamental limit on the accuracy with which certain pairs of physical properties of a particle, such as position and momentum (i.e., hardness and colour in our example), can be
simultaneously known (Bohm, 1979 pg.99-115). Thus, given any maximally uncertain case, any two variables that do not commute cannot be measured simultaneously. Heisenberg based this idea on a disturbance theory of measurement that for every measurement of a physical quantity there is an uncontrollable and unpredictable disturbance in the value of its quantity conjugate to the one being measured. In other words, the more precisely one property is measured, the less precisely the other can be controlled, determined, or known. Later on, we will see how Bohr develops his notion of complementarity around the issue of incompatibility and the uncertainty principle.

Classically, in any given system, it is maintained that all physical quantities possess variables with sharp, well-defined values at all times. Thus, the uncertainty relations gave rise to a set of questions about how to interpret such relations with respect to the classical paradigm of deterministic physics where well-defined measurable values represented true elements of physical reality. Some of the important questions that were raised concern whether the uncertainty relations apply to a single system or only to an ensemble of systems all in the same state. The other question that arose was whether the uncertainty relations implied merely a limitation on the making of certain kinds of measurements simultaneously, whether it suggested a limitation on the amount of possible knowledge one could obtain from a system, or whether it represented a limitation on the kinds of properties that can be assigned to objects at the atomic level. Once the groundwork has been laid for understanding some of the basic characteristics of quantum mechanics here in Chapter Two, I will return to some of these questions and examine Heisenberg’s uncertainty principle in a discussion about the disturbance theory of measurement when I outline the measurement problem in Chapter Three. In the next section, I explain the
double slit experiment and demonstrate how the formalism of quantum mechanics actually connects to physical setups like Albert’s black box example and the double slit experiment.

2.2 The Double Slit Experiment

The double slit experiment is a well-known experiment in quantum physics and is often chosen to demonstrate the particle-wave duality of light. However, more importantly, it is often highlighted because it is said to contain all the mysterious peculiarities of quantum mechanics which are simply impossible to explain in any classical way. I have chosen the phenomenon of particle-wave duality because it is truly the scientific and philosophic foundation of Bohr’s notion of complementarity. Thus, in order for us to understand Howard’s interpretation of Bohr’s complementarity and how it relates to the observer-observed entanglement thesis, an exploration of the double slit experiment is an excellent starting point. To begin, let us start with some basic attributes about waves and particles. A particle is essentially a microscopic localized object to which several properties like mass, solidity, etc. can be assigned at the sub-atomic level. One can visualize a particle somewhat like a tiny billiard ball that has a single discrete location. If the particle/billiard ball were moving in a closed box, it would ricochet all around, hitting different sides but with a precise and single location at all times. We can try to visualize the difference between particles and waves when we look at the following diagram (see Fig. A.10).

![Diagram of particle-wave duality of light](from Google Images)
On the other hand, a wave is not quite a thing like a particle. In fact, waves and particles are in completely different categories. The movement of waves and particles are similar in the respect that both move leftwards as depicted in the diagram above but different in the sense that a wave only really moves vertically in the sense that waves actually oscillate in place. So what a wave is is a moving pattern induced in some medium; but rather than saying waves move, it would be more accurate to say waves propagate in the medium of space and time. Another important difference is that whereas particles occupy discrete space–time points, waves propagate or ‘spread out’ in time and have no single location. So if a sound, water motion, or light wave were in a box ricocheting, it would fill the entire box with a changing pattern at all times because the waves would be bouncing of the sides of the box back towards oncoming waves, thus interfering with itself (depending on its wave frequency type), creating an interference pattern similar to that illustrated in Figure A.11.

Illustration of interference pattern of intersecting light waves

Now, armed with some basic facts about the nature of waves and particles, we are ready to examine how the double slit experiment works. Let’s consider that in the double slit experiment we have a light source that emits quanta, specifically electrons from an electron-emitting device, and a capturing screen that detects by flashing one electron upon impact. This apparatus setup allows us to record the location and time of when and where an electron is
detected on the capturing screen. Figures A.12 and A.13 will help us visualize the experimental setup. In the double slit with particles (Fig. A.12), the barrier has two slots, allowing many electrons to pass freely and thus is recorded as two horizontal streams of bright flashes or dots on the detection screen, with the highest density in the middle of the band. If there were only one slit, there would be only one horizontal stream of dots. If there were no barrier at all, the entire detection screen would be littered with dots lighting up like a night sky with flashes of stars. If the electrons go through both slits, they will most likely land directly behind the slit on the detection screen. If the electrons come in at a slight angle, they will land slightly to the sides. The resulting pattern on the detection screen is known as a particle band pattern and is the actual visual representation of the likelihood of an electron hitting each point, with the darkest bands revealing the most hits (Kafatos & Nadeau, 2000 pg.33-39) (see Fig. A.12).

Figure A.12

The Double Slit Experiment
(Images from Google)
In the double slit with waves (Fig. A.13), if only one slit is open, the pattern resembles that of behaving as a particle with one horizontal stream of dots (see the particle pattern illustrated in Fig. A.12). When both slits are opened, the waves pass through simultaneously, but as they do, they interfere with another. If the waves are in phase, they reinforce each other, but if they are out of phase, they cancel each other out. The resulting pattern is very different than the single particle band pattern pictured above. What happens is the capturing screen reveals many horizontal bands of streams of dots or an interference wave pattern (see illustration in figure A.13) with the greatest density in the middle (Kafatos & Nadeau, 2000 pg.33-39).

Figure A.13

(Images from Google)

Pattern of intensity bands of wave electrons
When both slits are opened, the waves pass through simultaneously, but as they do, they interfere with another. If the waves are in phase, they reinforce each other, but if they are out of phase, they cancel each other out. The resulting pattern is very different than the single particle band pattern pictured above. What happens is the capturing screen reveals many horizontal bands of streams of dots or an interference wave pattern (see illustration in figure A.13) with the greatest density in the middle (Kafatos & Nadeau, 2000 pg.33-39).

Here in this figure (Fig.A.14) imagine only 1 electron is emitted each second from the device. One would suppose that the pattern registered on the detection screen would be that of figure A.11.

Figure A.14

(Images from Google)

However, strangely, that is not the resulting pattern. Instead, the resulting pattern is one of an interference pattern, as shown in Figure A.13. Although the electrons behaved as particles before they hit the barrier, and presumably only one electron would pass through one slit, each one
seemed to ‘interfere’ with itself and created the resulting interference pattern seen below. In other words, before hitting the screen, they behaved as waves after leaving the slits (see the illustration in Fig. A.14)

Suppose we label the slits S1 and S2, respectively. When both S1 and S2 are open, each becomes the source of waves in Figure A.13. In that experimental arrangement, the waves spread out spherically in concentric circular waves and each comes together to produce interference patterns that appear as bands of light and dark on our detector screen, as seen in the diagram. Also, looking at our pictorial representation in Figure A.13, the dark bands reveal the areas where the waves cancel each other out, and the light bands indicate where the waves have reinforced one another. Now, if we close S2, we get a very bright or high density band on the detector screen that is directly in line with opening of S1, like in Figure A.12. Since there is no evidence of interference patterns or wave aspect in its behaviour, thus, the outcome in Figure A.12 can be understood as seeing the electrons behave as particles (Kafatos & Nadeau, 2000 pg.33-39).

In Figure A.14, we have an electron emitting device that is capable of conducting the experiment with a single particle at a time. When viewing the single electron as a particle, we naturally assume something ‘point-like’ is moving through space–time, and with both slits open, it also seems natural to expect that the particle would go through S1 or S2. But when we conduct the experiment with both slits open, we obtain a build-up of interference patterns that reveals to us the single electron’s wave aspect despite the fact that we have no way of knowing whether the single particle went through S1 or S2. Perhaps we make a certain modification to the experiment arrangement by adding sensory detectors D1 and D2 at slits S1 and S2 to find out which slit the single particle actually goes through. Suppose that we run the experiment several times by
allowing many single electrons to be emitted one at a time from the electron device which pass through slits S1 and S2 (Kafatos & Nadeau, 2000 pg.33-39).

By placing the detectors D1 and D2 at the slit openings, we are now in a position to record which slit each single electron goes through knowing from which detectors each single electron passed. The results we observe on the detector screen are that there are two bright bands like that illustrated in Figure A.12. Since no interference pattern associated with the electron behaving as a wave was recorded, we can assert that the electron at the moment of detection at D1 and D2 behaved like a particle. It would appear that the experimenter’s choice to measure and observe exactly which slit the electron passed through reveals only the particle aspect of the single electron. Thus, we cannot predict with certainty which slit the single electron will go through. We can only say that there is a 50/50 chance or probability the electron will exhibit its particle aspect once it is observed (Kafatos & Nadeau, 2000 pg.33-39).

So how can one make sense of this notion that electrons, or any other particles for that matter, are both waves and particles at the same time? It does not appear to make sense by any normal stretch of the imagination as it would seem that this particle-wave characterization is completely logically incompatible. However, given the precision of prediction and internal consistency in the formalism of quantum mechanics along with its repeatable experimental results, it is difficult to refute the theory of particle-wave duality no matter how contradictory the results seem. With this in mind, the best way to approach any kind of understanding of particle-wave duality is to view both the wave aspect and the particle aspect of an electron as physically real, but both are described as a mathematical entity, which is represented by a probability equation and has an element of statistical distribution with regard to where an object might be found in space or to what the probability of some event occurring is (recall the Born rule from...
Chapter One). Thus, when an electron behaves as a wave, its location is not well-defined and thus the Born rule is applied to the wave function to give us a probability distribution of where the location of an electron might be.

In Chapter One, I discussed how the state of a physical system can be represented mathematically by a state vector and that the collection of position basis vectors is in superposition. This means that the possibility of ‘superposing’ two states to form another is reflected by the wave function by the possibility of adding vectors to form another vector. What this suggests is that the physical state of the system—that is, the electron—when in its wave form, exists as a superposition of possible states. When this principle of superposition of multiple physical states is applied to our double slit experiment, it is possible to interpret that prior to a measurement, the electron particle travels in every kind of conceivable path since all paths generate interference. We will see when I take up the problem of measurement in Chapter Three that only when a measurement is made do we obtain a well-defined result with respect to location that corresponds to only one of the possible states determined by the Schrödinger wave function. Therefore, what the double slit experiment reveals, and that mathematics describes, is that superposition is one of the main characteristics of quantum mechanics and is also one of the more difficult aspects to logically comprehend from a metaphysical viewpoint.

Figure A.15 is a conceptual illustration of the complementarity of light, or its particle-wave duality. In physics, complementarity is also a fundamental characteristic of quantum mechanics. The principle of complementarity, first proposed by Niels Bohr, holds that some physical objects, like light, have multiple properties (e.g., wave aspects and particle aspects) that appear to be rather contradictory and mutually exclusive (McEvoy, 2001 pg.70-71). In the double slit experiment, we can observe under certain conditions the behaviour of light sometimes
as a particle and sometimes as a wave, but never simultaneously as both a wave and a particle. We will see in chapters three and four that Bohr used the uncertainty relations and particle-wave duality to expand the notion of complementarity beyond that of merely describing the properties of light and the uncertainty of position and momentum to that of describing physical reality as a whole. For Bohr, all properties of physical entities exist only in pairs, which Bohr described as complementary or conjugate pairs.

Interestingly, the formalism of quantum mechanics is well-suited for mathematically representing the characteristics of superposition and incompatibility. For instance, recall for a moment Albert’s black box example earlier in this chapter of electrons that are either black or white, and either hard or soft. Now, the rule that connects operators and their properties with
associated vectors and their physical states (for those operators) says that if a vector is associated with a particular physical state that happens to be a eigenvector with an eigenvalue of, say, ‘a,’ which also happens to be of an operator associated with a particular measurable property of the physical system being measured, then that state is the value ‘a’ of that particular measurable property. In other words, if V is some vector space, x can be a vector in that vector space, and some operator O can be a linear transformation that maps the vector space V into V, then x is the eigenvector of O with eigenvalue of λ as long as the eigenvalue equation Ox = λx obtains.

