

KARL POPPER, QUANTUM MECHANICS AND THE INCOMPLETENESS OF CRITICAL RATIONALISM

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Abstract

This paper provides a rigorous and critical engagement with Karl Popper's doctrine of critical rationalism, a methodological stance that decisively rejects inductivism and instead foregrounds falsifiability as the demarcation criterion for scientific knowledge. Through an interrogation of Popper's epistemological commitments, the paper elucidates how his emphasis on conjecture, refutation and the provisional status of theories underpins a non-dogmatic vision of scientific progress. Further, the paper interrogates Popper's scientific realism by advancing his conviction in an objective reality that persists beyond human observation and resisting the relativistic and instrumentalist currents that have proliferated in modern scientific discourse, especially within quantum theory. A substantial portion of the discussion is devoted to Popper's critique of the Copenhagen interpretation of quantum mechanics, where he challenges its entanglement with observer-dependent epistemologies and probabilistic determinism. Popper's counterposition is articulated through his innovative thought experiments aimed at scrutinising quantum nonlocality and the measurement problem. These are complemented by an in-depth analysis of his propensity interpretation of probability, which seeks to transcend classical and frequentist models by grounding probabilistic reasoning in the dispositional properties of physical systems. The paper concludes that objectivism, in Popper's analyses, emerges not as a fixed epistemic state of theories but as an achievement of dialogic rationality within scientific communities.

Keywords: Critical rationalism, epistemology, falsifiability, quantum mechanics, scientific realism

Introduction

In this paper, focus shall be placed to Karl Popper's philosophy of science, an intellectual paradigm that stands as one of the most influential ideologies in 20th-century philosophical discourse. Here, an evaluation of the principles of critical rationalism, Popper's hallmark approach, which fundamentally challenges the traditional reliance on induction, will be undertaken. Through this analysis, the centrality of falsifiability as a defining criterion for scientific progress and its implications for epistemology and methodology will be highlighted. The paper will further explore Popper's unwavering commitment to scientific realism, a defense of an objective reality that exists independently of human perception. This commitment shall be contrasted with the relativistic and instrumentalist tendencies that have emerged within contemporary science, particularly within the domain of quantum mechanics and efforts shall be made to show how he champions a provisional and non-dogmatic conception of scientific theories that emphasise their inherently conjectural nature and perpetual openness to refutation, rather than treating them as definitive or immutable truths. A significant segment of this paper shall be dedicated to Popper's engagement with the philosophical foundations of quantum mechanics where his critiques of the Copenhagen interpretation, which he criticised for its perceived reliance on subjective observer-dependence and probabilistic determinism, will be examined. After this, an exploration of

Popper's insistence on preserving the ontological status of physical phenomena as entities existing independently of measurement shall be done, and his thought-experiment, designed to interrogate and test the predictions of quantum mechanics, as an innovative contribution to addressing the challenges posed by quantum nonlocality, entanglement and the measurement problem will be analysed.

Popper's alternative vision, the propensity interpretation of probability, a philosophical stance that transcends the limitations of classical determinism and purely statistical interpretations shall also be evaluated. This paper will conclude on the note that Popper's critical rationalism, though champions objectivism, paradoxically reveals its reliance on subjective critique and the sociocultural nature of scientific communities, which makes objectivism an emergent property of collective human reasoning.

Principles of Critical Rationalism in Karl Popper's Philosophy of Science.

Popper's philosophy of science, particularly his principles of critical rationalism, represents a radical departure from traditional epistemological structures. Critical rationalism, as developed by Popper, is rooted in the belief that knowledge progresses through a process of conjectures and refutations, rather than through the accumulation of verified truths. This approach emphasises the importance of falsifiability as a criterion for scientific theories, arguing that scientific hypotheses should be subjected to rigorous testing and should never be considered conclusively verified (Ormerod, 2009; Gadenne, 2006; Kamino, 1994; Afisi, 2012; Afisi, 2015).

Popper's philosophy challenges the positivist notion of science as a system of justified beliefs, instead he proposes that scientific progress is achieved through the continuous cycle of proposing bold hypotheses and exposing them to potential falsification (Basilis & Shang, 2022; Holtz & Odağ, 2020). This methodology not only applies to the natural sciences but also extends to the social sciences, where it serves as a guiding epistemology that encourages openness to criticism and the rejection of dogmatic certainty (Bennett, 2009; Holtz & Odağ, 2020; Afisi, 2015).

Popper also advocates for an open society, where freedom of thought and critical discourse are essential for the advancement of knowledge. He believes in a societal model that supports the idea that through critical engagement and the willingness to revise or abandon theories in light of new evidence, both scientific and social progress can be achieved (Ormerod, 2009; Topitsch, 1984). For him, the resilience of a theory under sustained scrutiny, rather than the volume of evidence supporting it, constitutes the ultimate test of its scientific merit. This methodological shift underscores the prescriptive nature of Popper's critical rationalism.

At the heart of Popper's critical rationalism are three interrelated principles: falsifiability, which asserts that a theory is scientific only if it can, in principle, be refuted by empirical evidence; the methodological cycle of conjectures and refutations, through which scientific knowledge advances incrementally; and the pursuit of objective knowledge, defined as truths about the world that transcend subjective beliefs. These principles form the backbone of

Popper's critical rationalism and emphasise the iterative nature of scientific progress through conjectures and refutations. Although, they are not without their own critiques, particularly regarding their application and limitations in complex scientific paradigms.

