Is our world a deterministic one?

For many of the successful physical theories that accurately describe the world, all physical states are pre-determined by their antecedent states. The thesis of determinism embodies this view, asserting that every event is the inevitable consequence of the previous event. To investigate whether the world is deterministic, it is helpful to consider whether all uncertainty is due to missing information. Expressly, is all randomness apparent or actual? The purpose of this writing is to address this question by contrasting determinism and indeterminism, and further characterising quantum mechanics in relation to indeterministic collapse theories. It aims to show that interpretations of quantum mechanics that posit an inherently stochastic mechanism to explain contentious phenomena do *not* adequately justify rejection of determinism. I will show that this is because deterministic interpretations offer a more coherent and simple understanding that can be better unified with other successful physical theories. Firstly, I will outline the theses of determinism and indeterminism, explaining how they relate to prominent physical theories. Secondly, I will explicate the theory of quantum mechanics by introducing key concepts, such as the evolution of the wave-function, with respect to the prevalent double-slit experiment. I will then define the measurement problem in quantum mechanics, which concerns the apparent probabilistic transition from a wave-function to a single outcome upon observation. Furthermore, I will illustrate collapse theories which attempt to interpret the contentious phenomena exhibited by the measurement problem. These theories challenge determinism as they hypothesise an objective stochastic mechanism. They posit that the apparent physical randomness exemplified by the measurement problem is actual, subsequently endorsing indeterminism. I will conclude by offering a contrasted response to these collapse theories and argue that it is most reasonable to endorse determinism. I indicate non-local hidden variable theories as potential deterministic alternatives and contend that collapse theories comparatively lack simplicity and sufficient coherence with other successful physical theories.

Determinism

Determinism posits that every event in the world is the inevitable and necessary consequence of antecedent states. If the state of a system fixes its past and future states, it is deterministic (Werndl, 2016, p. 210). Proponents of determinism argue that reality operates according to certain fixed laws, and all events are predetermined because of these laws. van Inwagen (1983, p. 3) offers a neat definition of determinism which stipulates that at any moment there is "exactly one physically possible future". In a closed system, the set of antecedent states can only entail one outcome. The outcome is not probabilistic because *all* the antecedent states of the system are accounted. For example, once the first in a row of dominoes is knocked over, it inevitably triggers the fall of subsequent dominoes. The future state of the fallen dominoes is determined by the antecedent state of the dominoes and the physical laws dictating their movement. Accordingly, the set of micro-states within the domino's system, namely the position, velocity, and energy of all its parts, sufficiently determine the micro-states of the system in the next moment. If the universe is a closed system, all the current micro-states of its parts determine the states thereafter.

Everyday observations of changing events can practically reflect the deterministic nature of classical physical theories. For instance, when boiling an electric kettle, energy is transferred to the water from the heating element because the initial conditions of the kettle's mechanism are fixed to bring the water to boil. When the kettle's button is activated, it seems to follow an inevitable process which has been determined by the initial conditions of the system's mechanisms. Moreover, if we know the precise starting temperature, pressure, volume, and the exact amount of heat applied, the principles of classical thermodynamics reveal when the water will start to boil. This exemplifies the deterministic character of classical mechanics, where the future state of a system is pre-determined by its present properties and the laws governing their development. Newtonian Mechanics, Maxwell's Electromagnetism, and Einstein's General and Special Relativity, for instance, are all deterministic theories which assert the future state of a system can be precisely calculated from its present state, provided the governing equations and initial conditions are known. Notably, there are some disputed instances that violate determinism in classical physics. For instance, Norton's (2003) "dome" offers a mathematical solution positing that spontaneous behaviour of certain masses may be permissible in Newtonian Mechanics (see Santo & Gisin, 2019 for other contentious violations). Nonetheless, theories of classical physics are substantially regarded as deterministic (Hoefer, 2023). The outcome of these theories entails a deterministic reality and are reflected in the observed nature of fixed physical events.