Using Albert’s black box example, we can now sketch out how the state of being hard or white is mathematically represented by constructing a vector space using two two-dimensional column vectors |hard> = \[\begin{array}{c} 1 \\ 0 \end{array}\] and |soft> \[\begin{array}{c} 0 \\ 1 \end{array}\]. These two vectors constitute the basis of the two-dimensional space that they occupy. When combined in bracket form, <hard|soft> = 0, they form a matrix with an operator that signifies the hardness property, written as ‘hardness operator’ \[
\begin{pmatrix}
1 & 0 \\
0 & -1
\end{pmatrix}
\] where the ‘hardness’ of +1 would signify the electron being hard and the ‘hardness’ of -1 would signify the electron being soft. I should note that the properties of black, white, hard, or soft are really just analogues of spin. The electrons possess angular momentum or ‘spin’ so that if electron X has a +45 degree spin, electron Y has a -45 degree spin since there is always a conservation of angular momentum that adds up to zero—for example, <+45X|-45Y> = 0. This is analogous to why <hard|soft> = 0 using a colour basis, to keep things simple (Albert, 1992, pg.31).

We can see that if we were to look at the matrix, column one shows that we have a probability of 1 that it is certain that the electron is hard, and in the other column, a probability of -1 which means that it is certain that the electron is soft. We see that if we add up the columns, they equal zero and also reflect the characteristics of randomness and probability as there is a
50/50 chance that the electron being observed is hard or soft, which we can write using the notation \( |\text{hard}\rangle = \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix} \) and \( |\text{soft}\rangle = \begin{pmatrix} 1/\sqrt{2} \\ -1/\sqrt{2} \end{pmatrix} \). In addition, in the example, not only were electrons hard or soft, but they also possessed the characteristic of being black (+1) or white (-1). This is mathematically expressed in just the same way as for the basis for hardness, only this time the basis is one of colour, which is written as \( |\text{white}\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \) and \( |\text{black}\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \) and \( |\text{white}\rangle = \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix} \) and \( |\text{black}\rangle = \begin{pmatrix} 1/\sqrt{2} \\ -1/\sqrt{2} \end{pmatrix} \). From these written notations, we can see that just as hardness is a basis of this space, colour too can be a basis of this same space. So if \( |A\rangle = \begin{pmatrix} a \\ b \end{pmatrix} \) and \( |B\rangle = \begin{pmatrix} a \\ b \end{pmatrix} \) for some particular basis, then \( |A\rangle + |B\rangle = \begin{pmatrix} a \\ b \end{pmatrix} + c \begin{pmatrix} 1 \\ 0 \end{pmatrix} \). What we end up with is some notation that accurately and predictably reflects not only the randomness and indeterminism of quantum mechanics, but also the characteristics of superposition and incompatibility. All these characteristics are reflected in the series of notations listed in figure B.7. Thus, this hopefully demonstrates how the formalism of quantum mechanics successfully connects up with the physical experiment to predict and reveal various characteristics (Chart from Albert, 1992, pg.31-33).

1. \( |\text{black}\rangle = \frac{1}{\sqrt{2}}|\text{hard}\rangle + \frac{1}{\sqrt{2}}|\text{soft}\rangle \)
2. \( |\text{white}\rangle = \frac{1}{\sqrt{2}}|\text{hard}\rangle - \frac{1}{\sqrt{2}}|\text{soft}\rangle \)
3. \( |\text{hard}\rangle = \frac{1}{\sqrt{2}}|\text{black}\rangle + \frac{1}{\sqrt{2}}|\text{white}\rangle \)
4. \( |\text{soft}\rangle = \frac{1}{\sqrt{2}}|\text{black}\rangle - \frac{1}{\sqrt{2}}|\text{white}\rangle \)
As I have said, this example using the properties of black, white, hard, or soft is really just an analogue of spin using the Stern–Gerlach example with a spin filter. The first example is a manifestation of the uncertainty principle. There are three filters set up with simplified orientations of UP, PERPENDICULAR, and DOWN. The photon device emits a stream of photons towards the first of the filters, which is orientation UP, the second, which is PERPENDICULAR, and the third, DOWN. For each group of passing photons, only half the photons emerge as UP from the first filter, only one-half emerge as PERPENDICULAR from the second filter, and only one-half emerge as DOWN from the third. However, if the second filter is removed, then no photons emerge at all from the third. It is as if the second filter changes the orientation known as ‘UP.’ The idea here is essentially to showcase the uncertainty principle, and the formalism is supposed to reflect that along with the experiment and the outcome.

Similarly, there is another setup that is essentially a correlation experiment. In this experiment, a pair of correlated electrons is emitted from a device with one set travelling left and one set travelling right. There are two electron filters left and right of the emitting device that measures the spins of the electrons. These filters again can be orientated (for simplicity) as UP, PERPENDICULAR, and DOWN. When the experiment is run, we get the following results. Briefly, if two filters have the same orientation, the correlation is zero: if the right-hand electron passes, its companion does not. When the two filters have opposite orientations, the correlation is 100%. That is, if the right-hand electron passes, so does the left companion, and if the right-hand electron does not pass, neither does its left companion. However, if two filters have perpendicular orientations, the correlation is 50%. These results, the characteristics of uncertainty, indeterminism, incompatibility, and the experimental setup are supposed to be reflected in the chart above.
2.3 Nonlocality and Entanglement

The last two characteristics of quantum mechanics to deal with are the characteristics of nonlocality and entanglement. To illustrate these characteristics, I will be looking at the Stern–Gerlach experiment. The Stern–Gerlach experiment is indispensable for discussing not only entanglement and nonlocality, but also for introducing two very important ideas: angular momentum and how the process of measurement affects a quantum system. Bringing up the basic description and fundamentals of this experiment now will serve us well later when I discuss the concept of quantum measurement and the EPR hypothesis in Chapter Three. Basically, the Stern–Gerlach experiment sends a beam of particles (e.g., photons) through a certain type of magnetic field (inhomogeneous field), and then we observe any particle’s deflection. The observation reveals that particles possess an intrinsic angular momentum similar to that of a classically spinning object, but which takes on only certain quantized values when measured (Hughes, 1989 pg.1-8).

The experiment uses electrically neutral particles to avoid any large deflection effects to the orbit of the particle moving through a magnetic field. This permits the particle’s spin-dependent effects to be more readily displayed. To understand the Stern–Gerlach experiment, and eventually the discussion on EPR, a good place to start is to explain the concept of the polarization of photonic light. Consider for a moment that there is a beam of light that travels towards us. Since the light is an electromagnetic wave, there is an electric field vibrating many times per second at any point in space as it propagates along the wave. At any time, there is also a direction towards which the electrical field must be pointing. Maxwell’s equations require that the direction of vibration along the wave is always at right angles with respect to the direction of light. This means that if the light (photons) is coming towards us, the electric field can take on
any direction, left, right, up, and down, but it cannot be pointing in the direction of towards or away from us.

When the electric field of the light (photons) remains in a constant direction, it is said to be ‘polarized.’ A plane that consists of electric field vectors is called the plane of polarization, and the direction in which the electric field points is called the polarized direction. Although a plane of polarization is a classical description of light and therefore differs from a quantum description of light—that is quanta, or packets of photons—it is mentioned only to help demonstrate the conception of polarization since quantum particles like photons are fairly analogous (but not quite the same) to classical plane polarization. There are many ways by which photons at the quantum level can become polarized, but we will consider only some simple generic polarizing device that can divide the beam of light into two polarized components to illustrate the characteristics of nonlocality and entanglement. Any greater mechanical explanation of how the device works is unnecessary for our purposes. All we need to do is to conceive of another apparatus box—which we will call a polarizer box—one with an exit aperture that we’ll use to record which direction the photon particles in the electric field are pointing (see Figure A.16). In the diagram, the polarizing box will be marked with H/V to indicate that the photon’s beam emerging photons from the box will be divided and polarized into horizontal and vertical directions (Rae, 2004 pg.23 Diagram pg. 23).
In this representation, the incident light (photons) is previously known to have a 45 degree polarization to the horizontal. When the beam of light polarized at 45 degrees enters the box designed to measure horizontal and vertical polarization, the result is very much similar to that of Albert’s hardness/softness box as half the photons exit the horizontal aperture and the other half exits the vertical aperture. (Diagram from Rae, 2004 pg.24-25, 54)

Fig. A.17

We have a 50/50 split of photons being either horizontally or vertically polarized. If either of these two beams is then passed through another polarizing device that is designed to measure both +45 degrees and -45 degrees, the original beam of light polarized at 45 degrees is eliminated by the H/V measurement, and half the photons in each beam exits through each of the +45 degrees and -45 degrees channels (see Figure A.17 above). Thus, it seems that the measuring of the horizontal and vertical polarization of the photons has appeared to change the previous state of polarization the photons are in such that it cannot be determined what their new state of polarization is until the photon is measured once again (Rae, 2004 pg. 53-66)

This example of the Stern–Gerlach experiment reveals the same characteristic of incompatibility in the uncertainty relations as did Albert’s black box example concerning the hardness and softness of an electron. To demonstrate the characteristic of nonlocality, the Stern–Gerlach experiment needs to be slightly altered and modified using two correlated photons. What we will observe is that regardless of the distance between the two photons, if we make changes
in photon A, there are instantaneous changes in photon B. We will see that measurements made at the microscopic domain appear to reject the classical notion of locality where the direct influence of one object on another requires both proximity and contact. In this experimental setup, imagine that we possess a photon emitting device that emits two photons travelling in opposite directions of the device box.

We call this a two-particle system with zero spin since the conservation of angular momentum always cancels the spin of each photon out so that the net spin equals zero. For instance, if photon A is emitted from the device box and travels 5 meters to the left, photon B is entangled in a way such that its distance from the device box is also 5 meters, but to the right. In addition, their spins are correlated as well so that if photon A is spinning +45 degrees to the left, photon B is spinning -45 to the right due to the conservation of spin (see illustration below courtesy from Google images).

Now, if a Stern–Gerlach device is placed some distance away from the photon emitting device and turned on just as the travelling photon enters its aperture, we can artificially induce a change in the angular momentum of the photon (as seen above).
For instance, if we turn on magnets in the Stern–Gerlach device when photon A is in flight and about 5 centimeters from the point from which it emerged from the photon emitting device, we can observe a change in photon A’s spin, which initially was spinning +45 degrees to the left so that it undergoes a complete polarity reversal and is now spinning -45 degrees to the right. Since photons A and B conserve spin, according to the prediction of quantum mechanics, it is certain that photon B should undergo a change in polarity and be spinning +45 degrees to the left. And this is precisely what is observed. Photon B at 5 centimeters away (an arbitrary distance) from the photon emitting device is observed to be instantaneously spinning +45 degrees to the left the moment the magnets in the Stern–Gerlach experiment are turned on, which reversed the polarity of photon A. What is interesting is that no matter the distance traversed of each photon from the emitting device, the moment the reverse spin occurs in one photon, instantaneously there appears a reverse in the other. Under a classical paradigm, this should not occur, but what this shows is that the two photons are correlated in such a way that changes to one create changes in the other, no matter how far apart (Hughes, 1989 1-8).

It matters not whether the distance displaced from the emitter is 5 centimeters, 5 meters, 5 thousand miles, or 5 million miles (although not empirically verified); the change in spin instantaneously affects the spin in the other. Thus, there appears to be an unexplained ‘connectedness’ between the two photons no matter how far apart the photons get in different local places. That these photons act and behave as if they were twins reveals a deep correlation. Whatever change is done to one, there is an instant change in the other. These nonlocal influences are difficult to interpret as it may seem that ‘information’ is being super-luminally transferred and conveyed from one particle to the next, that cause and effect are happening instantaneously whenever measurements are made on such entangled particles regardless of
proximity or causal contact. However, the idea that Einstein’s special relativity is violated is generally considered to be impossible as it is not information that travels faster than the speed of light that makes it appear that cause and effect are happening instantaneously, but rather it must be considered that at the quantum level the two photons are connected in such a way that the idea of traversing distance and the concept of locality are not applicable or meaningful (Esfeld, 2001 pg. 206-212).