Popper's Rejection of Induction as a Method of Science

A central departure in Popper's philosophy of science which positions him alongside David Hume, is his rejection of inductivism, the notion that scientific knowledge arises from the accumulation of empirical observations. As briefly referenced earlier, proponents of inductivism, such as the early twentieth-century logical positivists, contend that repeated observations can ultimately confirm a general theory. However, Popper identifies a fundamental flaw in this reasoning. He opines that no matter how numerous the confirming instances, they can never ensure the truth of a universal generalisation. For example, observing countless white swans does not logically preclude the existence of a black swan elsewhere. This inherent flaw, recognised as the problem of induction (Hume, 1739), undermines the notion that scientific knowledge can be securely grounded in inductive reasoning.

In place of induction, Popper proposes the hypothetico-deductive method, wherein science begins with hypotheses that are rigorously tested against empirical evidence. The scientific process initiates with a hypothesis, a tentative, conjectural proposition about the world, which is then subjected to empirical scrutiny through predictions that can be observed. If the predictions are false, the hypothesis is falsified; if the predictions are corroborated, the hypothesis is not proven true but remains provisionally accepted and remains open to future refutation (Popper, 1959). This cyclical process of conjecture and refutation is the driving force behind scientific progress, standing in stark contrast to the inductive approach, which seeks to infer general laws from repeated observations. Popper insists that inductive reasoning is plagued by logical limitations, as no amount of confirmatory evidence can conclusively establish the truth of a universal statement (Popper, 1963). Thus, even theories that withstand rigorous attempts at falsification can only be considered tentatively reliable, as future evidence may still contradict them. Theories that endure such rigorous testing are not considered true but are instead corroborated, provisionally accepted as long as they remain unfalsified (Popper, 1959).

In rejecting the logical positivists' naturalistic approach to the demarcation problem, Popper disputes the inductive methodology that posits universal laws emerge from individual hypotheses grounded in experimental or observational reports. He critiques this traditional inductive method and contends that observations are inherently theory-laden, not theory-free, and that they require the application of concepts and frameworks in descriptive terms. Observing a phenomenon entails selecting an object and defining the research task, making it inherently problem-posing (Popper, 1963: 46). Moreover, scientific laws derived from inductivism fail the verification principle, as they constitute universal statements that cannot be logically justified. However, data-driven advancements in fields like artificial intelligence (AI) and genomics reveal that induction remains foundational to progress in science, both in theory generation and practical applications. Machine learning models, for instance,

generalise from specific datasets to make accurate predictions. Countering this, Popper reconceptualised the methodology of science, and asserts that the strength of a theory lies not in its capacity for verification but in its susceptibility to empirical disproof (Afisi, 2013, p.506). Therefore, the inductive system, wherein inferences are generalised from specific observations, remains within the domain of pseudoscience (Popper, 1963, p.53).

However, inductive reasoning serves as an indispensable pillar for constructing predictive frameworks that is grounded in the analysis of extensive historical data, especially in disciplines such as climate modeling, where methodological approach enables researchers to discern patterns, establish probabilistic trends and extrapolate future scenarios from observed phenomena. Jettisoning the significance of inductive inference will disregard the practical realities of theory formation, where empirical regularities often provide the foundation upon which further explanatory models are constructed. Such oversight risks undermining the pragmatic progression of scientific inquiry, particularly in contexts where deductive falsification alone is insufficient to address the complex interdependencies inherent in large-scale systems.

To reject induction is to overlook its practical necessity in formulating hypotheses and interpreting observations. Scientists routinely generalise from specific observations to propose theories, a process inherently inductive. For example, observing consistent planetary motion led to Newton's laws, an inductive leap foundational to physics. Without induction, the creative process of theory formation would lack structure as it remains indispensable for both generating and contextualising scientific knowledge. Practical science relies on degrees of confirmation, not solely falsifiability. Medical trials, for example, rely on accumulating supportive evidence, gradually inducing confidence in treatment efficacy, which Popper's framework inadequately accommodates. Although induction is fallible, modern science demonstrates that it is indispensable for generating, refining and validating knowledge in real-world contexts.

Falsification and the Demarcation Project

Building on his rejection of induction as a method of science, Popper draws attention to the necessity of distinguishing scientific theories from non-scientific ones, in alignment with the logical positivists. However, Popper diverges from the logical positivists' views by proposing an alternative criterion for demarcating scientific theories from non-scientific ones. Central to logical positivism is the principle of verifiability, which serves as a foundational tenet of their epistemological enterprise. In its more rudimentary form, this principle posited that "The meaning of a statement is the method of its verification" (Waismann, 1930, p. 229). Over time, it evolved into the more refined formulation that "A statement is held to be literally meaningful if and only if it is either analytic or empirically verifiable" (Ayer, 1936, p. 9). A common thread running through all variants of the principle is the assertion that a genuine statement must be capable of being conclusively verified and must possess the ability to be definitively confirmed through empirical evidence or logical analysis (Schlick, 1931, p. 150). Popper rejects the notion that experience could be entirely free from theoretical influence or bias. In Popper's view, all observations are theory-laden; they are shaped by the pre-existing

theoretical frameworks that guide our understanding of the world. As such, Popper sees the idea of a neutral, unbiased observation as untenable. He contends that the search for objective truth can not be based on the assumption that experience provides an unmediated and definitive foundation for verifying or falsifying theories. Instead, he proposes that scientific theories should be subjected to the method of falsification, rather than verification, to distinguish them from non-scientific or pseudoscientific propositions. This marks a clear departure from the logical positivists' reliance on verification and their commitment to an empiricist view of knowledge. Popper himself said that:

My point of view is, briefly, that our ordinary language is full of theories; that observation is always observation in the light of theories that it is only the inductivist prejudice which leads people to think that there could be a phenomenal language, free of theories, and distinguishable from a 'theoretical language' (Popper, 1959, p.59).

