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In 1926, Werner Heisenberg's Uncertainty Principle changed the direction and climate of physics and science as formulated at the time. A world committed to a sense of determinism, to the capability of human beings to penetrate the mysteries of the universe, radically shifted to a quantum notion of probability and spontaneity. Humankind's firm grasp on a knowable reality dwindled as Heisenberg elucidated the limitations of human knowledge in regards to the field of physics. The Principle exists as a defining feature of quantum mechanics, the mechanical model which replaced classical Newtonian mechanics. Whereas the classical worldview asserted a sense of causality and origin, the Uncertainty Principle made this irrelevant. The establishment of this Principle truly set the path of physics on a new course, allowing for new branches of the field to come to the fore and altering the world-view of the scientific community. In this way, the establishment and acceptance of the Uncertainty Principle closely matches many of the criteria of a paradigm shift posited by Thomas Kuhn in *The Structure of Scientific Revolutions*. However the correlation is not complete. Heisenberg's work exhibits some unique facets as well.

Thomas Kuhn's philosophical theory of scientific progress rejects the notion that science accumulates towards a final end. Rather than gradually gaining and increasing the amount of knowledge the scientific community possesses, periods of normal science carry on, elaborating on a given paradigm, until a total revolution sets the path of scientific progress on a new normal science tradition. In order for this revolution to take place, some sort of anomaly in the old tradition must arise. As the scientific community attempts to reconcile the anomaly, or a great number of anomalies, within the presiding paradigm, eventually a new paradigm may be chosen. The eventual choice may arise for a number of reasons, both rational and non-rational. The adoption of Heisenberg's Uncertainty Principle follows this and other criteria of Kuhn.

In first analyzing the means by which the Uncertainty Principle fits the mold of a paradigm shift, it is helpful to first address the main figure in the discovery: Werner Heisenberg. Kuhn's *The Structure of Scientific Revolutions* describes individuals who are "very young or very new to the field" as most likely to "achieve these fundamental inventions of a new paradigm". Not wholly engrained in or committed to the previous paradigmatic tradition, these youthful experimenters and scientists more likely "conceive another set" of rules which can replace "the traditional rules of normal science" (Kuhn 90). Explicating his discovery, Heisenberg certainly attacked the issues of quantum mechanisms "with a young man's purity of vision" truly "unburdened by the past" (Lindley 5, 68). Compared to his contemporaries, Heisenberg actually possessed a less complete education in physics. Again, he was less steeped in the classical traditions to which giants such as Albert Einstein adhered. In this way, rather than instantly assuming certain difficulties nullified his theory, Heisenberg could appreciate "the possibilities of strange but promising suggestions" (Lindley 80). Rather than ensuring his theories neatly fit into a classical sense of causality, Heisenberg "disdained such metaphysical fretting" (Lindley 137). The young physicist was primed to overhaul the prevailing conception of physical reality by being less committed to upholding the determinism of the past. His character embodied the ideal of the revolutionary scientist as described by Kuhn.

Having established Werner Heisenberg, then, as an individual capable and equipped for extraordinary research, anomaly must exist to prompt novel discovery. The origins of the

Uncertainty Principle come from many anomalies which, when seen in conjunction, showed flaws and incongruities in the classical conception of physics. The first such anomaly was Brownian motion. Brownian motion referred to the phenomenon first observed by Robert Brown in 1827. Brown, observing pollen grains under a microscope, observed an erratic motion of the pollen. The grains "jiggled endlessly this way and that" in an unpredictable manner (Lindley 11). This sense of unpredictability gave an insight into a flaw in classical mechanics. In what way could particles which supposedly move according to "orderly Newtonian rules of cause and effect" allow chance to seep into their movement? (Lindley 19).