To be clear, the characteristics of entanglement and nonseparability will be paramount to a discussion on solving the measurement problem in Chapter Four as there is a great deal more to say about how to philosophically interpret quantum entanglement and nonseparability than what has been covered here in Chapter Two. Here, I have only provided a preliminary understanding concerning what ‘nonlocal interactions’ are and what the concept of nonlocality means as well as have shown how the principles of nonlocality and entanglement are confirmed by experiment. In Chapter Four, I continue with the discussion of nonseparability by focusing on the EPR debate, Bell’s theorem, and quantum holism as it relates to the failure of supervenience and separability. Having explained these characteristics of quantum mechanics, I will now look at the von Neumann theory of observational measurement in Chapter Three.
CHAPTER THREE

So far in chapters one and two, we discussed quantum formalism and looked at the peculiar characteristics of quantum mechanics. In this chapter, I begin a thorough examination of the von Neumann’s theory of measurement in the Copenhagen interpretation, pinpointing what I believe is its major flaw: von Neumann’s ‘unphysicalized’ and detached observer. Believing that he was following Bohr’s complementarity thesis, which he believed called for a strong metaphysical and epistemological separation between subject and object, von Neumann separated subject from object and placed the subject or what he called the “abstract observer” outside the description of the physical system in order to break the von Neumann chain of entangled measuring devices (McEvoy, 2001 pg.88-93). According to von Neumann, the superposition of states was finally resolved at the level of consciousness when the researcher became aware of the experimental result. As a result, it seemed like it was the subjective consciousness of the observer that causally collapses the wave function. I take up five main objections to von Neumann’s theory of observational measurement in some detail that make this interpretation of complementarity and measurement philosophically untenable.

In Chapter Four, I argue that the source of our philosophic unease with Copenhagen is a direct result of von Neumann’s analysis of measurement and the metaphysical assumption of separation of subject and object. I go on to suggest that the Copenhagen interpretation would be better served if we rejected von Neumann’s theory of measurement altogether and replaced it with Howard’s interpretation of Bohr’s complementarity, which argues that Bohr’s complementarity can be read contrary to von Neumann and that it can be read as arguing for the inseparability and entanglement of the subject and object (Howard, 2004 pg.669-675). In doing so, I hope to point out the features in Copenhagen that are philosophically troublesome and also
to point to a direction for a possible solution and new theory of measurement from which to modify a more philosophically sound version of Copenhagen to be developed in Chapter Four based on the SON (again, subject–object nonseparability) principle. Ultimately, the SON principle will be used to modify Copenhagen into a non-collapse theory of measurement, which will be shown to be consistent to Bohr’s scientific and philosophical approach overall.

This chapter is divided into three sections. In the first section, I discuss Schrödinger’s cat as a way to illustrate the measurement problem and von Neumann’s solution to it. This section is mostly explanatory and serves as a basic introduction to the measurement problem. In the second section, I list five major philosophical objections to Copenhagen that arise from von Neumann’s postulate of collapse. I conclude that these objections are the product of von Neumann’s analysis of measurement and his postulate of collapse, which I argue is the result of von Neumann’s reading of Bohr’s complementarity that assumes a strong separation between subject and object. I conclude that we should reject von Neumann’s theory of measurement and look towards Howard’s reading as an alternative. In the last section, I discuss Bohr’s complementarity and Howard’s interpretation of it. I reveal how this interpretation differs vastly from von Neumann’s view of Bohr’s complementarity as Howard does not view complementarity as suggesting a strong separation between subject and object, but rather that the subject and the object form a joint and inseparable existence.

3.1 Schrödinger’s Cat, the Measurement Problem, and the von Neumann Solution

One way of understanding and illustrating the peculiarities of the measurement problem and superposition in a very simplified way is to consider Schrödinger’s cat paradox. In this thought experiment, we start with the supposition that someone has put a cat in a box with a radioactive atom and a Geiger counter. We know that the radioactive atom will decay in a
probabilistic manner in accordance with the laws of physics. The situation is that when the atom begins to decay, the Geiger counter will detect the decay event and tick, and the ticking will then trigger a hammer, and the hammer will then break a bottle of poison, and the poison will then kill the cat. Now there is a 50/50 chance of this occurring in a time interval of one hour (see Fig. A.18). Now, if physicists were to ask the question of whether the cat is alive or dead, they normally would make an observation and open the box and see what state the cat is in. However, if physicists were to ask that very same question without looking in the box, the most they could say using the formalism of quantum mechanics is that the cat is in a superposition of alive and dead with equal probability amplitudes. After opening the box, one has a 50% chance of observing that it is alive and a 50% chance it is dead (Kafatos & Nadeau, 2000 pg.47-50).

![Schrödinger’s Cat.](image)

**Figure A.18** Schrödinger’s Cat.

Prior to observation in the classical sense, there is a 50/50 chance the cat is either alive or dead, and we know the cat must be in one state or the other. But prior to observation in the quantum sense, we cannot say definitely that the cat is in one state or the other, alive or dead, because the state of the cat is described as a superposition. Being in a coherent superposition, as described by the Schrödinger equation, means that the cat is alive or dead with equal probability amplitudes. Therefore, according the quantum rules, the only way to know if the cat is alive or dead is to open the box, which is the equivalent of a measurement. In this simple example, there
are only two possible states or two possible outcomes to the physical systems that are being observed and that are described by the Schrödinger equation, but we cannot say the cat is in any definite state at all until a measurement is made. Only then we can we know for certain what state the cat is in. The Schrödinger equation describes both outcomes, but it cannot describe or account for what caused the cat to be in one state and not the other or really any state at all. The obvious question becomes, “What state is the cat actually in if we do not look inside the box?” and “What is unique about measurement that it results in resolving the superposition into the cat being one way or another?” The example of Schrödinger’s cat is designed to attempt to answer these problems (Kafatos & Nadeau, 2000 pg.47-50).

According to John von Neumann, what is unique about measurement is that it involves the consciousness of the experimenter at the point he or she becomes consciously aware of the results of the experiment in order to break what is now called the “von Neumann chain.” The von Neumann chain is the idea that no matter how many measuring devices we add to a physical system in order to obtain a definite result, each successive measuring becomes entangled with the physical system (Walker, 2000 pg 97-100). As a result, the superposition is never resolved, and no definite result can be obtained. The von Neumann chain was an argument based on the analysis of measurement and human perception that attempted to explain how the final resolution of entanglement was achieved and how the superposition was collapsed into a definite state. John von Neumann’s analysis of measurement held that the endless chain of entangled measuring devices would end the superposition by placing the final collapse at the edge of human consciousness. So von Neumann’s answer to the Schrödinger’s cat problem is that the cat collapses into a definite state the moment that the consciousness of the observer is aware of the measurement. Here is John von Neumann on how quantum mechanics works. He writes,
We wish to measure a temperature. If we want, we can . . . say: this temperature is measured by the thermometer. But we can carry the calculation further. . . . We can calculate its heating, expansion, and the resultant length of the mercury column, and then say: this length is seen by the observer. Going still further, and taking the light source . . . [and] quantum into the eye of the observer, . . . We would say: this image is registered by the retina of the observer. And were our physiological knowledge more precise than it is today, we could go still further. . . . And then in the end say, these chemical changes of his brain cells are perceived by the observer. But in any case, the matter how far we calculate—the Mercury vessel, to the scale of the thermometer, to the retina, or into the brain, at some time we must say: and this is perceived by the observer. . . . The boundary between the two is arbitrary to a very large extent. . . . But this does not change the fact that in each method of description the boundary must be put somewhere, . . . Indeed, experience only make statements of this type: an observer has made a certain (subjective) observation; and never any like this: a physical quantity has a certain value. (von Neumann 1955, pg. 419)

From this quote, we can see that von Neumann believes that the mechanism that will eventually cause the wave function to collapse in an experiment is the interaction of the consciousness of the observer at the point the experimenter becomes aware of the outcome of measurement. The state of the cat will be collapsed into one state or another—either alive or dead.

The implications of the von Neumann analysis of measurement caused Wigner to remark: The rules of quantum mechanics are correct but there is only one system which may be treated with quantum mechanics, namely the entire material world. There exist external observers which cannot be treated within quantum mechanics, namely
human (and perhaps animal) minds, which perform measurements on the brain causing wave function collapse. (Wigner 1967, pg.172, 1979)

In von Neumann’s measurement theory, there must be a separation between the object or quantum system that is being measured and the measuring apparatus—between the cat and the observer. John von Neumann also believed that Bohr’s complementarity required that there be a separate distinction between the subject during the act of measurement and the object being measured. In his own systematic and mathematical analysis of the quantum formalism, von Neumann demonstrated that the choice of where the ‘cut’ is placed, that is, where the transition from quantum to classical is made, between the measuring apparatus, which is described classically, and the system being measured, is not arbitrary. The cut was placed right at the level of consciousness. This transition, known as the Heisenberg cut, according to von Neumann occurs when the measurement is made at the level of consciousness as soon as it is registered. As a result, we end up with a theory of measurement in quantum mechanics that involves the conscious collapse of the wave function (McEvoy 2001, pg.88-92).

Of course, the subjective act of observational measurement being the mechanism that causes the wave function to collapse is the most interesting and controversial part in von Neumann’s analysis of measurement, which was accepted for the most part by everyone adhering to some form of the Copenhagen interpretation of quantum mechanics. John von Neumann noted that we as subjects do not directly observe the behaviour of particles, but rather interface with the measuring apparatus as a means of extending our perceptual fields to detect them. This interface is described by a set of postulates that distinguishes between two kinds of dynamical processes that govern the evolution of a quantum system. The first process governs the evolution of a quantum system which von Neumann called the projection process known as
process 1. Process 1 is not deterministic as the evolution of the state of the physical system, which is the outcome of a measurement, is not determined by the previous state of the system prior to measurement. Although probabilities were assigned to all possible outcomes of all possible measurements, nothing about the normal evolution of the quantum system as determined by the Schrödinger equation can predict with certainty which outcome of measurement will actually be the one achieved. According to von Neumann, process 1 is any act of measurement that results in a definite outcome (McEvoy 2001, pg.88-92).

The second process, known as process 2, is defined by Schrödinger’s equation and is thoroughly deterministic as it calculates what the state of the system will be like at any point in time as a function of initial state given the absence or interference of process 1. Process 2 determines all the probabilities that have been assigned to all possible outcomes of process 1. As a result, when process 2 assigns more than one possibility for the state of the physical system, the system is said to be in a superposition of states for whatever corresponding observable we are asking questions about. These two processes have become the orthodox formulation of quantum mechanics, but they are highly problematic as neither of these postulates describes or predicts which process occurs when. As a result, a number of important questions regarding the processes are left out. We do not know when a measurement occurs as the theory does not give us rules as to when to apply process 1 to a physical system instead of process 2 so that we can make predictions. Neither of the postulates tells us where a measurement occurs as we do not know where in the von Neumann chain of physical events, that is, from the photons bouncing off the object leading up to the registering of the event in the physical brain of the observer, where we make the cut or transition from quantum to classical (McEvoy, 2001 pg.88-92).
In his analysis of the measurement problem, von Neumann agreed with Bohr’s initial assertion that there must be a sharp distinction between the object of measurement and the subject. This led to further analysis as to where one should draw such a distinction or what was referred to by physicists as the ‘cut’ between the subject and the object of measurement. Previously discussed above as the Heisenberg cut, this cut is generally conceived of as the classical–quantum boundary that should be placed somewhere in between the quantum object and observer’s perceptions. However, as I have mentioned, it was not immediately clear as to where this cut should be placed as it is uncertain exactly where the quantum world ends and the classical world begins; nor is it clear what mental event triggered the collapse of the wave function. John von Neumann’s analysis was trying to find what caused a sudden and abrupt change in the description of the system from quantum to classical. This led von Neumann to use quantum mechanics to study what happens from the events surrounding the object being measured in the outside world right up into the eye and into the brain and mind (Walker, 2000 pg 97-100).

Von Neumann’s formalism divided the world into three systematic parts. Part I is the physical object or system being observed, part II is the measuring apparatus that is used to observe the system in part I, and part III is the observer. Von Neumann then wanted to analyze what happens between these three systems when taking a measurement in terms of an observation being made. He posed two general questions. First, what is happening when system I (physical object) is observed by the systems II (the measuring apparatus) + III (the observer) and second, what is happening to the systems I (physical object) + II (the measuring apparatus) when an observation is made by system III (the observer)? Von Neumann’s first achievement in his formalism was to show that the predictions and mathematical structures that were separately
defined were actually compatible with the combined product space of systems I and II. Second, he also showed that the states of the systems I and II are well-defined in the combined system of I+II if and only if the state of I+II can be written as the product of states I and II (McEvoy, 2001 pg.88-92).