Having attacked the empiricist assumption that experience is something theory-neutral, Popper had, in effect, attacked the fundamental assumption of logical positivism, since without a theory-neutral base the positivistic analysis of truth and meaning could not stand up. Popper accepts, however, the positivist view that scientific knowledge is objective; his own philosophical programme accordingly takes the form of an effort to reconcile the objectivity of scientific knowledge with the theory-laden nature of observation. The question Popper then takes to be important, is how possible it is to decide whether a theory is scientific or not. He writes that:

The problem which troubled me at the time was neither, 'When is a theory true?' nor, 'When is a theory acceptable?' My problem was different. I wished to distinguish between science and pseudo-science knowing very well that science often errs, and that pseudo-science may happen to stumble on the truth (Popper, 1963, p.33).

Popper avers that if a theory is structured in such a way that it is immune to refutation (for example, by explaining away any counterevidence as irrelevant or anomalous), then it is not scientific. He argues that scientific statement that speaks about reality must be falsifiable, otherwise, it does not speak about reality (Popper 1959, p.18). Popper's falsification principle challenges the verificationist view by asserting that no scientific theory can ever be proven to be true. Instead, theories are always open to being falsified, and science progresses not by confirming theories but by eliminating false ones. As he writes, "Science must begin with myths, and with the criticism of myths" (Popper, 1963). Science, therefore, is not about certainties but about critical discussion and error correction, a process driven by the identification of errors and the replacement of refuted theories with better, more testable alternatives. To explain this better, Popper writes:

I propose the following definition. A theory is to be called 'empirical' or 'falsifiable' if it divides the class of all possible basic statements unambiguously into the following two non-empty sub-classes. First, the class of all those basic statements with which it is inconsistent (or which it rules out, or prohibits): we call this the class of the potential

falsifiers of the theory; and secondly, the class of those basic statements which it does not contradict (or which it 'permits'). We can put this more briefly by saying: a theory is falsifiable if the class of its potential falsifiers is not empty (Popper, 1959, p.86).

On the basis of his falsification principle, Popper was able to put forward an alternative logic of scientific discovery to counter the positivist view that science begins with sensory experience and uses inductive logic to arrive at general truths. Scientific problems are invariably framed and influenced by pre-existing theories, which shape their formulation and resolution. Therefore, it is more accurate to suggest that the scientific process can initiate and conclude at various points within a theoretical schema, whether it begins with one set of tentative theory (TT1) and concludes with another tentative theory (TT2), or starts with an error elimination (EE1) and progresses to a subsequent one (EE2) (Popper, 1974a, p. 105).

He argues further that scientific theories gain their credibility by making risky predictions, which are precise claims that could easily be proven false if incorrect. He emphasises that "The more a theory forbids, the better it is (Popper, 1959, p. 36). Higgs boson, a fundamental particle predicted by the Standard Model of particle physics, prime example of a risky prediction. The theory forecasts the Higgs boson's mass range and its interactions with other particles which makes it a testable claim. For decades, physicists built experiments to search for the Higgs boson and in 2012, experiments conducted at the Large Hadron Collider (LHC) confirms its existence within the predicted parameters (ATLAS Collaboration, 2012; CMS Collaboration, 2012). Had the Higgs boson not been detected, the Standard Model would have required significant revision or rejection. This alignment with Popper's falsifiability criterion demonstrates the significant nature of the scientific process, where risky predictions serve as rigorous tests of theoretical frameworks.

Conversely, pseudosciences often accommodate any observation by making ad hoc adjustments to their claims and rendering them immune to falsification. Popper criticises Freud's psychoanalysis and Marx's historical materialism for their unfalsifiable nature. For example, Freud's explanations of behaviour, such as attributing dreams to repressed desires, could accommodate any possible outcome and make them irrefutable. Similarly, Popper avers that Marxist predictions about class struggle were modified post hoc to fit historical developments which turns Marxism into a pseudoscience. Similarly, astrology fails the falsifiability test. Astrological claims are typically vague and can be retrofitted to any situation. For example, a horoscope predicting that someone will face challenges in relationships is so general that it could apply to countless scenarios and evades meaningful scrutiny.

However, even in the domain of practical science, certain theories challenge the principle of strict falsifiability. A notable example is string theory in physics, which endeavours to unify quantum mechanics and general relativity by conceptualising particles as one-dimensional vibrating strings rather than point-like entities. With its mathematically elegant structure, string theory has yet to yield testable predictions, hence, the limitations of rigid adherence to falsifiability in contemporary scientific contexts. To dismiss such theories outright would risk

unduly constraining the boundaries of scientific progress. It overlooks the iterative and progressive nature of scientific exploration, wherein theories initially beyond empirical testing may eventually become verifiable as advancements in methodology, experimental precision or conceptual paradigms unfold. Neglecting the potential for indirect validation or future empirical corroboration not only narrows the scope of inquiry but also impedes the epistemological process by which science expands its explanatory capacity and refines its foundational constructs.

The provisional and non-dogmatic nature of scientific theories

From the foregoing, it is true to say that Popper's demarcation criterion posits a more explicit and prescriptive methodology; one that seeks to delineate genuine science from pseudoscience through an emphasis on empirical testability. At its core, Popper's ideology aims to construct a theory of scientific rationality that faithfully represents the logical relationships between observable data and theoretical propositions within scientific research. He posits that the central concern of epistemology is the growth of knowledge and argues that studying the evolution of scientific theories provides the best pathway for understanding how knowledge itself progresses (Popper, 1959, p.15). In this regard, the demarcation task is not merely a classificatory exercise but a critical philosophical endeavour that bears implications for the conduct and interpretation of scientific research. For Popper, epistemology must be viewed through the lens of scientific methodology, where the rigorous scrutiny of theories through testing and potential refutation forms the basis of rational inquiry (Popper, 1959, p.49).

While Popper's idea of scientific theories as provisional and non-dogmatic is insightful, it becomes problematic when critically examined. It is true that his emphasis on fallibility promotes open inquiry, but systematic issues emerge in the application of this principle because the idea risks undermining scientific consensus. For instance, in climate science or vaccine efficacy, acknowledging theories as provisional can be misused to fuel skepticism and hinder public trust and critics may exploit this openness to reject well-supported conclusions, despite overwhelming evidence in their favour.