Indeterminism

Despite the success of deterministic classical theories, some critics assert that true randomness/unpredictability may inherently exist within the laws of nature. This opposing view is termed *indeterminism*. There are two primary reasons to investigate whether natural laws are in fact deterministic. Firstly, the experience of free will generates disputes around the consequences of determinism which challenge the possibility of not actually being able to choose otherwise (Horgan, 1985; Lewis, 1981; van Inwagen, 1983). Secondly, various interpretations of contentious outcomes from quantum mechanics suggests that the universe is perhaps inherently probabilistic (Bassi, 2023; Ghirardi & Bassi, 2020). The former reason offers a consequence that is counter-intuitive to our experience of free will, and thus motivates further examination. The latter, concerning the subject of this writing, suggests that the fundamental nature of physics may undermine the thesis of determinism. Quantum mechanics may provide empirical grounds on which to accept indeterministic laws of nature.

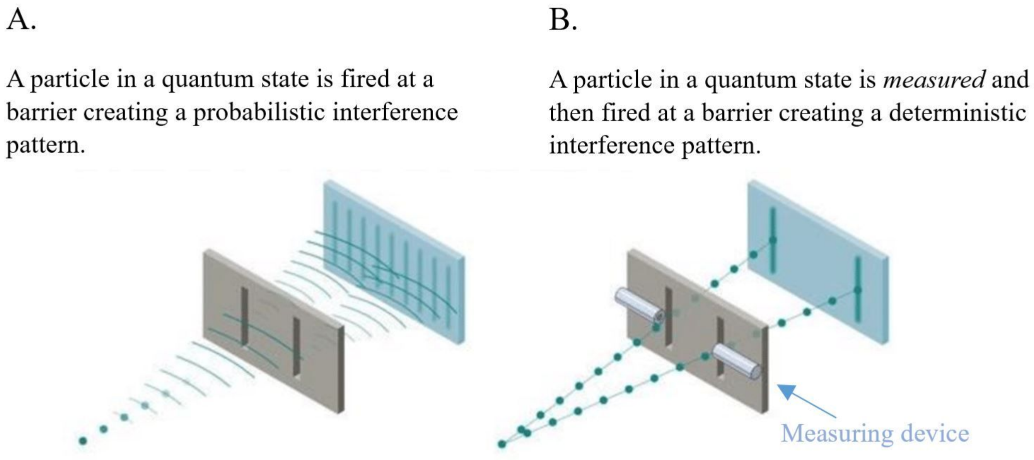
By illustrating interpretations of unclear phenomena in quantum mechanics, namely the *measurement problem,* an argument by inference to the best explanation may be used to support determinism over indeterminism. The following sections will outline quantum mechanics and aim to characterise an indeterministic interpretation of physical phenomena. It will conclude by contrasting responses to the suitability of theories that endorse indeterminism. The evaluation will argue that deterministic interpretations offer the best explanation due to simplicity and coherence with other successful physical theories.

Quantum Mechanics

Quantum mechanics is a branch of physics that concerns the nature of matter and energy at the most fundamental level of atomic and subatomic particles. The theory produces probabilities rather than precise predictions about outcomes, moreover, it is empirically verified and widely approved as an accurate description of microscopic phenomena in the world (Ismael, 2021). Microscopic phenomena such as radioactive decay and photon emission/absorption cannot be precisely predicted given the initial state of a system. Instead, the theory indicates that observed outcomes of microscopic phenomena can only be understood within a range of probable outcomes (Albert, 1992, p. 1-2). The theory describes the state of microscopic particles as a wave-function, a mathematical representation which encapsulates all potential states of that particle (Albert, 1992, p. 30-43). A wave-function is in a superposition of all these potential states. From the wave-function a probability density function can be derived, with each potential state associated with a certain likelihood of occurrence. Furthermore, the future quantum state of a wave-function from an initial quantum state can be calculated using the Schrödinger equation below (Griffiths, 2013, p. 295). Using this equation, quantum mechanics can determine the evolution of the wave-function over time (Appendix A).

$$i\hbar\frac{\partial}{\partial t}\psi(\vec{r},t) = -\frac{\hbar}{2m}\nabla^2\psi(\vec{r},t) + V(\vec{r})\psi(\vec{r},t)$$