What this showed was that it was possible to view the measuring apparatus and the physical system being observed not as separate physical systems, but as an entangled composite physical system. In order to observe some object in the physical system, the physicist requires a measuring apparatus. However, every time a measuring apparatus is added to the experiment, it becomes entangled as part of the composite physical system such that another measuring apparatus would need to be added to measure the first combined system of the physical object plus the first measuring apparatus in order to get a result. But then the second measuring apparatus that was just added would also become entangled with the composite system of the first measuring apparatus plus the physical object being measured, requiring a third measuring apparatus to obtain a result. This would carry on as an infinite regress requiring additional measuring apparatus one after the other after the other ad infinitum. The Schrödinger equation simply calculates that every time we add a measuring apparatus, we just get more and more possibilities as to what physical state the system will be in (Esfeld, 2001 pg. 275-279).

Von Neumann concluded that it must be the act of measurement that reduces the general state of |A> and |B> in systems I+II into a mixture of these products and that the collapse of the wave function determines one particular product in accordance with the Schrödinger equation. To stop the infinite regression of adding measuring devices, von Neumann conjectured that information about the results of the measurement were obtained by the light reflected back from the object into the eye of the observer, across the retina, down the optic nerve, and then into the
brain, which then became somehow registered in the consciousness of the observer (Hebert, 1985 pg. 147-148) (see the earlier von Neumann passage on the von Neumann chain mentioned above).

In this way, von Neumann attempted to trace the act of observation back to the very edge of the human mind. However, since the human brain is physical, it too became entangled just as the measuring apparatus did, becoming part of the composite system. Von Neumann believed that no matter how far back we calculated—from the object to the light hitting the eye to the image registered on the retina, down the optic nerve and into the brain, and indeed right down into the chemical changes in the brain cells themselves—there must be some point where our conscious selves say that we have observed the results of the measurement. For von Neumann, consciousness stops the regression and is the very boundary or cut between the quantum and the classical worlds. Although the boundary’s placement appeared to be arbitrary, von Neumann argued that such a boundary must be placed at the level of consciousness. Although von Neumann’s analysis does not explicitly say that the very mechanism that causes the collapse of the wave function is the causal intervention of the consciousness of the experimenter precisely when and where the experimenter becomes consciously aware of the result, it seems to be implied by von Neumann as all measuring devices were treated the same as all other physical objects made up of a collection of sub-atomic particles and thus subject to the very same quantum laws (Walker, 2000 pg 97-100).

As a result, the collapse of the wave function became tied to the subject state of the observer. Eugene Wigner took this analysis even further when he suggested “Wigner’s friend paradox.” In Wigner’s friend paradox, Wigner’s friend conducts the Schrödinger’s cat experiment and obtains a result that either makes him happy or sad. Wigner’s friend is happy if
the cat is observed alive and sad if the cat is observed dead. Wigner’s friend looks inside Schrödinger’s box to find out whether Schrödinger’s cat is alive or dead and thus collapses the wave function. However, Wigner has left the laboratory, but he comes back after lunch and opens the door to the lab. The friend then tells Wigner what state the cat is in, revealing to Wigner whether the friend is happy or sad. However, in this example, Wigner followed the same line as von Neumann’s analysis asking if Wigner’s friend’s observation is just another addition in the von Neumann chain and interaction in the long series, similar to that of the measuring apparatus eventually leading to Wigner’s knowledge of the event, or whether when Wigner’s friend observed the cat, the cat was already in one specified state. So where and when does the collapse of the wave function actually occur? Did it occur when Wigner’s friend opened the box and obtained the state of the cat or did the wave function collapse when Wigner found out the result from his friend? For von Neumann, the collapse occurs exactly when the observer first becomes aware of the result.

Wigner’s point regarding the moment before the second collapse of Wigner’s friend is that if we allow Wigner’s friend to be part of the experimental setup, then quantum mechanics predicts that before Wigner asks his friend whether the cat is dead or alive, Wigner’s friend is in a superposition of definitely believing the cat is dead and definitely believing that the cat is alive. According to Wigner, his friend collapsed the wave function of the cat when he observed it, and then Wigner collapsed the event of his friend telling him about the result, determining whether the friend is happy or sad. Wigner’s point is that if a material measuring apparatus is substituted for a conscious friend, then each step or interaction is simply part of a larger indeterminate system. Therefore, since consciousness must be in one state or another, as understood from
human experience since we never experience the phenomenology that would be acquired from being in a superposition, consciousness cannot then be in a superposition (Rae, 2004 pg.68.)

Thus for Wigner, conscious observations must be different in kind than observations and measurements that are performed by material objects. Therefore, Wigner, like von Neumann, held that the consciousness of the observer during the act of measurement is necessary for the collapse of the wave function. Von Neumann’s theory of measurement seems to have been accepted by the majority of physicists, making the Copenhagen interpretation the accepted version of quantum mechanics. However, many physicists and philosophers are not at ease with the Copenhagen interpretation—and specifically with von Neumann’s theory of measurement. In the next section, I explore the problems associated with von Neumann’s theory of measurement, revealing why it is very problematic by highlighting some of key criticisms.

3.2 Problems with von Neumann’s Collapse Postulate

In this section, I list five major philosophical objections to Copenhagen that result from von Neumann’s collapse postulate. I argue that the postulate of the collapse is itself the result of von Neumann’s analysis of measurement and interpreting Bohr’s complementarity thesis as indicating a strong separation metaphysically between subject and object. As noted, one of the main objections to Copenhagen is that von Neumann’s account of measurement with its postulate of subjective collapse is that it seems to suggest a privileged role for the subjective consciousness of the observer to select a definite outcome. The problem with subjective collapse is that it raises more questions than it solves. For instance, if von Neumann is correct, and the only things that count as measuring devices capable of collapsing the wave function are conscious minds, then we seemingly fall into some type of subjective idealism where only consciousness creates reality.
This is a kind of Berkelyan idealism where to be is to be perceived, where no phenomena is real until it is an observed phenomena (Dancy, 1998 pg.5-17), and where the reality of the objective world seems contingent upon there being conscious observers that are continually perceiving objects and events. As a result, believing in this position commits us to an anti-realism stance: the idea that only what we see and experience is real, that is, only phenomenal reality is real and any phenomena outside conscious observation are not really there. Such a position undermines the idea of a mind independent and objective world, because if there were no conscious observers, there would be no external world which arguably no physicist would agree to. Moreover, even if it were granted that consciousness creates reality, then it would seem that we would be involved in assigning a subjective account of what reality is; thus, one has to wonder how everything does not breakdown into solipsism where metaphysical and epistemological truths are ‘whatever is true for me’ and ‘whatever is true for you.’

We shall see that according to Howard, Bohr may not have agreed with this anti-realism/idealism view and that it would be wrong of us to attribute to Bohr anti-realist leanings (Howard 2004, pg.669-680). Bohr once stated that there is no quantum world, no deep reality at bottom, but this needs to be taken in context with respect to his views on what the wave function represents (Herbert 1985, pg.15-17). Bohr would have said there is no quantum reality when we try to interpret the wave function realistically (i.e., nonsuperposed) suggesting it has some kind of ontological status. According to Bohr, it does not have any ontological status but is merely of an abstract and symbolic character that is representative of quantum description (Faye, Stanford Encyclopedia of Physics. section 4). Howard has argued that the subjective causal collapse of the wave function in Copenhagen is not something that Bohr would have endorsed or even remotely advocated but is influentially acquired from Heisenberg’s scientific bias for the von Neumann
postulate of collapse during Copenhagen’s formulation as the orthodox version of quantum mechanics. Moreover, Howard points out that, in fact, Bohr never mentions the collapse of the wave function at all (Howard 2004, pg.669-680).

The second kind of problem that follows from the idea that there is a privileged role for the subjective consciousness of an observer with regard to collapse is that we run into the untenable charge of dualism. If we follow the consequences of von Neumann’s analysis of measurement, that is, his strong assumption of the separation of subject and object, his desire to not physicalize the observer, his placement of the observer outside the physical system as a separated observer and abstract ego, then it would seem likely that we would have to postulate the category of a different kind of ontological substance other than physical matter. Thus, it seems that we have a kind of Cartesian ontology of distinct and separate substances: a physical substance and a thinking substance (Gaukroger 2006 pg.69,86)—if we follow the von Neumann chain up until it is resolved at the level of consciousness. Consciousness then seems to be its own separate category that is over and above physical matter as it does not obey any of Schrödinger’s dynamical laws and is not included as part of the quantum system but is instead apart from it.

This is highly problematic as it leads to the third problem with subjective collapse of the wave function: causal interaction. The wave function describes the dynamics of a physical system, and presumably changes in physical systems are the results of physical causes. The idea that a nonphysical entity like a mind can have a physical cause and collapse the wave function seems to violate causal closure. Causal closure is the metaphysical idea about the nature of causation within the physical domain where physical effects have only physical causes (Kim 2005, pg.15-16). According to the idea of causal closure, a physical event cannot have a cause outside the physical domain. Von Neumann’s abstract ego appears to be a violation of causal
closure for two reasons. It is nonphysical and outside the physical system. In addition, even if von Neumann had placed consciousness as part of the physical system, it would still generate other problems concerning the nature of causation as now we would seemingly have a case of over-determination where could have more than one cause, mental or physical, to create an effect. These are serious problems that the von Neumann theory of measurement does not address and that were not foreseen.

Causal collapse of the wave function is our third serious objection to the von Neumann theory of observational measurement as it would appear that the collapse of wave function seems to require some type of mysterious and unexplained causal nonphysical interaction between the observing subjects and object being observed in order for objects in space–time to exist. We run into the problem of interaction between von Neumann’s abstract and detached observer, which is nonphysical, existing outside physical reality and physical quantum phenomena. First, there needs to be an explanation about how something that is nonphysical like von Neumann’s detached observer can causally interact with something that we know is presumably physical, like quantum waves and particles. If they are separate and distinct things, then an explanation is needed to show how causal contact is achieved between a nonphysical entity like the mind and a physical system. How is this contact achieved, and should there be a measurable exchange of some type of physical force where there is a transfer of energy that induces the wave function to collapse? However, this does not appear so. This notion of a mysterious interaction between mind and matter is an improbable solution to the measurement problem as it would appear that our minds are not subject to the laws of physics and can readily break the von Neumann chain, putting a quantum system into a possible state.
The fourth kind of problem associated with the idea that Copenhagen requires consciousness for collapse is that it does not explain what kinds of physical systems can be considered conscious or even what it means for a physical system to be conscious. We know from our own experience that a photon detector has either registered a hit or it has not. We know that when we open the box, Schrödinger’s cat is either alive or it is dead. But we never observe the cat in a kind of suspended animation being both alive and dead simultaneously like a quantum superposition suggests. Can human beings really be considered a kind of ‘ultimate measuring apparatuses’ as the example of Wigner’s friend asserts that we are? Suppose conscious human beings really are these ‘ultimate measuring apparatuses’; we would then need an explanation to account for this special ability to create reality around us. Also, it would generate the need for other explanations to address the idea of how animal minds collapse the wave function and to answer the question of how the universe could collapse itself if there were no conscious beings at all, animal or human. All of these issues are highly problematic since the von Neumann analysis of measurement seems to require conscious observers of some type.

Lastly, the subjective collapse of the wave function creates addition problems, namely that of subjectivism as it would seem that scientific realism and the pursuit of scientific truths are both undermined by anti-realist and subjectivist interpretations of quantum mechanics that stem directly from subjective collapse theories. For instance, if each of us is collapsing our own wave functions, then it becomes difficult to assign any notion of objective reality to anything outside our own awareness of what we are experiencing. But there needs to be an account as to why two observers observe the same state of affairs. For instance, if I open the box and observer the cat is alive, then it should not be the case that a different observer observes that the cat is dead. Under a subjective collapse theory of quantum mechanics, we cannot explain why two different
observers see the same state of affairs given that each observer collapses their own function, the outcome of which is a probabilistic affair.