Defense of an objective physical reality

Having systematically addressed the non-dogmatic nature of scientific knowledge and the method of demarcating science from pseudo-science, Popper firmly asserts that scientific knowledge is inherently objective. He contends that true scientific knowledge exists independently of the individual beliefs, claims or interpretations of scientists, a position rooted in his epistemological stance of fallibilism. According to Popper, the objectivity of science is secured by the impersonal nature of its discovery process, which is driven by empirical testing rather than by subjective intuition or authority. He maintains that the distinction between objective knowledge and the knowing subject is both feasible and essential, as this separation upholds the impartiality of scientific inquiry and facilitates the cumulative advancement of knowledge (Krausz, 1974, p. 1).

A critical element of Popper's epistemology is his concept of the three worlds, which delineates the nature and scope of knowledge. World one pertains to the domain of physical

objects and material states that represent the tangible and concrete aspects of reality. World two, by contrast, refers to the realm of mental states, including emotions, perceptions and subjective experiences. Most significantly, World three encompasses the objective content of thought, comprising scientific theories, logical constructs, mathematical proofs and cultural artifacts such as literature and art (Irzik, 1995;1 De Araujo Neto, 2014). This tripartite framework highlights Popper's belief that the products of human intellect, particularly scientific theories, possess an autonomous existence in World three, independent of the mental states of their creators. According to Popper, the contents of World three, such as theoretical constructs, can be subjected to critical evaluation and empirical testing without reference to the beliefs or intentions of the individuals who conceived them (Irzik, 1995).

In stark contrast, subjective knowledge is inextricably linked to the personal beliefs and cognitive processes of individuals, residing within World two. Popper argues that this form of knowledge is inherently fallible, and is shaped by human error, bias and the limitations of perception. He insists that genuine scientific progress arises not from the accumulation of subjective beliefs, but through a rigorous methodology of conjectures and refutations (Sachs, 1974, p. 399). This methodology involves the formulation of bold hypotheses, followed by sustained efforts to disprove them. Through this iterative process of falsification, scientific understanding is progressively refined, although absolute certainty remains an unattainable ideal. However, the empirical realities of scientific practice suggest that the universe operates through varying degrees of statistical regularity and approximate patterns and not merely under rigid, deterministic laws. Nature exhibits behaviours that range from entrenched regularities to fluid unpredictability instead of total, exact predictability, such that at some point, macroscopic objects like cars, ball and even planets follow near-lawlike behaviour, and at another, they get distorted by human cognition and spontaneity. At the subatomic level, phenomena are governed by probabilities and chance rather than deterministic certainty. This variability undermines the notion of an entirely objective physical reality as championed by Popper, and reveals a cosmos where regularity coexists with randomness and creative spontaneity. Consequently, Popper's insistence on objective reality seems ill-suited to capture the interconnection of order and unpredictability inherent in both the natural world and human thought.

Popper's further commitment to the objective nature of scientific knowledge is evidenced in his vigorous opposition to relativism and subjectivism within the philosophy of science. He argues that the objectivity of scientific theories is protected through the critical scrutiny of the scientific community (Afisi 2017, p. 46). The collective efforts of researchers to test, validate or refute theories serve as a safeguard against individual biases that might distort scientific reasoning. This communal aspect of inquiry serves as the foundation of scientific objectivity and ensures that knowledge claims are assessed based on empirical evidence and logical coherence, rather than on subjective consensus or cultural perspectives (Ovchinnikov, 2020). However, in social sciences, where subjective experience and cultural contexts shape understanding, Popper's objective stance can be limiting. For example, economic models often assume rational actors, but real-world phenomena like the present financial crisis in Nigeria illustrate how emotions and biases deviate from objective predictions. These

deviations suggest that subjective realities, though inconsistent, influence outcomes and thus merit consideration alongside objective metrics.

The idea of an objective reality also marginalises the lived experiences of marginalised communities. For example, indigenous knowledge systems like the *Ifa* Corpus which are founded on subjective and communal epistemologies, and are often dismissed as unscientific despite their empirical successes.

Moreover, although Popper's idea of objective reality promotes rigorous scientific inquiry, its exclusivity can lead science to subjective dimensions critical to understanding complex, layered phenomena. A more inclusive epistemology, which integrates subjective and intersubjective realities, would address these criticisms without undermining the objectivism central to empirical validation.

On Conjectures and Refutations

Having laid the foundation for falsifiability and objectivity in scientific inquiry, Popper argues that scientific knowledge grows through conjectures (hypotheses or theories) and refutations (attempts to falsify these hypotheses). This opposes the empiricist view, which holds that knowledge comes from experience. Popper argues that observation is theory-laden; we interpret data based on prior theoretical commitments, and thus observation alone cannot serve as the foundation for scientific knowledge (Popper, 1963). Instead, we begin with conjectures, creative leaps or guesses about the world, and then test these guesses through empirical scrutiny. On the role of conjectures, Popper notes that:

Science does not rest upon solid bedrock. The bold structure of its theories rises, as it were, above a swamp. It is like a building erected on piles. The piles are driven down from above into the swamp, but not down to any natural or 'given' base; and when we cease our attempts to drive our piles deeper, it is not because we have reached firm ground. We simply stop when we are satisfied that they are firm enough to carry the structure, at least for the time being (Popper 1959, p. 111).