Quantum mechanics, however, cannot determine the exact outcome of a system's future state *after* measurement. When the properties of a quantum system are measured, the evolution of the wave-function is seemingly interrupted, and a single state is observed (Myrvold, 2022, s. 2.3). Importantly, the measured outcome of a system's properties cannot be certainly determined from the initial wave-function. The future observed state of the system is indeterminate such that the initial quantum state does not fix an exact outcome. Empirical evidence suggests that a future state can only be expressed with a degree of uncertainty (Albert, 1992, p. 1-15). For example, the double-slit experiment fires many particles at a barrier with two slits to create a recorded pattern on the background (see Figure 1). According to classical mechanics, each particle should only pass through one slit and land at a determined point on the screen (Figure 1, B). However, if these particles are in a quantum state, behaving as a wave-function, they pass through both slits simultaneously and create an interference pattern on the background that represents the underlying probability density function (Figure 1, A). Using the initial wave-function of a system cannot predict the measured future state of the system, as the eventual outcome of a quantum state at measurement is probabilistic. If the state is measured before the slit, the particle behaves deterministically, and the background does not follow a probabilistic pattern (Figure 1, B). If the quantum object is *not* measured before the slits, the position of the impact on the background is based on the probability density function. Such evidence suggests that we cannot determine a measured outcome from the initial quantum state of the system.



A.

A particle in a quantum state is fired at a barrier creating a probabilistic interference pattern.

B.

A particle in a quantum state is *measured* and then fired at a barrier creating a deterministic interference pattern.

Figure 1. A representation of the double-slit experiment outlined by Albert (1992, p.1-15) to exemplify the measurement of a quantum state. Adapted from Worth (2022).

The apparent probabilistic transition from a wave-function representing many outcomes to a single outcome upon observation is known as the *measurement problem* (Myrvold, 2022, s. 4). Unusually, the quantum state seems to represent a complete description of the initial state of a system, yet it does not correspond to one definite outcome. What then determines the particular outcome from the antecedent wave-function? It is a contentious interpretational problem as to how the initial state of a quantum system reaches a definite outcome (Myrvold, 2022, s. 4.2). The measurement problem suggests that the observed state of an event is not predetermined by the quantum state alone.

Collapse Theories and Inherent Indeterminism

Unlike classical mechanics, quantum mechanics produces probabilities when the Schrödinger evolution of the wave-function is interrupted by a measurement. The measurement problem illustrates an indeterministic jump from a quantum state to a discrete future state. If quantum mechanics is an accurate description of the world, and the evolution from a quantum state to a measured state is probabilistic, the world may be inherently indeterministic. If the world is *inherently* indeterministic this means that the derived probabilities from the wave-function are *not* a consequence of missing information. They are a consequence of fundamental randomness, due to underlying indeterminism in the laws of nature.

The measurement problem may be due to an indeterministic phenomena whereby the wave-function *collapses* into a fixed state. Objective collapse theories, such as the Ghirardi-Rimini-Weber (GRW) and Continuous Spontaneous Localization (CSL), characterise mechanisms to explain the collapse of a wave-function from a superposition of states to a well-defined value (Bassi, 2023). In collapse theories, the evolution of the wave-function is deterministic until it is interrupted by the collapse of the wave-function. Each collapse is caused by a fundamentally stochastic mechanism. The CSL for example posits that wave-function collapse is indeterministic, with a higher probability of collapse being proportional to the number of interacting particles (Ghirardi & Bassi, 2020, s. 6). The measurement problem is claimed to be a consequence of the inherently indeterministic nature of the wave-function collapse. Subsequently, collapse theories undermine determinism due to this intrinsic randomness. The apparent uncertainty from measuring a quantum system is addressed by collapse theories which posit an indeterministic process fundamental to natural laws.

Responding to Collapse Theories

One may object that the probabilistic nature of quantum mechanics is a consequence of missing information rather than indeterministic mechanisms of collapse. This is expressed by *local hidden variable* theories, which offer a deterministic explanation to the apparent indeterminism exemplified by the measurement problem (Hoefer, 2023). The hidden variable interpretation asserts that the indeterminacy of calculating a future outcome from a quantum state is due to unaccounted local variables that affect the outcome. However, this conjecture has been largely discredited by empirical evidence, specifically, the violation of Bell's inequalities (see Appendix B and Kwait, 1999). To overcome this, some hidden variable accounts, such as Bohmian Mechanics, have continued to challenge the completeness of quantum mechanics (Goldstein, 2021). These contemporary accounts reject the assumption of locality to avoid implications of Bell's theorem. Explicitly, the consequences of non-locality are such that objects on either side of the galaxy may instantly affect each other without travelling through space-time (see Albert, 1992, p. 61-72 for further discussion on locality). Although contemporary hidden variable accounts come at the cost of rejecting locality, *so do* collapse theories (Hoefer, 2023). Thus, contemporary hidden variable theories may offer an alternative deterministic interpretation of the measurement problem.