In 1905, close to eighty years after Robert Brown first observed the sporadic motion of his pollen grains, Albert Einstein presented a "quantitative treatment of its true cause" (Lindley 28). Einstein's analysis, though, appealed to a statistical representation of the motion of a large number of atoms. The behavior of any individual atom remained beyond his grasp. Still, Einstein's quantitative assessment allowed for a sense of determinism to survive, despite that fact that the behavior of a single atom eluded his theory. This inability to know the motion of a single atom opened the door for Heisenberg. The limitations of human knowledge had been revealed; scientists could not penetrate the means by which the "inner design" of the universe was realized (Lindley 30). More anomalous atomic properties prepared a proper climate for Heisenberg's work. Issues of spontaneity and unpredictability arose further in the Borh-Sommerfeld model of an atom and the implications of light quanta. The transitions and jumps between different energy levels, in this model, carried with them "spontaneity [far from] the familiar certainties of old" (Lindley 67). These uncertainties would not simply fade away, though, as many hoped that they would. They would be indoctrinated by the work of Werner Heisenberg.

The revolutionary work done by Heisenberg combatted the more classical-leaning explanations of quantum mechanics attempted by Albert Einstein and Erwin Schrödinger. Schrödinger devised a series of wave equations which worked to explain “the nature of physical reality” in a continuous and predictable way (Kumar 211). This theory perpetuated a sense of determinism with which many physicists were comfortable. Discussing the two competing explanations given by Heisenberg and Schrödinger, Einstein remarked that he “[liked] Schrödinger’s best…I can’t help but admire the Heisenberg-Dirac theories, but to me they don’t have the smell of reality” (Lindley 133). Einstein thoroughly clung to the idea that determinism could survive in these explanations of quantum mechanics. With Schrödinger’s equations allowing for this, he could not help but be supportive. Eventually, a probabilistic explanation was attached to Schrödinger’s wave equations by Max Born, dismissing a causality Einstein and Schrödinger attempted to maintain in their theories. Still, the opposition for Heisenberg and his Copenhagen interpretation had been set.

The story of Heisenberg’s realization of the Uncertainty Principle fits the mold of borderline legend, founded on a “eureka” moment befitting the popular concept of scientific illumination. Working late into the night one evening, Heisenberg took a walk through a park to clear his head, contemplating the notion of whether physicists could precisely measure the path of an electron in a cloud chamber. Heisenberg, recalling the words, “it is the theory that decides what we can observe,” spoken to him by Einstein, suddenly realized how “quantum mechanics…placed restrictions on what could be known and observed” (Kumar 231). As a conclusion to this night of wondering, Heisenberg posited his Uncertainty Principle. The original context of Heisenberg’s principle came in describing the position and momentum of an electron. At any given time, Heisenberg stated, one cannot know both the position and momentum of an electron simultaneously. Quantum mechanics, according to Heisenberg, forbids this knowledge (Kumar 232). Heisenberg explicated his principle by describing the measurement of an electron’s position by a microscope. In taking this measurement, one uses light of a certain wavelength from the microscope. This light, though, interacts with the electron in a collision. This collision alters the momentum of the electron. As such, the more precisely one knows the position of the electron, the more collisions the electron may have from the light in the microscope, and the less accurately one may know its momentum (Hilgevoord). Heisenberg, then, established mathematical representations of this and other Uncertainty relations, expanding them to other “conjugate variables” such as energy and time (Kumar 233).