Since even well-corroborated theories are always provisional and subject to future refutation, scientists must remain open to the possibility that any current theory could be wrong. He avers that knowing the truth of our theories is uncertain but there lies certainty in knowing its falsity, especially when our theories clash with observable facts (Popper, 1963 p.36). In this sense, Popper's critical rationalism rejects any notion of absolute certainty in science and insists on the continuous testing and improvement of knowledge. Thus, the underpinning of scientific inquiry lie in its emphasis on self-criticism and its readiness and willingness to challenge its own ideas (Popper 1959, p.17).

However, Popper's rejection of absolute certainty and his emphasis on continuous testing and self-criticism, becomes inconsistent, particularly when juxtaposed with his insistence on objective reality. For instance, the former aligns with a fallibilist view and suggests that all scientific knowledge is provisional, but the latter implies a fixed, observer-independent truth. This creates a methodical tension. If knowledge is perpetually subject to revision, the notion

of approaching an objective reality becomes analytically tenuous and raises the question of whether such a reality is an achievable endpoint or merely an abstract ideal. In some fields like social sciences or climate studies, where variables are complex, and controlled experiments limited, continuous testing is not always feasible. The readiness to challenge ideas is constrained by lived experiences such as incomplete data or ethical considerations that weaken the applicability of Popper's ideals.

It is important to note that Popper's philosophy extends beyond individual scientists to the wider scientific community and even to society at large. He argues that the process of conjecture and refutation is inherently social, one that requires intersubjective open discourse and the free exchange of ideas (Afisi 2017, p. 46). This is linked to his defense of liberal democracy, where institutions and policies are similarly viewed as conjectures that must be subject to constant criticism and revision. In his political philosophy, he advocates for an open society where individuals are free to challenge authority and where decisions are made based on rational discussion rather than dogma. He said that "The growth of knowledge depends entirely upon disagreement. The kind of agreement that is required for intellectual progress is agreement to submit to the basic rules of reason and honesty, the rules of rational and critical discussion (Popper 1945, p. 225)." Just as scientific theories must be open to refutation, so too must political systems and policies. However, his focus on open criticism overlooks the importance of confirmation and positive reinforcement in maintaining stability and trust within political systems. His priority of critique over affirmation risks undermining the collaborative efforts and shared values essential for effective governance and societal cohesion.

Popper's Philosophy of Realism

Popper's philosophy of science is often associated with a form of realism that is both metaphysical and epistemological. Metaphysically, he is considered a realist because he posits that the world exists independently of human perception or knowledge. This view aligns with common-sense realism, which suggests that the existence of the world is not contingent upon human awareness or understanding (Prahani et al., 2020). In this sense, he argues against the explanations provided by proponents of quantum mechanics to explain reality based on the judgements of observers. Epistemologically, his realism is reflected in his belief that scientific theories aim to describe the structure of the universe, even though they are always subject to falsification and revision (Basilis & Shang, 2022).

However, while he advocates for scientific realism, which seeks to develop true theories about the universe, he simultaneously promotes a methodology that focuses on the refutation rather than the justification of theories (Basilis & Shang, 2022). This apparent contradiction has led some scholars to reinterpret Popper's realism as a form of critical realism, which balances the optimistic pursuit of truth with a critical approach to scientific inquiry (Basilis & Shang, 2022).

Although he self-identified as a realist, his reluctance to provide clear definitions of philosophical concepts has led to varied interpretations of his realism. Some scholars argue

that Popper's realism is precarious and even fake, and that he was more of a Kantian realist, who acknowledges the limits of human knowledge in accessing the true nature of reality (Febrer, 2013).

However, Popper maintains that physicists, especially those who champion the course of quantum mechanics, have often explained the world through an instrumentalist approach which he believes are only used as predictive tools rather than a true explanation of objective reality. This critique of physicists who adopt instrumentalist approach to quantum mechanics overlooks the pragmatic role that prediction plays in scientific practice. It underestimates the significance of practical applicability, which, though abstract in nature, has led to technological advancements such as semiconductors and quantum computing that demonstrate its explanatory and utilitarian value in ways that transcend a simple commitment to objective reality.

Critique of instrumentalist interpretations of quantum mechanics

The adoption of instrumentalism in quantum mechanics has been influential, particularly within the Copenhagen interpretation, which emphasises the role of the observer and the probabilistic nature of quantum events (Vervoort, 2012; Balsas & Videira, 2013). This instrumentalist interpretation is closely tied to the concept of probability, as it often relies on probabilistic predictions rather than deterministic ones. The connection is highlighted by the standard frequency interpretation of probability, which inherently involves an observing system (Vervoort, 2012). This is why Popper asserts that this reliance on probability and observation limits the explanatory power of quantum mechanics, reducing it to a mere predictive tool rather than a comprehensive theory of reality (Ronde, 2020). Some scholars argue that instrumentalism is a practical framework for reconstructing quantum theory and suggest that it provides a sensible approach to understanding the theory's mathematical structure and predictions (Dickson, 2015) but the view is contested by Popper, who sees instrumentalism as an inadequate response to the philosophical questions posed by quantum mechanics.

Popper criticises instrumentalist explanations of quantum mechanics because it fails to provide a coherent logical framework for understanding reality. The standard quantum logic, which instrumentalism sometimes adopts, is puzzling due to its departure from classical logic, particularly the failure of the law of distributivity (Hermens, 2011). This has led to the development of alternative logical systems, such as intuitionistic logic, which is argued to be more compatible with the instrumentalist viewpoint (Hermens, 2010). These logical challenges underscore the difficulties in reconciling instrumentalism with a philosophical understanding of quantum mechanics.

The tension between realism and instrumentalism thus persists, as the former, as proposed by Popper, argues for the ontological status of quantum entities, while the latter views that these entities are mere tools for predicting reality (Dzelajei, 2023). For instance, proponents of realism argue that quantum particles, such as qubits, possess intrinsic properties independent of observation, which is essential for understanding the seemingly paradoxical behaviour of

quantum systems, while instrumentalists emphasise the predictive utility of qubits in computing tasks that focus on their ability to yield practical results without committing to their ontological existence. This division becomes especially evident when considering the success of quantum technologies, such as quantum cryptography, which depend on quantum principles to solve real-world problems without requiring a full metaphysical explanation of quantum entities, hence, the distinction between theoretical interpretation and practical application.