Furthermore, by introducing a stochastic mechanism, collapse theories may somewhat undermine the goal of a coherent and unified physical theory. The Schrödinger equation suggests that the evolution of the wave-function is deterministic, and classical mechanics suggests that macro-behaviour of particles is deterministic. Why should it be that only one unique phenomenon, the collapse of the wave-function, is indeterministic? Evidently, the fundamental nature of collapse theory is not coherent with other descriptions of the physical world. Whether collapse theory reasonably adheres to a coherent, unified physical theory depends upon the mutual exclusivity and necessity of determinism and indeterminism in the world. Having a multiplicity of deterministic and indeterministic natural laws forfeits simplicity, weakening the interpretation's strength due to the principle of Occam's Razor (Baker, 2022). By inference to the best explanation, a deterministic interpretation, such as non-local hidden variable theories may be preferred. Conversely, the collapse theorist may claim that alternative theories are *not* simpler by highlighting the supplementary mechanisms posited by non-local hidden variable theories. Bohmian Mechanics, for instance, relies on a deterministic *pilot-wave* that guides particles in a way that reproduced the probabilities of quantum mechanics (Goldstein, 2021). Nonetheless, introducing a stochastic phenomenon is incoherent with the deterministic nature of other successful physical theories. non-local hidden variable theories only endorse the addition of a deterministic mechanism, making them preferable. Their framework has better coherence with other physical theories, and more simply, does not posit an extra uniquely indeterministic ontological entity.

While collapse theories provide a potential solution to the measurement problem, they contend that the world has an inherently indeterministic nature. The collapse interpretation undermines determinism by defending that the observation of quantum states is due to the inherently probabilistic collapse of the wave-function into an undetermined fixed state. The interpretation is alluring because it remains consistent with quantum mechanics and empirical observations. However, other deterministic interpretations, such as non-local hidden variable theories, also fit the predictions made by quantum mechanics. Because collapse theories posit a uniquely indeterministic physical mechanism, they may not offer the best interpretation of the measurement problem. The indeterministic nature of collapse theories is not sufficiently coherent or unified with other successful physical theories. Therefore, a simpler deterministic interpretation, such as non-local hidden variable theories should be preferred. Consequently, the world may reasonably be considered deterministic. Further investigation is required concerning the *apparent* or *actual* nature of a collapse and the contentious measurement problem particularly in relation to formally defining the *measurement* of a quantum system. It may still be necessary to invoke a stochastic phenomenon into natural laws if other deterministic solutions prove inadequate. Until then, alternative deterministic explanations should be endorsed if they offer a simpler framework and better unification with other successful physical theories.

References

Albert, D. Z. (1992). *Quantum mechanics and experience*. Harvard University Press.

Baker, A. (2022). *Simplicity*. Retrieved from The Stanford Encyclopedia of Philosophy

Bassi, A., Dorato, M., & Ulbricht, H. (2023). *Collapse Models: A Theoretical, Experimental and Philosophical Review*. Entropy, 25(4).

Dupré, J. (2001). *Human Nature and the Limits of Science*, Oxford: Oxford University Press.

Ghirardi, G., & Bassi, A. (2020). *Collapse Theories*. Retrieved from The Stanford Encyclopedia of Philosophy

Goldstein, S. (2021). *Bohmian Mechanics.* Retrieved from The Stanford Encyclopedia of Philosophy

Griffiths, D. J. (2013). *Introduction to Quantum Mechanics* (2nd ed., Pearson new international edition.). Pearson Education Limited.

Hoefer, C. (2023). *Causal Determinism*. Retrieved from The Stanford Encyclopedia of Philosophy

Horgan, T. (1985). *Compatibilism and the Consequence Argument.* Philosophical Studies: An International Journal for Philosophy in the Analytic Tradition, 47(3), 339–356.