If the state of a quantum system is uncertain until it is measured, then it would seem that every observation we make assigns some property or value to some observable that does not exist until it is registered by our minds. What guarantees the reality of objects outside ourselves as well as the properties we perceive those objects to possess? And how do we account for the fact that each of us shares some common and objective experience about the world that we communicate through dialogue if there is no semblance of some kinds of objective reality? Subjective collapse seems to entail the idea that we would inevitably slide into subjectivism where truth becomes whatever is true for me and whatever is true for you given that we collapse our own wave functions with our minds. This raises the issue of solipsism, making any meaningful talk of objective reality and propositional truth impossible.

I believe it is for these reasons that the notion of subjective collapse is very questionable. The von Neumann theory of observational collapse makes no practical sense when analyzed with these criticisms in mind. It also seems that these criticisms arise out of the fact that the mind is somehow separate and distinct from physical reality and not subject to any physical laws, let alone any of the probabilistic laws of quantum mechanics. Therefore, if these are the consequences of subjective collapse, it cannot be the case that von Neumann’s assumption of the separation of subject from object, as a detached observer collapsing quantum phenomena, is a good approach to solving the measurement problem. Therefore, what this thesis is suggesting is that if these difficult philosophical objections arise from subjective collapse, and if the reason for subjective collapse is a consequence of metaphysically separating subject from object like von Neumann does with his detached observer existing apart from the physical system and not
subject to any physical laws, then it makes good philosophical sense to start looking towards alternative ways of understanding the subject–object relation in quantum mechanics. And this is precisely what I believe Don Howard’s interpretation of Bohr’s complementarity thesis does, which is the subject of the next section.

3.3 Howard on Re-interpreting Bohr’s Complementarity

The concept of complementarity was first introduced by Bohr to deal with the newly found quantum reality of particle-wave duality as well as other quantum phenomena known as complements, or what the formalism calls conjugates. Conjugates are pairs of related variables, like position and momentum, which are mathematically and philosophically defined in a way to be binary aspects of one another. As discussed in chapters one and two, both classical and quantum formalisms share similar physical mechanics. Both classical and quantum physics make extensive use of these paired observables. For instance, the Heisenberg’s uncertainty principle in quantum mechanics is an example of such conjugate quantities and complements as it demonstrates that each member of any conjugate pair (e.g., position and momentum) represents and describes some fundamental property of a quantum system and is nomologically independent of the other (Esfeld, 2001 pg.197-201). Recall that position and momentum in Heisenberg’s uncertainty principle are said to be complements because both are required to describe a complete view of the physical state of the quantum system, yet only one of these conjugates can be measured and quantified at a time. If obtaining a definite value for position, there is a minimum amount of uncertainty with respect to the observable’s momentum, and when obtaining a definite value for momentum, there is a minimum amount of uncertainty with respect to the observable’s position.
Subsequently, it is the experimental situation that determines which complementary construct or property will be displayed. For instance, the double slit experiment reveals that under certain experimental conditions, light behaves as a particle, and under other experimental conditions, light behaves as a wave—but never both as light is never observed behaving both as a particle and as a wave. However, even though they are exclusionary, both of aspects of light, whether particle or wave, are necessary and constitute a complete view of the circumstances even though only one can be applied in a given situation. Not so with classical physics as quantities like position and momentum, Einstein’s space–time constructs, and laws such as the conservation of energy and momentum can be simultaneously applied and known in a single given experimental situation. Therefore, the results of classical experiments are exactly those predicted by the physical theory. Not quite so when dealing with quantum mechanics, in which Bohr understood that these constructs are complementary and mutually exclusive as when dealing with the indeterminacy principle of Heisenberg and the double slit.

To understand the meaning of complementarity, it might help to understand that Bohr viewed quantum mechanics as a complete description and claimed that the measuring devices in quantum mechanical experiments obeyed quantum dynamical laws, but that classical mechanics was an approximation of quantum mechanics with a limited domain of validity. Bohr held that quantum effects are practically negligible at the macroscopic level and thus are small enough to be ignored, but that quantum effects are still present (Kafatos & Nadeau, 2001 pg.72-82). In other words, when studying the behaviour of macroscopic objects, the quantum of action is statistically averaged out so that we do not need to use the laws of quantum mechanics to get reliable results. According to Bohr, this means that,
The fundamental postulate of the quantum of action . . . forces us to adopt the new mode of description designated as complementary in the sense that any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of phenomena. (Bohr, 1934 pp. 54-5)

Because the quantum of action is always present at the macro level, Bohr argued that this presence required the final renunciation of the classical idea of causality and a radical revision of our attitude toward the problem of physical reality. Although Bohr realized that physical quantities like position and momentum, constructs like space–time, and the conservation laws of energy and momentum can be simultaneously applied in classical physics within a single circumstance where the results of classical experiments are well predicted by physical theory, Bohr also realized that in quantum physics, these quantities, constructs, and laws were complementarity and mutually exclusive (Kafatos & Nadeau, 2001 pg.72-82).

As a result, Bohr argued that given the ubiquitous presence of the quantum of action, we are required to take on a new kind of description as complementary because the application of classical concepts does not allow for the simultaneous use of other classical concepts when dealing with quantum phenomena. In other words, it is easy to coordinate our experience of the macroscopic world using classical concepts because our descriptive language is primarily based on the nature of our visual experience. But the applicability of classical concepts breaks down when dealing with quantum phenomena that we do not visually experience directly because the world that we experience supervenes on quantum phenomena. Thus, the idea of complementarity was Bohr’s way of dealing with some of the philosophical paradoxes quantum phenomena
generated—namely the transition from quantum to classicality and of how to deal with some of its conjugate exclusion problems.

When discussing the idea of complementarity, Bohr writes,

\[\ldots\] the very nature of quantum theory thus forces us to regard the space-time coordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealizations of observation and definition respectively. Just as relativity theory has taught us that the convenience of distinguishing sharply between space and time rests solely on the smallness of velocities ordinarily met compared to the speed of light, we learn from the quantum theory that the appropriateness of our visual space–time descriptions depends entirely on the small value of the quantum of action compared to the actions involved in ordinary sense perception. Indeed, in the description of atomic phenomena, the quantum postulate presents us with the task of developing a complementary theory the consistency of which can be judged only by weighing the possibilities of definition and observation. . . (Bohr, 1927,1934 pg.54-55)

What Bohr is saying here is that classical mechanics and quantum mechanics are analogous to relativity and classical mechanics in the sense that we can ignore the effects of the finite speed of light when dealing with classical dynamics because the speed of light is so fast that relativistic effects are negligible and that we also ignore the quantum of action on the microscopic level because its effects are so small (Kafatos & Nadeau 2001, pg.72-82). Thus according to Bohr’s passage here, classical physics is a working approximation that appears to be precise simply because the speed of light is so great, and the quantum of action, since it is so small, gives rise to negligible effects. The idea of complementarity is Bohr’s way of coming up with these new
modes of description in an effort to deal with this ever-present quantum of action. So, just as space and time in the new space–time continuum are complementary constructs forced upon us by Einstein’s theory of relativity, the complete description of this reality requires both, even though they may exclude each other in some application or experimental situation. Bohr also points out that space and time are complementary constructs because, just as the finitude of the speed of light demonstrates that we cannot distinguish a separation between space and time (relativity), the finitude of the quantum of action demonstrates that we cannot distinguish a separation between the behaviour of a system and its interaction with the measuring instruments and the agencies of observation (Kafatos & Nadeau, 2001 pg.72-82). Here we are getting at what I believe is the prime meaning of Bohr’s complementarity thesis: that the subject and the object are complementary aspects and share a joint existence.

For instance, one of Bohr’s implications here suggests that the classical idea that the observer and the observed system are separate and distinct has been challenged by relativity in the sense that we cannot consider the observer to be outside the observed system since it is necessary to assign that observer a specific space–time coordinate relative to the entire system (Kafatos & Nadeau 2001, pg.72-82). This idea can also be applied to quantum mechanics as complementarity would suggest, contrary to von Neumann’s reading of complementarity, that the observer is an essential component of the observed system. What this analogy reveals is that there is no ‘outside perspective’ from which to view the physical system. I believe that this is the line of thinking in Howard’s analysis of complementarity as it relates to the relation of subject and object in that we cannot regard subject and object in a classical sense as a von Neumann detached observer because of the ever-present quantum of action. Instead, we must afford the
subject–object relation a new mode of description from one that is based not on separation but on nonseparability.

In “Who Invented the ‘Copenhagen Interpretation?’ A Study in Mythology,” Don Howard attempts to disentangle Bohr’s views from those of other philosophers who claimed to speak with authority on Bohr’s philosophy of complementarity. Howard rejects their view that Bohr’s complementarity thesis ever remotely entailed the idea of subjectivity and subjective collapse of the wave function. He states that if we regard measurement interactions as different in kind from other physical processes, then it is quite easy to believe the observer plays an active role in the quantum domain. It is no wonder then why this view of the observer and measurement is met with the charge of subjectivism, especially since the post-measurement state of the system seems to crucially hinge upon the state of the observer’s knowledge. Instead, Howard argues against interpreting Bohr’s notion of complementarity as suggesting that there is a privileged role for the subjective consciousness of the observer when it comes to the selection of a definite outcome. Howard points out that Bohr makes no mention of subjective collapse of the wave function due to measurement and consciousness (Howard 2004, pg.669-682).

Howard does point out that Bohr was always careful to physicalize the observer and emphasized that observation in quantum mechanics was consequent upon measurement being just another form of physical interaction. Furthermore, Howard’s interpretation of Bohr’s complementarity is based on entanglement, not subjectivity. Howard claims that measurement for Bohr entailed that the post-measurement joint state of the object and the measuring apparatus form an entangled pair. Howard also contends that as a result of this entanglement of the object and the measuring apparatus, the agencies of observation, i.e. that which is doing the viewing on the end that the measuring apparatus is also entangled in a way that neither the subject (agencies
of observation) nor the object (quantum phenomena) can be afforded an independent reality. So, far from being the anti-realist that many have often attributed to Bohr, Howard claims that Bohr never said that one cannot ascribe reality to quantum phenomena, rather that one cannot ascribe an independent reality to quantum phenomena and the agencies of observation and that the subject and the object share a joint and inseparable existence characterized by an ontological dependence (Howard 2004, pg.669-682). This concludes my brief introduction on Howard’s main points re-interpreting Bohr’s complementarity. There is more to be said here on Bohr’s thesis of complementarity, and I intend to revisit the idea of complementarity in Chapter Four, where I continue the discussion on subject–object nonseparability by discussing at length the EPR debate.
CHAPTER FOUR

In this final chapter, I make the case for accepting the nonseparability of subject and object by examining the EPR debate, which I argue demonstrates the reality of subject–object nonseparability, or SON. I argue that the discussions generated by the EPR debate moves us towards accepting the idea that quantum systems are actually one holistic system where all properties are realized as relational properties or relations within this one holistic system. In this holistic view, I draw attention specifically to the subject–object relation as I argue that it is not to be seen as two distinct and separate parts of the physical system, but rather as a nonseparable subject–object whole comprising the physical system that is ultimately more than the sum of its parts. What this means is that the subject–object relation in the quantum realm is a relation of ontological dependence, which is to say that objects like quantum phenomena are ontologically dependent on subjects, or what Bohr calls “agencies of observation,” if and only if it is not possible that there is something that is an object without there also being something that is a subject (Esfeld, 1999 pg. 319-317).

In addition, I will show that the SON principle and ontological holism implied by Bohr in EPR is consistent with Bohr’s philosophical and scientific approach overall. Subsequently, I believe that my discussion of the EPR debate validates Howard’s reading of Bohr’s complementarity thesis. As a result, we are in a position to reject von Neumann’s reading of Bohr’s complementarity thesis, which calls for a sharp distinction and separation between subject and object, both metaphysically and epistemologically, and replace it with Howard’s interpretation where the subject–object relation is not one of separation, but one of inseparability, where neither the subject nor the object has a distinct reality apart from one another, but they actually possess joint reality. Not only does it require us to reject von Neumann’s separation of
subject and object, but it also requires us to reject the idea that the relationship of subject and object is a causal one. My main argument is that if the relationship between the subject and object in a quantum system is a holistic relationship of ontological dependence, then it gives us a new way of dealing with the measurement problem that avoids causal collapse as causal relations are not sufficient in themselves to describe the kind of ontological dependence among the parts of a holistic system (Esfeld 2001 pg.6-8).