Popper's Engagement with Quantum Mechanics

Building on his realist view of phenomena, Popper makes immense critical contribution to the interpretation of quantum mechanics (Del Santo & Freire, 2021), despite lacking formal training in physics. Popper's first major critique of the Copenhagen interpretation is grounded in his philosophical commitment to scientific realism (Shields, 2012; Shields, 2004). He is particularly critical of the Copenhagen interpretation which posits that the behaviour of subatomic particles, like electrons, cannot be fully understood in classical deterministic terms. His critique is founded on his philosophical commitment to falsifiability as the defining criterion of scientific inquiry.

For Popper, scientific theories should aim to describe reality, even if that reality is hidden behind layers of complexity. He opposes the idea that quantum mechanics should abandon determinism and retreat into a purely probabilistic framework. Popper believes that the Copenhagen interpretation went too far in its denial of an underlying, objective reality in the quantum realm. In *Quantum Theory and the Schism in Physics*, Popper views the probabilistic nature of quantum mechanics as an epistemological limitation rather than an ontological feature of reality. In other words, the fact that we cannot predict both the position and momentum of a particle with certainty is a reflection of our incomplete knowledge, not of the fundamental nature of the particle itself (Popper, 1982, p. 96). Popper therefore rejects Bohr and Heisenberg's notion that quantum mechanics signified a breakdown of determinism at the micro level and contends that their interpretation undermines scientific realism by making unfalsifiable claims about the completeness of quantum theory (This aligns his critique with figures such as Albert Einstein, who similarly challenges epistemological assumptions of quantum mechanics) (Shields et al., 2012; Howard, 2012; Santo, 2018a). In contrast to the Copenhagen interpretation, Popper prefers the idea of objective reality (Popper 1972, p.109) and determinism as exemplified by his realist conviction of reality. To this end, he favours Louis de-Broglie's pilot-wave theory (later developed by David Bohm), a theory that postulates the existence of hidden variables that could potentially explain the apparent randomness of quantum events. Popper's critique focused on the epistemological and ontological weaknesses of the Copenhagen interpretation. He avers that its instrumentalist perspective, which treats unobservable phenomena as mere predictive tools, erodes the notion of an objective reality for quantum entities. To correct this, he introduces the propensity interpretation that posits that probabilities reflect the inherent propensities of particles, rather than being mere statistical descriptions (We, 2007; Howard, 2012; Dzelajei, 2013).

Furthering his research on quantum mechanics, Popper's article "Quantum Mechanics without

the Observer" which he published in 1967, became influential among physicists. He maintains that the Copenhagen interpretation is a total drift from scientific realism which leads to an unfalsifiable underscore of the completeness of quantum mechanics (Santo 2018b, p.58). Therefore, rather than the mere addition of explanations to confirmatory experiments, he opts for the continual and relentless effort at falsifying all the underlying assumptions of quantum mechanics. He criticises the Copenhagen interpretation for its acceptance of indeterminacy and the rejection of the principle of causality. He views indeterminacy not as a fundamental property of nature but as a reflection of the limitations of current scientific tools and theories. He is concerned that the Copenhagen interpretation leaned too heavily on instrumentalism as it focuses on what we can observe or measure without adequately considering the underlying reality that might exist independently of our observations (Popper, 1959, p. 173).

He argues that the interpretation's reliance on probability and the idea that the outcome of a quantum event is fundamentally unpredictable conflicts with his philosophy of science, which emphasises the importance of falsifiability and determinism. He contends that the Copenhagen interpretation does not lead to the development of new testable predictions or the growth of scientific knowledge. He opines that a scientific theory should generate new empirical knowledge and that the interpretation's emphasis on probabilities and wavefunctions does not contribute to scientific progress. (Popper 1957b).

His opposition to the Copenhagen interpretation reflects his engagement with foundational problems in the philosophy of science. He opines that scientific theories must be subject to falsification. The Copenhagen interpretation, by contrast, seem to suggest that certain aspects of quantum mechanics were beyond falsification, due to the inherent uncertainty of quantum measurements. However, for Popper, this represents a serious epistemological shortcoming, as it appears to place quantum mechanics outside the reach of traditional scientific critique and reform (Popper, 1982, p. 98). Werner Heisenberg's uncertainty principle, for example, implies fundamental limits to the precision with which certain pairs of physical properties, such as position and momentum, can be simultaneously measured, but this uncertainty complicates the process of falsification, as it introduces inherent limitations on the predictability and repeatability of quantum measurements.

Popper also opposes the Copenhagen interpretation for its emphasis on the role of the observer. In the Copenhagen scheme, measurement plays an active role in collapsing the wave function, thereby determining the state of a quantum system. Popper finds this idea philosophically troubling, as it suggests that reality is not fully independent of human observation. He is of the opinion that scientific theories should aim to describe an objective reality that exists regardless of whether it is being observed or not (Popper, 1982, p. 100). He maintains that science must avoid falling into a kind of subjective idealism, where the act of observation becomes inseparable from the phenomena being studied. Instead, Popper insists that the goal of science should be to uncover truths about the world that exists independently of our perception by series of conjectures and refutations. In the realm of quantum mechanics, where counterintuitive phenomena abound, such as superposition and entanglement, the process of conjecture and refutation will play a vital role in refining our understanding of

quantum phenomena. Rather than seeking to confirm preconceived notions or interpretations, Popper's approach encourages scientists to propose bold conjectures and subject them to rigorous empirical testing. While the Copenhagen interpretation posits an instrumentalist view that treats unobservables as mere tools for prediction, Popper's propensity view is a realist perspective that attributes ontological status to subatomic particles.