Ismael, J. (2021). *Quantum Mechanics*. Retrieved from The Stanford Encyclopedia of Philosophy

Kwiat, P. G., Waks, E., White, A. G., Appelbaum, I., & Eberhard, P. H. (1999). *Ultrabright source of polarization-entangled photons.* Phys. Rev. A, 60, R773–R776.

Lewis, D. (1981). *Are We Free to Break the Laws*? Theoria, 47(3): 113–121.

Myrvold, W., Genovese, M., & Shimony, A. (2021). *Bell's Theorem*. Retrieved from The Stanford Encyclopedia of Philosophy

Myrvold, W. (2022). *Philosophical Issues in Quantum Theory.* Retrieved from The Stanford Encyclopedia of Philosophy

Norton, J. D. (2003). "*Causation as Folk Science*," Philosopher's Imprint, 3 (4)

Santo, F. D., & Gisin, N. (2019). *Physics without determinism: Alternative interpretations of classical physics.* Physical Review A, 100(6).

Trimmer, J. D. (1980). *The Present Situation in Quantum Mechanics: A Translation of Schrödinger's "Cat Paradox" Paper.* Proceedings of the American Philosophical Society, 124(5), 323–338.

Van Inwagen, P. (1983). *An Essay on Free Will.* New York: Oxford University Press.

Werndl, C. (2016). *Determinism and indeterminism*. The Oxford handbook of philosophy of science, 210-232.

Worth, P., Jr, Valdez, J., & Pande, S. (2022). *Ideological Reference Architecture (IRA): an epistemological interpretation of quantum mechanics.*

Appendices

A. Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}\psi(\vec{r},t) = -\frac{\hbar}{2m}\nabla^2\psi(\vec{r},t) + V(\vec{r})\psi(\vec{r},t)$$

The time-dependent Schrödinger equation is fundamental to quantum mechanics and describes how the state of a quantum system evolves over time. It is a mathematical representation that predicts the behaviour of microscopic objects that classical physics cannot. Expressely, the equation has three main parts:

$i\hbar\frac{\partial}{\partial t}\psi(\vec{r},t)$

The left side of the equation shows how the wave-function □ evolves over time. □ is used to derive the probability density function for observing the particle at a specific space and time. The other terms, such as the imaginary unit *i* and the reduced Planck's constant ħ, may be translated to how rapidly or slowly □ changes with time. *i and* ħ are complex numbers that allow the wave-like nature of quantum particles.

$-\frac{\hbar}{2m}\nabla^2\psi(\vec{r},t)$

The first term on the right side concerns how □ changes in space. The terms represent the spatial movement of the particle, which relate to its kinetic energy. If the wave function has rapid spatial fluctuations, it signifies higher kinetic energy. The term is scaled by $\hbar^2/2m$, where m is the particle's mass, illustrating that heavier particles have lower kinetic energy.

$V(\vec{r})\psi(\vec{r},t)$

The second term on the right side describes the affect of external forces/constraints on □. For example, the effects of a gravitational field on the quantum state. V is the "potential energy function", and it is multiplied by □ to show that external force/constraints have a direct effect on the energy of the quantum state.

The time-dependent Schrödinger equation integrates the kinetic and potential energies into a description of how □ evolves through time. It describes the interplay between the particle's energy, its interactions with the surrounding environment, and the probabilities of finding it in various locations. See Griffiths (2013, ch. 7) for further discussion on this equation.

B. Bell's Theorem

Bell's theorem is a principle in quantum mechanics that suggests no theory based on local hidden variables (i.e., missing information about undetectable variables that might pre-determine the outcomes of quantum measurement) can reproduce all the predictions of quantum mechanics. The theorem presents a set of mathematical inequalities (Bell's inequalities) that local hidden variable theories must satisfy. However, quantum mechanics itself predicts situations where these inequalities are violated (Kwait, 1999). A simplified form of one of Bell's inequalities is adapted from Myrvold (2021) below.

$$E(a,b) - E(a,b') + E(a',b) + E(a',b') \leq 2$$

Empirical experiments have consistently shown violations of Bell's inequalities, supporting the non-local predictions of quantum mechanics and challenging the idea of local hidden variables (Myrvold, 2021, s. 8). This means that if there are hidden variables determining quantum outcomes, they must be able to influence each other instantaneously over any distance, an idea that goes against assumptions of cause and effect being limited by the speed of light. See Kwait (1999) for an example of violations to Bell's inequalities.