With the establishment of these two theories, the debate began. This debate between the two theories of Schrödinger and Heisenberg further discloses the way in which this development of physics matches the philosophy of Thomas Kuhn. Quite evidently, the period of normal science which existed prior to these explanations was based on a Newtonian explanation of classical physics. Max Planck’s discovery of quanta of energy in 1900, and subsequent models of the atom which resulted, set physics on a new path into quantum mechanics. As a result, many physicists attempted to establish an explanation of quantum mechanics analogous to Newton’s explanation of classical mechanics. In this way, the debates between Schrödinger and Heisenberg, these attempts at reestablishing truth, fit Kuhn’s model of crisis. Kuhn describes research within a crisis as beginning "with the blurring of a paradigm and the consequent loosening of the rules for normal research" (Kuhn 84). Schrödinger's equations attempted to "blur" the past paradigm with the new paradigm of quantum mechanics by at least retaining a semblance of determinism in the movement of an electron. Heisenberg, conversely, operated under a new set of rules, allowing for spontaneity and uncertainty to meaningfully contribute to his theory. Kuhn actually cites this particular debate in *The Structure of Scientific Revolutions* as an example for the crisis period. He quotes Wolfgang Pauli before Heisenberg's paper on matrix mechanics saying, "At the moment physics is again terribly confused," and again after Heisenberg's paper saying, "Heisenberg's type of mechanics has again given me hope and joy in life" (Kuhn 84). In this way, the debate between the two theories, for Kuhn, seems emblematic of this crisis between paradigms. How, then, was the choice made between to two?

In a chapter entitled, "The Resolution of Revolutions" Kuhn describes the means by which a new paradigm is eventually chosen and agreed upon by the scientific community. His explanation resembles the eventual acceptance of Bohr and Heisenberg's Copenhagen interpretation of quantum mechanics. Kuhn asserts that "the transfer of allegiance from paradigm to paradigm is a conversion experience that cannot be forced" and that the switch does not always occur solely by rational justifications (Kuhn 151). Often, as Kuhn points out, competing paradigms "appeal to the individual's sense of the appropriate or the aesthetic" (Kuhn 155). Rather than choosing on the facts within a given paradigm, the temperament of the scientist tailors his or her receptiveness to a paradigm shift. For Kuhn, though, this is not to completely dismiss the roles that rationality and scientific fact have in choosing a paradigm.

Rather, as a corollary to the facts, non-rational factors also play a part. In the case between Schrödinger and Heisenberg, the role of the non-rational became intensely involved. Interestingly, though, rather than the aesthetic causing scientists to approve of the Uncertainty Principle, non-rational factors made Heisenberg's work particularly detestable.

Heisenberg's greatest detractor, in this regard, was Albert Einstein. As previously stated, Einstein remained devoted to a sense of determinism in his view of reality, one for which quantum mechanics under Heisenberg's Uncertainty relations had no room. One of the main ramifications of Heisenberg's principle was that the individual observer tailored the reality which he or she examined. For example, one must choose whether he or she looks at an electron with the momentum-eye or the position-eye; to do both simultaneously is impossible. As Pauli stated, "if one opens both eyes together, then one goes astray" (Kumar 238). Einstein, however, stressed that nature possessed its own reality wholly independent of the observer. The disdain Einstein felt towards Heisenberg's principle became clear in his famous quote, "The theory yields a lot, but it hardly brings us any closer to the secret of the Old One. In any case I am convinced that *He* does not throw dice" (Cassidy). Quite obviously, Einstein's refusal to accept Heisenberg's theory did not arise from factual flaws. Rather, the older physicist believed that the role of physicists was to uncover the laws which determined reality, presupposing that such laws existed. For Einstein, these laws had to have been put there by some Creator, some "Old One" who created an ordered universe "out there" to be known. To deal with probabilities, spontaneity, and uncertainty would be to abdicate the scientists' roles as illuminators of reality. Erwin Schrödinger expressed a similar sentiment in his Nobel Prize Lecture in 1933. His most crucial goal in establishing his wave equations was "to save 'the *soul* of the old system' of mechanics" (Lindley 126). His fight with the Copenhagen interpretation was one which debated to what extent human beings could actually penetrate and explicate reality.