However, it is important to note that Popper's critiques often oversimplify the complexities of quantum mechanics and the entirety of reality. The role of the observer and the probabilistic nature of quantum mechanics are unavoidable aspects of the quantum world, not mere artifacts of our measurement tools.

Moreover, the Copenhagen interpretation of quantum mechanics, which asserts that the act of measurement collapses the wavefunction, presents challenges to Popper's falsifiability criterion. The collapse of the wavefunction is not directly observable but rather inferred from experimental outcomes, which makes it difficult to subject the interpretation to direct empirical testing. As a result, interpretations of quantum mechanics often rely on philosophical arguments rather than empirical evidence, although there have been many sophisticated advancements in science through the application of quantum mechanics.

Popper's Critique of Measurement in Quantum Mechanics

In earlier interpretations of quantum mechanics, the outcomes of future measurements cannot be predicted with certainty, even with a complete physical description of the system and the measurement apparatus. This inherent unpredictability is a central feature of quantum theory, as demonstrated by experiments on entangled photons, which refute any alternative theory with more predictive power than quantum mechanics (Stuart, Slater, Colbeck, R., Renner, & Tittel 2011). The measurement problem highlights the challenge of reconciling the deterministic evolution of quantum states with the probabilistic nature of measurement outcomes. One of the approaches involves revising the fundamental hypotheses of statistical mechanics to reconcile the microscopic and macroscopic worlds without altering the core principles of quantum mechanics. This involves concepts such as special states and two-time boundary conditions, which aim to provide a fully quantum model of measurement apparatus (Schulman, 1991). Another perspective is offered by hidden variable theories, which suggest that underlying deterministic processes could account for the apparent randomness of quantum measurements. However, these theories often face challenges, such as those posed by Bell's theorem, which demonstrates the incompatibility of local-realist theories with certain quantum predictions (Bohm & Bub, 1966; Handsteiner, et al. 2016).

In order to escape this measurement problem, Popper rejects subjective observer-dependence in physical theories, a cornerstone of his philosophical stance on the objectivity of scientific knowledge. His approach is rooted in his commitment to an epistemology that excludes the knowing subject and emphasises on the autonomy and objectivity of knowledge once it is created. This perspective is vividly illustrated in his interpretation of quantum mechanics, where he endeavours to eliminate the observer's role and focus instead on the propensity attributes of physical objects which attributes tendencies or propensities to physical systems,

independent of observation. However, this approach has been critiqued for not fully achieving its intended effect, as it neither aligns with a purely subjectivist nor objectivist stance as Popper envisioned. Instead, it incorporates the element of intersubjectivism that shows that complete objectivity may be elusive (Zabierowski, 1995).

In his evolutionary epistemology, Popper insists that knowledge, once created, becomes an autonomous entity, existing independently of human subjective awareness. This concept aligns with his critical rationalism where knowledge is seen as a natural product of human activity that transcends individual consciousness. Popper's notion of 'world three', the realm of objective ideas and theories, illustrates this autonomy, as it exists alongside the physical and psychological worlds and influence human life and technology without being contingent on subjective perception (Currie, 1978).

Popper's rejection of subjectivism is further reinforced by his emphasis on realism and intersubjective consensus in the empirical basis of scientific theories. He advocates for a tentative realist metaphysics, which supports the idea that scientific observations and theories should be grounded in a shared reality, rather than being subjectively constructed. This stance is a direct challenge to sensationalism and supports Popper's commitment to a scientific methodology that seeks objective truth through collective verification and falsification (Shearmur, 2022). However, Popper's dismissal of the observer's role in quantum measurement is challenged by quantum cryptography, where measurement inherently alters the system and makes the observer effect a practical tool for security. For example, in the BB84 protocol developed by Charles Bennett and Gilles Brassard in 1984, eavesdropping is detectable because any measurement of quantum states disturbs them and ensures secure communication. Hence, Popper's radical belief in determinism, which overrules the importance of an active observer of reality, overlooks the probabilistic successes of quantum mechanics.

In order to strengthen his argument against observer-dependence and probabilistic outcomes, he puts forth an experiment involving spatially separated entangled particles to test the Copenhagen interpretation and solve the measurement problem. This experiment, akin to the Einstein-Podolsky-Rosen (EPR) thought experiment, sought to challenge the empirical basis of the uncertainty principle. Popper theorises that if the position of one particle becomes well-defined, its entangled partner would exhibit increased diffractive spreading — a result he believes will challenge the Copenhagen view (Bolduc et al., 2016).

Popper wants to test whether this observer effect is a fundamental part of quantum mechanics or just an artifact of the theory. In his thought experiment, Popper imagines a setup involving a pair of entangled particles. These particles are created together and have opposite momenta (if one moves left, the other moves right). He suggests placing the particles in a scenario where they travel in opposite directions where they pass through two slits with adjustable widths. According to the Copenhagen interpretation, narrowing one slit to measure a particle's momentum would also affect the momentum of the other particle, even though it is far away and not directly measured.

Popper argues that if the second particle's momentum was affected by the narrowing of the first slit, it will confirm the Copenhagen interpretation's claim about the observer's influence, but if no such effect occurs, it will suggest that quantum mechanics can be explained without assuming that measurement fundamentally alters reality. His goal is to demonstrate that the observer effect may not be necessary to understand quantum mechanics.

This thought experiment, which involves particle diffraction through a double-slit setup is contradicted by advancements in weak measurements, which reveal partial information about quantum states without destroying coherence; and his critique of Heisenberg's uncertainty principle, which he deems epistemic rather than ontological, is refuted by its validation in atomic and particle physics, such as the precision limits in the LIGO experiment that detects gravitational waves. However, to further strengthen his thought-experiment, Popper proposes a propensity interpretation of probability which seeks to address the inherent problems of quantum mechanics and measurement altogether.