With Howard’s interpretation of Bohr’s complementarity thesis in place, I then attempt to sketch out a non-collapse theory for Copenhagen. This requires the von Neumann theory of measurement to be replaced by a modified theory of measurement that is based on the SON principle. I try to explain how that might work, and I try to show how the SON principle can answer some of the criticisms raised in Chapter Three regarding the untenable position left to Copenhagen as a result of its undefined conception of measurement and von Neumann’s subjective collapse theory. As a result, I argue that resolving some of these objections is an improvement and serves as a beginning to clarifying the role of measurement in Copenhagen. I point out how a non-collapse theory of measurement based on the SON principle is actually consistent with Bohr’s overall philosophical and scientific approach. Although this thesis does not solve the measurement problem entirely, it does point towards developing a more coherent theory of measurement that finds subject–object nonseparability and ontological holism as its foundation.

In the first section, I discuss how the EPR debate reveals two things: (i) that Einstein’s claim that physical objects have an independent existence because they lie in different parts of space is not correct and (ii) that Einstein’s principle of local action is also not correct. Einstein believed that quantum mechanics was incomplete because he did not believe that the wave
function provided a complete description of the state of the physical systems. Instead, Einstein argued that the wave function only statistically represented the state of the physical system and its observables (Faye Stanford Encyclopedia of Physics. Section 4). We shall see in the EPR debate that the failure of these two claims to show that quantum mechanics is incomplete leads Bohr to imply that physical reality at the quantum level is both nonlocal and inseparable. If we accept the philosophical consequences of Bohr’s implicit assertions of inseparability and nonlocality (and possibly ontological holism), then I argue it becomes difficult to hold that subjects and objects have an independent and separate existence. If subjects and objects are inseparable, then it calls into question the validity of von Neumann’s postulate of collapse, which is formulated on the metaphysical separation of subject and object, resulting in a problematic interaction between a physical system and a non-physicalized observer. To clarify a distinction then, the whole universe is one holistic system in the sense that its constituent parts possess some of the properties that are characteristic of these things only within the whole, and everything—including subjects and objects—are a way of being of this one holistic system, but a quantum system cannot be understood by examining the subject and object independently or in isolation from one another. They must be considered jointly (Esfeld, 1999 pg.319-337, Esfeld, 2001 Ch.7&8)

In the second section, I conclude the thesis by arguing that the Copenhagen interpretation of quantum mechanics can be modified by a non-collapse theory of measurement that is formulated on subject–object nonseparability. This eliminates the need for von Neumann’s postulate of collapse as the subject is no longer placed outside of the physical system as a ‘detached observer,’ but is instead a physicalized and inseparable part of the quantum system. Since subjects cannot be separated from objects, I argue that we must characterize and recognize
that both the measured object, the measuring apparatus of the subject, and ultimately subjectivity itself form an indissoluble whole and simultaneously evolve together during acts of measurement, and always in the context of an observation by the agencies of observation (McEvoy, 2001 pg 369-379). As a result, the idea of subjective causal collapse to break the von Neumann chain is avoided as there is no call for the collapse of the wave function. I conclude the thesis by showing how a non-collapse theory is consistent with Bohr’s overall philosophical and scientific approach. I end the section showing how subject–object nonseparability might be used to solve some of the criticisms raised in Chapter Three in an effort to make improvements to the Copenhagen interpretation.

4.1 The EPR Debate

In this section, I discuss the EPR debate in which physicists began questioning the completeness of quantum mechanics—that is, that quantum mechanics and its quantum states vectors are necessarily in one-to-one correspondence with the elements of reality (Bohr, 1935 pg. 696-702). Soon the issue of completeness raised even subtler ideas about locality and separability, which became central in any further discussion of quantum mechanics. Thus, a discussion on the EPR debate will be essential in defending the reality of the nonseparability of subject and object (SON) in this thesis. In addition, examining the EPR debate between Bohr and Einstein will also provide us with some of that necessary background information for further discussions in the coming sections. The beginning of the EPR debate started in 1935 when Einstein, Podolsky, and Rosen wrote a paper critiquing quantum theory looking at some of the problems with the disturbance theory of measurement and questioning what was an implicit assumption about the independence of distant systems (McEvoy, 2001 pg.100). EPR attempted to establish criteria for the idea of an objective reality. EPR held on to the notion that objective
reality is “independent of any theory” and has “physical concepts with which the theory operates” (McEvoy, 2001 pg.100-107). Einstein, Podolsky, and Rosen argued that the idea of an objective reality meant that there was an external world of objects that have intrinsic properties with real physically measurable quantities existing outside observer whether someone observed those objects and their properties or not.

EPR went further on to say that the concepts of quantum theory can be judged as satisfactory only if the theory is correct and if the description given by the theory is also complete. They argued that the correctness of quantum theory is to be judged by seeing whether the conclusion agrees with the experimental results. To judge the completeness of quantum theory, EPR stated that the completeness of quantum needed two conditions: a necessary condition that “every element of the physical reality must have a counterpart in the physical theory” and a sufficient condition for an element of physical reality, which stated that “if, without in any way disturbing system, we can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity” (McEvoy, 2001 pg.100-107). Einstein, Podolsky, and Rosen maintained that quantum theory did not meet the first necessary condition that every element of the physical reality must have a counterpart in the physical theory; nor did it meet the second (Esfeld, 2001 pg.206-212). Therefore, quantum mechanics was incomplete.

The idea of incompleteness stemmed from physicists like Einstein who believed that the wave function did not provide a complete description of the physical system. Since the wave function provided a probabilistic account of the dynamics of a system, Einstein thought that quantum mechanics’ statistical nature indicated that it was incomplete. He had trouble with Heisenberg’s principle of uncertainty as its paired conjugates like momentum and position could
not be pinned down with exact values simultaneously. He argued that quantum objects possessed distinct properties with definite values even if they were unobserved and that there must be some hidden variables (i.e., microscopic properties of fundamental particles) that would account for the behaviour of quantum phenomena. Although these hidden variables were unseen, Einstein believed that they could explain some of the inherent uncertainty in quantum mechanics (Esfeld, 2001 pg.206-212).

Heisenberg had shown that whenever you measure a particle’s momentum, you cannot obtain a definite value for its location, and whenever you measure its location, you cannot obtain a definite value for its momentum. This issue of incompatible conjugates led physicists like Einstein to question the completeness of quantum mechanics as the uncertainty principle seemed to suggest that observables like momentum and location are not just unobservable when measuring one or the other, but that they might not actually exist outside of the context of an observation. Einstein and his associates, Podolosky and Rosen, felt that such a position challenged our basic sense of realism, and therefore the idea that quantum objects did not possess definite properties until measured was not a position they were willing to accept. As a result, using a kind of thought experiment, EPR came up with a hypothetical test involving measurement that used experimental information gathered about one particle to deduce information about other complementary properties, like position and momentum, of the other particle (Kafatos & Nadeau, 2000 pg. 58-61).

In this thought experiment, we are given the idea that two photons have been prepared in a zero spin state inside of a photon emitting device. (I should note that I am using the Bohmian modified version of the EPR thought experiment here.) The photons are then emitted in different directions apart from one another without interacting with anything else until we make the
decision to measure and observed one of them. Quantum formalism enables us to calculate the momentum of the two photon particles, which have been paired together prior to separation. EPR believed that the individual momentum of each particle will be correlated after the particles separate. Basically, if two photon particles in the given quantum state are emitted from a photon emitting device, the momentum of one particle will strictly correlate with that of the other particle. In the EPR thought experiment, if particle A is travelling left and moves 5 feet away from the device, its twin, particle B, travelling right also has moved 5 feet away from the device. Also, if particle A is spinning right, then its correlated twin, particle B, is spinning left (Kafatos & Nadeau, 2000 pg. 58-61).

When the particles have moved a sufficient distance away from the device and from each other in order to achieve “space-like separation,” we would then take the measurement of one of the particles, either A or B. It should be noted that space-like separation implies that it does not permit faster than light travel of a signal where one particle could communicate with another particle. Of course, as Einstein pointed out, the experimental situation requires that the distance between the two correlated particles must be sufficient enough of a distance that no signal travelling at the speed of light (or faster than light) can carry information between the two particles in the time allowed for the measurement. This is what Einstein meant by space-like separation (Esfeld, 2001 pg.206-212). EPR argued that, given the assumption that the momentum of the two particles is conserved due to the fact that they are correlated, we should then be able to calculate with certainty the momentum of the correlated particle that was not measured or observed based on the measurement or observation of the first correlated particle. In other words, if we measure particle A, and calculate its momentum to be 100, then in principle, particle B’s momentum should also be 100, even though it was not observed, because the paired particles A
and B are correlated, and no signalling can occur faster than the speed of light. The same would apply for position as well. If particle A moved left by 50 feet, then we would see that particle B moved right by 50 feet as well, given the two particles’ correlated natures.

It is important to recall at this point Heisenberg’s principle of uncertainty, which restricts us from knowing both the momentum and the position of a particle simultaneously. For when we are trying to measure the momentum of a particle, we cannot know its position, and when we are trying to measure its position, we cannot know its momentum. At all times, only one variable, either position or momentum, can be measured and known. For this reason, Einstein and his colleagues conceded in their thought experiment that we cannot know the precise position of a particle while knowing its momentum. However, EPR assumed that the momentum of particle A that they actually measured would not affect or disturb the momentum of unobserved particle B, no matter how far apart their distance (Esfeld, 2001 pg.206-212). Of course, this assumption was based on Einstein’s view of reality, which is characterized by the principles of separability and locality. Since EPR held the assumption that the momentum of the two particles is conserved due to the fact that they are correlated, knowing the momentum of particle A, which was actually measured, enables us to calculate with certainty the momentum of particle B, which is unobserved.

Einstein and his colleagues then pointed out that since we can calculate the momentum of the unobserved particle B, and we can know the position of particle A that was measured, then it follows that we can know both the momentum and the position of the particle that was not measured. The idea was that if we can know both the position and the momentum for a single particle, we have then violated Heisenberg’s uncertainty principle and undermined quantum indeterminism and, by doing so, it would still be possible to assume a one-to-one correspondence
regarding every aspect of physical theory and the physical reality (Kafatos and Nadeau, 2000 pg. 58-61). In other words, EPR felt they contradicted the uncertainty principle. Initially, physicists had asked whether it was the case that you simply couldn’t know the two variables of momentum and position simultaneously, thus making it an epistemological problem, or whether it was the case that it was a metaphysical problem, and one of the two properties didn’t actually exist depending on which observable, either momentum or position, we were currently measuring. EPR figured they had an argument that showed that you could know both position and momentum.

EPR felt that this was an effective blow to the indeterminacy of quantum mechanics and the measurement problem because it would side step the observational rules it takes in quantum mechanics to obtain a definite result. EPR believed that they reinstated classical determinism and restored objective realism because they argued that the EPR paper showed that if you can predict the value of a physical quantity with certainty, and if you can predict that value without interfering with the system, then you can conclude with certainty that the physical system or whatever observable you are currently measuring has this value independently of your predictions and the measuring operations to verify your prediction (Esfeld, 2001 pg.206-212). As a result, Einstein and his colleagues asserted that the Copenhagen interpretation made the reality of position and momentum of the particle in the second system dependent upon the process of measurement conducted on the first system, and since this process of measurement of the first system does not disturb the second system in any way, they argued that “no reasonable definition of reality could be expected to permit this” (Einstein., 1935 pg.777-778).

The reason why Einstein, Rosen, and Podolsky believed this could not be permitted was that physical things like photon particles must lay claim to an existence independent of one
another because they lie in different parts of space (Einstein, 1935 pg.780, 1948 pg.323). According to Don Howard’s formulation and his reading on Einstein, this is known as the principle of separability, which states that physical systems each have a state in the sense that (1) the state completely determines the state-dependent, local properties of the system and (2) the joint state of two or more systems supervenes on the states that each of the systems has (Howard, 1989 pg.224-231). In addition, in the EPR paper, Einstein stipulated a further requirement as to why things like photon particles must lay claim to an independent existence: the principle of local action. The difference between separability and local action means that separability refers to the states of physical systems at a given time, whereas local action concerns changes in the states of physical systems in time (Esfeld, 2001 pg.254-255).