Further complications arose in choosing between the two theories as it became apparent that the two were mathematically identical. They could agree in their calculations despite their contradictions. Could one simply resign to say that the choice between the two "came down to questions of taste and convenience?" (Lindley 130). Perhaps this conclusion would have correlated with the importance Kuhn gives non-rational factors in theory choice. However, if this was the case, Heisenberg's principle would not have emerged victorious. It did not fit the comfortable conceptions of reality which had existed for decades prior: it rejected a classical sense of determinism. As such, continuous attempts were made to experimentally defend the validity of the Uncertainty Principle, even as late as 2006 (Kumar 354). By this time, though, Einstein's influence on the subject of quantum mechanics had been dwarfed by that of Neils Bohr. As Kuhn writes in *The Structure of Scientific Revolutions*, only with the passing of a generation engrained deeply with the paradigm of the past will "the whole profession…again [practice] under a single, but now a different, paradigm" (Kuhn 152). In accordance with this criterion, Bohr successfully convinced a generation of physicists that "the problem had been solved" and many researchers rode the scope of physics in this new direction (Kumar 358-359). The Copenhagen interpretation was widely accepted as the governing explanation for quantum mechanics.

According to Thomas Kuhn, what follows this acceptance of a new paradigm is a process by which "more scientists will then be converted, and the exploration of the new paradigm will go on" (Kuhn 159). Essentially, a new period of normal science will continue to delve into the depths of a particular paradigm until it too exposes its own downfall. In many ways, this did take place with the very gradual acceptance of the Uncertainty Principle as it currently acts as a pillar of the quantum mechanical understanding of the physical world (Hilgevoord). Heisenberg's work gave quantum mechanics that which separated it the most from classical mechanics: a sense of limitation that is simply unavoidable. In this sense, the uncertainty principle gave quantum mechanics the explanation which allowed for its elucidation.

However, the Uncertainty Principle does not carry with it the same irrefutable weight as does something like the Copernican Revolution. The existence of a heliocentric universe is accepted in both the scientific community of astronomers and the general public alike. In fact, someone who may advocate for a geocentric universe may be seen as ignorant. This is not the case for those who still take issue with the Copenhagen interpretation of quantum mechanics. One may see more merit in questioning whether human beings truly cannot know everything about reality than in asserting that we live in a geocentric universe. In this way, continual dispute still surrounding the Uncertainty Principle suggests a departure from Kuhn's philosophy.

One such detraction from the Copenhagen interpretation of quantum mechanics is the Many-Worlds Interpretation, first suggested by Hugh Everett in 1957. Rather than dealing with the probabilities and indeterminacies inherent in Heisenberg's Uncertainty Principle, the Many-Worlds Interpretation essentially suggests that any time a quantum event with some probability occurs, rather than one outcome prevailing over another, all outcomes occur. Each unique outcome is “obtained…in a different world” (Vaidman). Rather than confining oneself to probabilities or abandoning a deterministic universe, the Many-Worlds Interpretation allows scientists to “view quantum mechanics as a complete and consistent physical theory” (Vaidman). The fact that such an interpretation exists suggests that the adoption of the Copenhagen interpretation does not fit the mold of a paradigm shift in the strictest Kuhnian sense imaginable. Yes, as the dominant explanation of quantum mechanics Heisenberg’s principle expanded the problems available for analysis. However, it did so in a unique way. While it gave parameters to the measurements employed by scientists observing quantum events, it also provided the problem of disproving its own existence! With a great number of scientists still unsatisfied with resigning to the fact that science cannot penetrate all of human ignorance, individuals sought and still seek a unified principle to do away with Heisenberg’s Uncertainty.

According to Kuhn, the shift from one paradigm to another is complete; little to no connection between old and new survives. In this way, perhaps the Uncertainty Principle stands apart from other scientific revolutions. Perhaps the paradigm shift from classical mechanics to quantum mechanics still haunts the scientific community in the field of physics today. Perhaps that all-encompassing principle for which Einstein searched remains hidden from the scientific community and one day it will return physics back to a more “realistic” and less probabilistic arena. Whether this occurs or not, the Uncertainty Principle uniquely provided functional problem solving capabilities in the realm of quantum mechanics, was generally accepted by physicists, while still garnering negative criticism on philosophical grounds.