Popper's Propensity Interpretation of Probability

In response to the foundational issues he identified in the Copenhagen interpretation of quantum mechanics, Popper proposes the propensity interpretation of probability as a solution. This view differs from the frequentist interpretation, which defines probabilities in terms of long-run frequencies of events, and the Bayesian interpretation, which views probabilities as subjective degrees of belief. Unlike the Copenhagen interpretation, which treats probabilities as reflections of our ignorance or as purely subjective, Popper argues that probabilities reflect objective propensities or tendencies in nature itself (Popper, 1959, p. 183). The propensity interpretation therefore suggests that probabilities are not merely subjective or epistemic but have an objective, physical basis. Popper believes that this approach could resolve the measurement problem, specifically the reduction of the wave packet (Bub, 1975; Suppes, 1993). In other words, the propensity interpretation suggests that probability in quantum mechanics is not a measure of ignorance or subjective belief but rather a reflection of the inherent propensity of quantum systems to exhibit certain outcomes (Dzelajei, 2023). According to this interpretation, probabilities in quantum phenomena are objective characteristics of the systems themselves, rather than a representation of our knowledge or lack thereof. This approach aims to provide a more deterministic understanding of quantum mechanics by attributing the probabilistic nature to the underlying properties of the quantum systems. Popper frames probability in this way in order to maintain the falsifiability of quantum mechanics, since the propensities of a system could be tested and revised based on empirical observations. He likens propensities to dispositional properties, such as the tendency of a glass to break when dropped, which exist independently of human observation or intervention.

When applied to physical scenarios, it becomes doubtful whether Popper's assertion that probabilities reflect tendencies inherent in physical systems can be upheld consistently. For example, in clinical trials, the observed effectiveness of a drug often does not align with Popper's notion of inherent propensities, as data reveals that outcomes are influenced by

myriad uncontrolled variables, such as patient behaviour, genetics and environmental factors, which cannot be simply reduced to a probabilistic propensity.

Furthermore, meteorologists rely on probabilistic models to predict weather events, such as the likelihood of rain. Although these models incorporate physical laws and empirical data, the observed outcomes often deviate from predicted probabilities due to complex and unpredictable variables. For example, the 60% chance of precipitation in a region may reflect a statistical pattern based on past conditions, but localised microclimates, sudden shifts in the atmosphere and chaotic influences defy reduction to an inherent propensity for rain. This means that probabilities often emerge from aggregated patterns rather than intrinsic propensities in isolated systems

It is important to note that while Popper's objections to the probabilistic nature of quantum mechanics are influential, they do not lead to a resolution of the longstanding debates about the interpretation of quantum mechanics. Quantum mechanics remains a highly successful and empirically validated theory, despite its probabilistic nature, and alternative interpretations continue to be discussed in the philosophy of physics. It is also important to note that the absence of a subjective interpretation of outcomes may seem unachievable in both microscopic and macroscopic worlds.

Conclusion

In Popper's contributions to the philosophy of science, particularly his engagement with quantum mechanics, it is evident that his critical rationalism provides a timeless paradigm for addressing the most challenging questions of scientific inquiry. Popper's rejection of induction, coupled with his emphasis on falsifiability, compels one to approach science as an iterative and inherently provisional endeavour, one grounded in bold conjectures that are perpetually exposed to rigorous testing and potential refutation through intersubjective analysis. This non-dogmatic approach is the vitality of skepticism and the ongoing quest for deeper truths in science.

As elucidated in one segment of this paper, Popper's defense of an objective physical reality, particularly in the context of quantum mechanics, stands as a counterweight to the interpretative inclinations of the Copenhagen school, which often leans toward epistemological subjectivism. His critique of instrumentalism and his alternative, the propensity interpretation of probability, invite one to reconsider the ontological commitments underpinning modern physics.

As explained earlier, Popper recognises that the mysteries of quantum mechanics, nonlocality, entanglement and the measurement problem, demand more than mathematical formalism or pragmatic expediency. They demand a philosophical engagement with the foundational assumptions of science itself. Thus, Popper's insistence on realism and his bold exploration of hidden variables challenge us to interrogate the limits of current paradigms and resist the complacency of consensus.

In light of the continued debates in quantum mechanics and the advent of experimental technologies, Popper's methodology acquires renewed urgency. His thought experiment on testing quantum predictions exemplifies the creative interplay between philosophy and empirical science and reminds us that theoretical speculation is not an impediment to progress but its precursor. Furthermore, his rejection of observer-dependence in physical theories highlights the tension between subjective experience and objective reality, a tension that lies at the core of not only physics but the entirety of human quest for knowledge.

A reflection on Popper's works will make clear that his philosophical approach is not merely a set of doctrines but an invitation to critical engagement. In a world increasingly dominated by specialised knowledge and fragmented disciplines, there is a pressing need to revisit the foundational assumptions that guide our understanding of nature. As one embraces the spirit of conjecture and refutation, and refusal to settle for pragmatic convenience or epistemological resignation, one honours the true spirit of science that Popper so passionately and persuasively articulated.

However, it should be critically noted, that Popper's critical rationalism, though asserting objectivity, is inherently reliant on intersubjective processes of critique and validation that reveals its fundamentally subjective foundation. The act of falsification, central to his philosophy, depends on the collective judgment and agreement of a scientific community, which is shaped by shared paradigms and sociocultural contexts. Through the provisional nature of scientific theories and their continuous refinement through conjectures and refutations, Popper implicitly acknowledges the subjective interplay of human reasoning in the construction of knowledge. Thus, the objectivism he champions is, paradoxically, an emergent property of subjective discourse rather than an intrinsic feature of the theories themselves.

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