Einstein’s idea of local action or the principle of local causes states that a physical event cannot simultaneously influence another physical event without direct intervention, such as sending a signal (Esfeld, 2001 pg.206-212). Classical mechanics and Newton gave us the idea that physical systems can be thought of as being localized points in space or in space–time points. Thus, local actions are interactions or ‘forces’ that propagate from space-point to nearby space-point in succession with a finite velocity in relativistic terms (i.e., not faster than the speed of light). What this means in terms of the EPR thought experiment is that measurement on particle A cannot simultaneously affect the measurement on particle B in a separated region of space given the assumptions of locality and separability. This is what is meant by “without in any way disturbing the system.” (Einstein, 1935 pg.777-780) If Einstein’s principle of local causes is correct, then the only way for both particles to influence each other across a separated distance of space would be to send the signal faster than the speed of light. This is impossible according to Einstein relativity theories.
Einstein and his colleagues knew that the mathematics of quantum mechanics predicts that there should be correlations between the two particles no matter how far apart the particles are. However, their point was that, since these correlations cannot occur under the experimental conditions described by the EPR thought experiment without violating the principles of locality and separability, then we can conclude that quantum theory is incomplete as there are elements of reality quantum mechanics does not account for, and it does not undermine the classical view of correspondence between the physical theory and the physical reality as we can know definite numerical values for two or more incompatibles, thus defeating the Heisenberg uncertainty principle (Einstein, 1935 pg.777-780). Locality is assumed because Einstein’s relativity assumes that signals or energy transfers between space-like separated points cannot occur at speeds greater than light. And realism is preserved because we can know two or more definite values for incompatibles at once, thus proving that physical reality exists independently of the observer and that the state of reality is not dependent on acts of observation or measurement.

However, Bohr’s response to EPR was that quantum theory was not incomplete and that it was capable of dealing with the issues raised by the EPR example. Bohr writes,

The statement of the criterion in question is ambiguous with regard to the expression “without disturbing the system in any way.” Naturally, in this case no mechanical disturbance of the system under examination can take place in the crucial stage of the process of measurement. But even in this stage there arises the essential problem of an influence on the precise conditions which define the possible types of prediction which regard the subsequent behaviour of the system . . . their arguments do not justify their conclusion that the quantum description turns out to be essentially incomplete. . . . This description can be characterized as a rational use of the
possibilities of an unambiguous interpretation of the process of measurement compatible with the finite and uncontrollable interaction between the object and the instrument of measurement in the context of quantum theory. (Bohr, 1935 pg.696-702)

Although this passage is often called obscure and understanding its meaning can prove difficult, it is generally regarded that Bohr may have been contemplating the possibility of Einstein’s “spooky action at a distance” by giving up the classical assumption of locality. Bohr’s response to EPR suggested that the example using two particles travelling away from each other should not be considered as separate quantum systems or separate entities until after measurement has been made to separate them (McEvoy, 2001 pg. 100-107).

As a result, Bohr responded that it was a mistake to assume that the two systems had not been disturbed by the measurement on one of the particles as it is this action of measurement that first causes the separation between the two particles (Bohr, 1935 pg.696-702). What Bohr may be suggesting here is that the failure of separability means more than just entanglement over vast distances. Instead, the failure of separability means that we cannot view seemingly spatially separated systems as two distinct systems, but that actually there is really one holistic and physically undivided system. Thus, Bohr indirectly could be interpreted as making a genuine case for ontological holism (Howard, 2004 pg.669-682). Therefore, instead of there being two separate photons that remain entangled regardless the distance, there is actually only one entity but in two locations when no measurements are being taken. As a result, we can interpret Bohr as suggesting that Einstein’s notion of classical separability does not obtain and that reality is nonlocal. Moreover, many philosophers, such as Don Howard, have argued that not only was Bohr hinting at nonseparability—what Bohr had in mind was genuine ontological holism.
According to Howard, the notion of separability entails two things: (1) that spatially separated systems each possess their own distinct state and (2) the joint state of two or more spatially separated systems is wholly determined by their separate states. Howard argues that quantum entanglement exhibits nonseparability and regards nonseparability as a sufficient condition for ontological holism—especially in the context of violations of Bell’s inequalities, which held that no theory of local hidden variables can account for all of the predictions of quantum mechanics (Howard, 1992 pg.306-314). Thus, Howard’s version of Bohr’s ontological holism argues that objects cannot be metaphysically separated from their subjects. So, for example, when two photons are entangled, they exhibit nonseparability and can be considered as one nonlocal object, or one holistic system. This requires us to give up the assumption that these two photons are distinct individuals. What Howard is saying is that in order for us to have knowledge of any object as distinct individuals, it cannot be thought of as existing independently of its subject in order to have any metaphysical reality.

Howard bases his interpretation of Bohr’s complementarity on Bohr’s view that one can only meaningfully ascribe properties to observables like position and momentum in a quantum system in the context of a well-defined experimental setup designed for measuring the corresponding observable. It is argued that when Bohr uses the term “quantum phenomena,” he is referring to what happens to the entire arrangement, that is, the observable and the classical apparatus that is measuring it. So, although Bohr takes the quantum phenomena to be entirely physical, it cannot be said to be comprised of events involving separately characterizable physical objects. In fact, Bohr had argued against any interpretation of the wave function independent of measurement. Therefore, even if a quantum system existed outside the context of a measurement, nothing meaningful could be said about its properties. It is for this reason that
Howard and others have argued that Bohr’s idea of complementarity is really a case for genuine ontological holism as we would be mistaken to think that Bohr would take a quantum object as actually existing independently of the experiment setup, measurement, and the agencies of observation (Howard 2004, pg.669-682).

Furthermore, Bohr also points out that EPR’s indirect method of measurement does not actually undermine the rules of quantum mechanics or his notion of complementarity. Using the double slit experiment to prove his point, Bohr demonstrated that the experimenter has the choice of determining how light behaves—either as a wave or as a particle—depending on the choice of experimental setup. Bohr said that this choice was imposed upon the experimenter, but that it was not an arbitrary one. Bohr writes,

\[\ldots\] rational discrimination between essentially different experimental arrangements and procedures which are suited either for an unambiguous use of the idea of space location, or for legitimate application of the conservation theorem of momentum. Any remaining appearance of arbitrariness concerns merely our freedom of handling the measuring instruments, characteristic of the very idea of experiment.

(Bohr, 1935 pg. 699)

In other words, the experimental setup determines which observable is going to be measured, and if the experimenter changes the setup of apparatus, then he/she changes the measurable properties of the system. This is consistent with the idea of complementarity, and hence nonseparability, because it shows that agencies of observation and the choice of experimenter on which observable to measure are entangled and cannot be viewed as distinct parts of the quantum system and that objects are invariably ontologically tied to their subjects.
Subsequently, on this point Bohr maintained that this choice of experimental procedures is imposed upon the experimenter because it is impossible to measure both spatial location and momentum accurately and simultaneously, but that the inability to know location and momentum accurately is not the fault of the experimental setup, but rather of the results of the implications of complementarity. Bohr states,

\[ \ldots \] the impossibility of closer analysis of the reactions between the particle and the measuring instrument is indeed no peculiarity of the experimental procedure described, but is rather an essential property of the arrangement suited to the study of the phenomena of the type concerned, where we have to do with a feature of individuality completely foreign to classical physics. (Bohr, 1935 pg.698)

Bohr continues on to say that because further additional measurements are needed to obtain numerical values for both position and momentum, and that these measurements cannot be predicted prior to an observation, EPR cannot conclude that these numerical values exist as elements of reality before the actual measurement is made to determine the value. I believe that what Bohr was getting at is that quantum mechanics was going to challenge our classical assumption of a mind-independent objective reality. Again, Bohr’s contention was that since we cannot assume the Schrödinger equation represented anything ontologically substantive, we would be mistaken to think that elements of reality exist independently of measurement and the agencies of observation. Instead, Bohr was arguing that the subject and the object do not have distinct independent metaphysical realities, but are rather an inseparable part of the whole quantum system.

What EPR saw as the source of the problem was the indeterminacy associated with the statistical interpretation of the Schrödinger equation coupled with the fact that the equation does
not predict the outcome of a measurement. For EPR, we see that it raised a deeply metaphysical problem concerning whether the physical system actually had the attribute of the observable in question prior to measurement, as the realist would have wanted; or, whether the act of measurement actually caused the wave function to collapse and thus make the property or attribute appear and materialize, which came to be the orthodox position for those physicists like Heisenberg, Wigner, and von Neumann that subscribed to a subjective causal collapse theory of measurement. For the realist camp, quantum mechanics had to be an incomplete theory because, even if the Schrödinger equation gives you everything you need to know about the state of the physical system, you still cannot determine all its aspects (Kafatos & Nadeau, 2000 pg. 76-79). Therefore, it seemed reasonable to EPR that some other information about the physical system was lacking—some ‘hidden variables’ that along with the Schrödinger equation could tell you everything you need to know about the state of the system.

Although Bohr, in his response to EPR, was ultimately trying to confirm the fundamental idea in Copenhagen that a quantity can only be considered an element of reality or real if it has been measured or if it is in an experimental situation where the outcome of the measurement is predictable, we see from Howard’s examination of Bohr that we cannot truly count him in the orthodox camp where the act of measurement creates a property that was not previously there by collapsing the wave function. Bohr never endorsed the collapse of the wave function or the von Neumann theory of measurement. Instead, the EPR discussion appears to show that Bohr was arguing for two things: (i) that Einstein’s claim that physical objects have an independent existence because they lie in different parts of space is not correct and (ii) that Einstein’s principle of local action is mistaken. As a result, Bohr is best understood as endorsing the nonseparability of subject and object by implicitly arguing the idea that separability must be
given up because the entanglement of the observed object, the measuring apparatus, and the agencies of observation occurs over vast distances. But also that it means more than just nonseparability for Bohr, as his view can be seen to support the idea that quantum systems exhibit genuine ontological holism.

To further argue this case of subject–object nonseparability, Bohr used his example to reveal what he called “an essential ambiguity in the EPR criterion of physical reality”. Bohr argued this ambiguity was revealed in the meaning of the expression “without in any way disturbing the system.” Bohr pointed out that there is little question of a mechanical disturbance of one system due to a measurement made on the second system, but that there was, as Bohr described it,

... the question of an influence on the very conditions which define the possible type of predictions regarding the future behaviour of the system. Since these conditions constitute an inherent element of the description of any phenomenon to which the term physical reality may be attached, we see that the argumentation of the mentioned authors does not justify their conclusion that the quantum-mechanical description is essentially incomplete (Bohr, 1935 pg.700).

Although cryptic and obscure, Bohr seems to be indicating that not only does separability need to be relinquished, but that we may also be required to give up the idea that quantum interactions are local. This seems to be a way for Bohr to resist the incompleteness conclusions of EPR by suggesting that there is an ambiguity concerning the influence on conditions which define the possible types of predictions regarding the future behaviour of the system. The best way of understanding Bohr on this point is that instead of viewing quantum particles, like photons or electrons, as two separate, individual particles existing in two separate parts of space, where if
one particle is acted upon, its twin simultaneously is affected, it is better understood to view the two seemingly separate regions of space and the two particles as one nonlocal and holistic space with one entity existing in two locations. By giving up locality, Bohr can resist the incompleteness arguments of EPR and indirectly imply that his idea of complementarity entails a wholeness or metaphysical unity of subject and object.