Despite these incongruities with Kuhn's philosophy, there still existed other aspects in which the Uncertainty Principle modeled a paradigm shift. First, it provided a reappraisal of suitable conclusions one could make when measuring objects on the quantum level. Specifically, it did so through uncertainty relations. As previously stated, in classical mechanics the idea that something about a physical system could be entirely impenetrable was absurd. The Copenhagen interpretation of quantum mechanics, though, placed limitations on the way in which scientists could simultaneously measure two properties of a quantum object. Never before had this been acceptable for the community of physicists. With Heisenberg, though, it was a reality "forced" upon scientists. Heisenberg also rejected the notion that certain valid conceptual systems were necessarily "suitable for the representation of new realms of experience" (Heisenberg, *Daedalus*, 106). In this way, his theory disallowed universal applicability to be attributed to a given mathematical representation.

Perhaps the most striking resemblance Heisenberg's Uncertainty Principle has with Kuhn's description of a scientific revolution or paradigm shift, though, is in the changed worldview which accompanied this new theory. The quantum world which emerged, equipped with the Copenhagen interpretation as its explanation, displayed something very different from the classical worldview. Kuhn describes this change in worldview in his tenth section of *The Structure of Scientific Revolutions*. The section lists a number of examples in which scientists operating under one paradigm view a particular circumstance or experiment in a manner dependent on the constrictions of their paradigm. For example, Aristotelians viewed an object swinging back and forth on a chain or string as an object attempting to find its natural state. For Galileo, that same object was a pendulum. From this new view, Galileo derived relationships for things such as the height at which the pendulum was released and its resulting velocity (Kuhn 119). From the perspective of classical mechanics, an electron was an objective particle whose nature was there to be known by scientists. For quantum mechanics under the Copenhagen interpretation, though, this view changed.

One aspect of this changing worldview was a movement away from dogmatic realism as paramount in the development of science. In light of quantum theory, Heisenberg and other scientists "learned that exact science is possible without the basis of dogmatic realism (Heisenberg, *Physics and Philosophy*, 44). Those who dissented from the Copenhagen interpretation (Einstein, most notably) did so because it neglected dogmatic realism. For Heisenberg, this sort of disagreement with the implications of his principle was "a very natural attitude" (Heisenberg, *Physics and Philosophy*, 45). According to Heisenberg, scientists who engage in research seek "something that is objectively true" (Heisenberg, *Physics and Philosophy*, 45). This is especially true for a field such as physics which seeks to elucidate the basis of physical reality. However, in the wake of quantum theory and its Copenhagen interpretation, Heisenberg altered this perspective on science.

The worldview to which many scientists subscribed prior to Heisenberg's work also included a "reality concept of classical atomism" (Heisenberg, *Daedalus*, 99). This tradition extended all the way back to Democritus. First, atoms were imagined to be "the final indivisible building blocks of matter" (Heisenberg, *Daedalus*, 99). Then, with the discovery of radioactivity calling into question the indivisible nature of atoms, the new particles (electrons, protons, and neutrons) were simply labeled as the smallest building blocks. The underlying foundation of objectivity remained the same either way: everything could be broken down into these small particles. However, Heisenberg noted that soon after this discovery of radioactivity, the scientific community realized “that the hoped-for objective reality of the elementary particles represents too rough a simplification” of what actually takes place (Heisenberg, *Daedalus*, 99). The physical process of observing these particles altered that which was measured. In this way, the Uncertainty Principle hindered the worldview of classical atomism, disallowed the completely “objective reality of the elementary particles” (Heisenberg, *Daedalus*, 100). The Copenhagen interpretation rejected a deterministic and realistic classical world in which the building blocks of matter could be seen “in themselves” (Heisenberg, *Daedalus*, 104).