Therefore, from the discussion on EPR, we learn that Bohr may be proposing a kind of subject–object holism as he regards the experimental arrangement including the measuring instruments and the measured quantum system as a whole where a separate analysis of its components, including the subject as the ‘agency of observation,’ is not possible. The end result here is that the idea that quantum systems are nonseparable and nonlocal has profound implications for the subject–objection relation as subjects and objects must be treated ontologically dependent and nonseparable. And thus Bohr implies nonseparability of subject–object in the following passage,

The quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation. . . . (Bohr, 1927, 1934, pg.54-55)

If we interpret Bohr in this manner, then Howard’s reading of Bohr’s complementarity gains considerable traction as we can reasonably lay claim that quantum systems do exhibit the kind of ontological holism of subject–object nonseparability (the SON principle) that arises out of the EPR paradox and ensuing dialogue between Bohr and Einstein.
4.2 A Non-collapse Theory of Measurement for Copenhagen

In this section, I conclude the thesis by arguing that the Copenhagen interpretation of quantum mechanics can be modified by a non-collapse theory of measurement that is formulated on the subject–object nonseparability of Howard’s interpretation of Bohr’s complementarity. Such an interpretation is contrary to how von Neumann reads complementarity as von Neumann assumed a strong metaphysical separation between subject and object. This assumption resulted in von Neumann’s failure to physicalize the observer by placing it outside the quantum system as a detached observer, thus giving an essential role to the mind, a non-physical entity. As a result, von Neumann’s analysis of measurement required this detached observer to function as the mechanism of collapse, reducing the wave function into a nonsuperposition or an eigenstate of the measured observable. However, many intractable problems have arisen from von Neumann’s theory of measurement as it gives a privileged role to the subjective consciousness of the observer to select a definite outcome by collapsing the wave function. In addition, the metaphysical separation of subject and object creates dualism, leaving the question of how a nonphysical detached observer interacts with a physical quantum system without any physical laws. And there are other problems raised in Chapter Three that the postulate of collapse entails, like subjectivity, defining conscious systems, and anti-realism.

Given the problematic nature of the postulate of collapse that results from the metaphysical separation of subject and object, I argue that the Copenhagen interpretation should reject von Neumann’s analysis of measurement and embrace the subject–object nonseparability of Howard’s thesis on Bohr’s complementarity. This eliminates the need for von Neumann’s postulate of collapse as the subject is no longer placed outside of the physical system as a ‘detached observer’ but instead is a physicalized and an inseparable part of the quantum system.
If we adopt this interpretation of complementarity where subjects cannot be separated from objects, I will argue that Copenhagen will be in a much better place philosophically with regards to understanding the role of measurement. What I am advocating is a non-collapse theory of measurement based on the SON principle where we characterize and recognize that the measured object, the measuring apparatus of the subject, and ultimately subjectivity itself form an indissoluble whole and simultaneously evolve together during acts of measurement and always in the context of an observation. As a result, the idea of subjective causal collapse to break the von Neumann chain is avoided as there is no call for the collapse of the wave function.

This lack of collapse does not mean that there are no particles and only waves. Bohr’s complementarity thesis does not argue this nor does this thesis hold that position. Instead, Bohr’s complementarity thesis argues that although it is impossible to observe both the wave and particle aspects simultaneously in any experimental setup, a complete knowledge of light phenomena would require both a description of its wave and particle properties. Both wave and particle properties are indeed empirically validated by experimental setup, just not simultaneously. A non-collapse theory of measurement simply entails that the wave function does not represent anything substantively real, only that it can be used to mathematically represent the different outcomes. So, there is nothing to physically collapse, only different outcomes to calculate. Bohr’s complementarity asserts that quantum phenomena such as the particle-wave duality of light are complementary in the sense that the manifestation of whether light behaves as a wave or as a particle depends completely on mutually exclusive measurements within the context of an experimental setup. Contrary to von Neumann’s theory of measurement, the role of observation in Bohr’s complementarity thesis does not collapse the wave function;
instead, it merely manifests a single aspect of particle-wave duality within an experimental context.

The idea of a non-collapse theory of measurement in quantum mechanics differs from collapse theories of measurements in the sense that in collapse models of quantum mechanics, such as the Copenhagen or Ghirardi–Rimini–Weber (GRW) models, some mechanism always induces the collapse of the superposition into a well-defined eigenstate of a measured observable—that is, a nonsuperposition from microscopic bodies to macroscopic bodies (Albert, pg. 92-111). We saw that for von Neumann, the mechanism that collapsed the wave function into a nonsuperposition was the observation of a conscious observer. So, when Schrödinger’s cat is in superposition, the mechanism that tells us whether the cat is alive or dead and in one state or the other is our observation. We have to open up the box, look inside, and see what state the cat is in. Some physicists, like Roger Penrose, have argued that a gravitation mechanism is sufficient to cause collapse from microscopic bodies to macroscopic bodies (Penrose, 1996 pg.584), but that most of these collapse models have not been fully worked out to explain how this happens nor is there any experimental evidence so far that has been able to detect or demonstrate when collapse actually takes place.

A non-collapse theory of measurement would either propose that the dynamical evolution of the Schrödinger equation can be applied to both macroscopic and microscopic bodies, like the Everett ‘many worlds’ interpretation, or, like Bohr, it would deny that the collapse of the wave function is a real process and would deny that the Schrödinger wave function depicts anything real and is therefore only mathematically representational. In the Everett interpretation, all results of a measurement are realized and manifested at every moment from the microscopic to macroscopic. The idea is that we can understand the world as splitting or branching into multiple
worlds, all equally real, whenever a superposition occurs. Every time a world branches off, what we are seeing is one the macroscopic possibilities that has occurred (Albert 1992, pg.112-113). Therefore, although macroscopic positions have well-defined locations in the classical sense, we can understand the superposition of macroscopic objects as the collection of all possible worlds, and thus it is still true that there is a superposition of macroscopic objects. Similarly, at the microscopic level of a radioactive atom, whenever we observe the decay of the atom at some definite moment, the Everett interpretation also asserts that we ourselves are really in a superposition of observers recording the many different times of the atom’s decay. But there is no collapse of the superposition going on here at either the macroscopic level or the microscopic level of reality.

In addition, accepting subject–object nonseparability is also helpful in avoiding the problem of the interaction between a nonphysical detached observer and the physical quantum system. As discussed in Chapter Three, the von Neumann collapse of the wave function seems to require some type of mysterious and unexplained nonphysical causal interaction between the observing subject and object being observed in order for objects to have any kind of reality. Howard has commented that Bohr was always careful to physicalize the observer and regarded observations in quantum mechanics as consequent upon measurements being just another kind of physical interaction. Therefore, the first step to making sure measurement is a kind of physical interaction is to physicalize the observer by placing the observer as part of the quantum system, not apart from it. Thus, we avoid the nonphysical vs. physical interaction problem.

What the SON principle offers us is that it is indicative of quantum systems exhibiting metaphysical holism. By metaphysical holism, I mean the kind of characterization as Howard defines it. According to Howard, separability means that spatially separated systems possess
their own distinct physical states and that the joint state of two or more spatially separated systems is wholly determined by their separate states. Following Bohr’s lead, Howard also asserts that quantum entanglement exhibits nonseparability (Howard, 1989 pg. 225-231). As a result, Howard contends that nonseparability is a sufficient condition for ontological holism (i.e., metaphysical holism). Specifically, Howard holds that Bohr’s notion of complementarity is to be interpreted as subject–object nonseparability, and from this he concludes that the best way of understanding Bohr is that Bohr was implying the ontological holism of subject and object.

Therefore, while it is true that quantum systems do exhibit some kind of holism (i.e., nonseparability as a sufficient condition), I argue that we need to view the relationship between the subject and object in a quantum system as a relationship of ontological dependence and not a causal relation as von Neumann apparently assumed. What I am proposing here is a way to develop a fundamentally different theory of measurement for Copenhagen, which is not a collapse theory of measurement where the resolution of the entangled, superposed state of the object is generally seen as being causally dependent on the act of observation. Instead, what we need is a kind of metaphysical holism that Esfeld has argued for, where the kind of ontological dependence or relation that holds between the observed object and observing subject is distinct from causal dependence or a causal relation (Esfeld, 2001 pg.6). According to Esfeld, causal relations are not sufficient in themselves to describe the kind of ontological dependence among the parts of a holistic system. Causal relations may offer an arrangement for the way things are so that the arrangement constitutes a holistic system, but the ontological dependence among the parts of a holistic system must be conceived of differently than from the mere causal understanding of the interaction of the parts (Esfeld, 2001 pg.6).
Therefore, the best way to understand measurement in a quantum system that is based on subject–object nonseparability is to view the subject–object relation as a relation of ontological dependence. Hence, we do not require anything from outside the quantum system to collapse the wave function. In fact, we do not require collapse at all. The other significant problem with the von Neumann theory of measurement is that it undermines scientific objectivity as the idea of subjective causal collapse carries with it the charge of subjectivity and anti-realism. The problem with subjective collapse is that the state of the physical system becomes heavily contingent upon the state of the observer’s knowledge. Subjective collapse gives the impression that observation creates the physical attributes of quantum phenomena such that without observation there is no deep reality.

But I argue that this is not what the SON principle demonstrates. The nonseparability of subject–object does not say that we cannot ascribe reality to quantum phenomena, only that we cannot ascribe an ‘independent reality’ to quantum phenomena and to the agencies of observation (i.e., the subject) separately as quantum phenomena and the agencies of observation have a joint reality that is based on ontological dependence. Bohr pointed out that since the object and the measuring apparatus form an entangled pair, they lack and independent reality and cannot be afforded a separate distinct reality. What the SON principle reveals to us is that there is no ‘outside perspective” by which we can know physical reality in itself, but it does not mean there is no deep reality or that things are unreal or that reality is subjective. The SON principle can account for objective reality, except that it is an objective reality that must be based on the joint ontological dependence of subject and object. For example, the EPR debate demonstrated that to speak about a change in properties, or that observation creates the physical attributes of quantum phenomena, is categorically mistaken as it presupposes some pre-existing state of
affairs that we can describe independently of the experimental setup designed to examine and investigate the very phenomena in question. Bohr’s point in EPR was that if our experimental arrangements are going to tell us anything about the physical world in terms of providing us with well-defined results, the data must include us and our measuring devices.

In addition, a non-collapse theory of measurement is consistent with Bohr’s philosophical and scientific approach overall for several reasons. First, Bohr never talked about the subjective collapse of the wave function, nor did Bohr accept the von Neumann theory of measurement (McEvoy, 2001 pg.92-93). Furthermore, it would not have made sense for Bohr to advocate for collapse as Bohr consistently resisted any ontological interpretation of the wave function. He was clearly against any ontological approach to the interpretation of quantum mechanics that assigned a measure of ‘reality’ to the wave function itself (McEvoy, 2001 pg.401).

Also, Bohr would not have endorsed a literal collapse of the wave function because he argued that the quantum mechanical formalism does not provide physicists with a ‘pictorial’ representation of quantum phenomena rather than a symbolic representation of the quantum world (Faye, Stanford Encyclopedia Physics, Section 4). Bohr would have argued that since the wave function involves only imaginary quantities, it can only have a symbolic character, and he would have granted a representation of collapse only in so far as would be used to predict the outcome of measurement and establish the conditions under which concepts like position, momentum, time, and energy apply to the phenomena (Faye, Stanford Encyclopedia Physics, Section 4). With this understanding of Bohr, it is hard to see how he would have accepted any talk of a collapse. Therefore, the idea of a non-collapse theory of measurement would be quite consistent with Bohr’s philosophy and his overall scientific approach.
4.3 Summary

The points that have been discussed in this chapter attempt to point towards a more philosophically solid foundation for Copenhagen. I have argued that most of our unease with the von Neumann approach to measurement results in part from von Neumann’s failure to physicalize the observer. By placing the observer outside the physical system, von Neumann’s theory of measurement inevitably leads us to an untenable theory of subjective causal collapse, which carries with it additional philosophical and conceptual problems that I have outlined in this thesis. In an effort to deal with the philosophical unease of Copenhagen, I have argued that the start to a possible solution to the measurement problem in Copenhagen can be based on subject–object nonseparability using Howard’s interpretation of Bohr’s ideas on complementarity. The main advantage to re-tooling Copenhagen based on subject–object nonseparability (i.e., quantum holism) is that it changes the relation between subject and object from a causal one to a relation of ontological dependence where neither the subject nor the object is given ontological priority or a prominent causal role, but rather are assumed to represent a joint and simultaneous metaphysical reality.

I have made only some preliminary remarks regarding how Copenhagen could be modified using the SON principle. Of course, many of the details still need to be worked out, but I hope that my discussion at the very least encourages more inquiry into how quantum holism fits into the general picture of how the world is and what kind of new realism would be brought about by an interpretation of quantum mechanics that is based on subject–object nonseparability. It is hoped that more studies into this area of quantum holism will yield a contribution to further a contemporary scientific and philosophical view of the world and ourselves.