Another shift in the worldview of physicists came in their outlook on explicating nature. Physicists, prior to the acceptance of a quantum world under the Copenhagen interpretation, sought to explain an objective nature that is “there” to be known. In modern physics, though, the emphasis has changed to providing “a picture of our relation to nature” (Heisenberg, *Daedalus*, 107). The Uncertainty relations implied that the individual observer somehow tailored that which he or she observed. The more one looked into a particle’s position, the less its momentum could be deduced. Science can no longer ignore the “interplay between man and nature” the worldview of the scientist must account for its reality as the “procedure” of observation necessarily effects the outcome in the realm of quantum mechanics (Heisenberg, *Daedalus*, 107). The new scientific eye of the physicist had to account for the scientist itself following the acceptance of Heisenberg’s relations; the change required a self-appraisal of one’s own influence on his or her research.

One may be inclined to believe that the worldview which results from a paradigm shift would be a wholly new one. A scientific revolution would usher in a new view of existence, one tailored around the implications of that new paradigm. However, many Eastern philosophies possess a worldview similar to that most often associated with the Copenhagen interpretation of quantum mechanics. The philosophy of Tagore actually influenced Heisenberg on a trip to India (Capra 529). During a time where Heisenberg grappled with the seemingly absurd reality his theories illustrated, becoming familiar with a philosophy which subscribed to similar notions proved cathartic for him. In this way, quantum mechanics and Heisenberg's principle inspired a change in worldview specifically for the western world. In some pockets of an Eastern tradition, such experiences with reality already existed. Perhaps this aspect of Heisenberg's revolutionary discovery reflects the fact that Kuhn posited the altered worldview mostly in the hands of the scientific community. For scientific revolutions such as the Copernican revolution, the change in worldview may be more global in scale. In this case, though, the shift is partly isolated in the West.

Kuhn also suggests that the change in worldview which accompanies a paradigm shift involves a linguistic transformation. An issue of incommensurability inherently arises between the old and new paradigms: to what extent, if any, can meaningful dialogue exist between members of a scientific community engrained in one tradition or the other? As Kuhn states, "within the new relationships, old terms, concepts, and experiments fall into new relationships one with the other" (Kuhn 149). The only difficulty in language for Heisenberg, though, was the word which he would eventually attribute to his Principle. Heisenberg wrestled with calling it "indeterminacy," "inexactness," or (what stuck in the English language) "uncertainty"

(Lindley149-150). In this way, rather changing the lexicon surrounding a definition of quantum mechanics, the linguistic difficulty with which Heisenberg struggled emerged with no word to accurately describe his observation. In fact, a true sense of incommensurability did not and has not occurred. In college physics classes or in describing every-day, non-atomic processes, Newtonian language of forces still fits and functions quite well. Again, in this instance Heisenberg's revolutionary principle is unique.

Werner Heisenberg's Uncertainty Principle provided the explanation for quantum mechanics for which scientists searched since Max Planck first described light quanta in 1900. As Newton explained classical mechanics, Heisenberg explained quantum mechanics. In this way, his discovery was truly revolutionary, truly offered a paradigm shift. A Western scientific tradition of penetrating the unknown and explicating all that nature had to offer no longer truly held in light of this theory that stated some factors and variables simply eluded human capabilities. By these criteria, Thomas Kuhn's philosophy of scientific progression fits this profound turning point in physics. However, the particularly divisive metaphysical implications of Heisenberg's work resulted in decades of dissension, with experiments conducted to try and prove the Uncertainty relations (again) even within the past ten years. Physicists today still seek a single, unifying "Theory of Everything" which can reclaim a deterministic and objective understanding of reality. Perhaps these scientists will fail and Heisenberg's work will more firmly embody Kuhn's vision of a paradigm shift. More ontologically satisfying, though, would be if these scientists succeed and once again show a way in which human beings can penetrate an existence "out there." Either way, it seems as though Kuhn's crisis, in many ways, still rages today in this realm of physics. One can only hope that the current trajectory of physics, one day, definitively reveals if “the Old One” truly does “throw dice” or not.

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