Quantum Weirdness and the Birth of Man

On Foucault and the Copenhagen Interpretation of Quantum Physics

Nick Werle – Brown University ‘10
www.runningthezoo.com
nickwerle@gmail.com

> BOHR: It works, yes. But it's more important than that. Because you see what we did in those three years, Heisenberg? Not to exaggerate, but we turned the world inside out! Yes, listen, now it comes, now it comes… We put man back at the center of the universe. Throughout history we keep finding ourselves displaced. We keep exiling ourselves to the periphery of things. First we turn ourselves into a mere adjunct of God's unknowable purposes, tiny figures kneeling in the great cathedral of creation. And no sooner have we recovered ourselves in the Renaissance, no sooner has man become, as Protagoras proclaimed him, the measure of all things, than we're pushed aside again by the products of our own reasoning! We're dwarfed again as physicists build the great new cathedrals for us to wonder at – the laws of classical mechanics that predate us from the beginning of eternity, that will survive us to eternity's end, that exist whether we exist or not. Until we come to the beginning of the twentieth century, and we're suddenly forced to rise from our knees again.
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> HEISENBERG: It starts with Einstein.
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> BOHR: It starts with Einstein. He shows us that measurement – measurement, on which the whole possibility of science depends – measurement is not an impersonal event that occurs with impartial universality. It's a human act, carried out from a specific point of view in time and space, from the one particular viewpoint of a possible observer. Then, here in Copenhagen in those three years in the mid-twenties we discover that there is no precisely determinable objective universe. That the universe exists only as a series of approximations. Only within the limits determined by our relationship with it. Only through the understanding lodged inside the human head.
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> *Michael Frayn,* Copenhagen*, (59-60)*

> For [man's limits] would not be there, in the light that partly illuminates them, if man, who discovers himself through them, were trapped in the mute, nocturnal, immediate, and happy opening of animal life; but nor would they posit themselves in the acute angle that hides them from their own direction if man could traverse them without residuum in the lightning flash of an infinite understanding.
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> *Michel Foucault,* The Order of Things, *(314)*

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Nineteenth century physics was a proud discipline. The world's leading experts were confident that they were nearing completion of the greatest intellectual edifice the world had ever known. Classical mechanics, a nearly continuous line of thought stretching from Newton's *Principia* to Maxwell's equations, provided physicists with a model of the universe that satisfied the science's ultimate goals: explaining the past and predicting the future. From planetary motion and fluid dynamics to electromagnetism and optics, classical physicists possessed theories that they claimed were capable of mathematically parsing the universe and articulating matter's past and future. This fully determined model of physics perfectly matched the deistic view of God as a clockmaker who set initial conditions for his universe and then allowed it to run according the laws of science. The prevailing view was that future physicists would be charged merely with refining and expanding the existing knowledge about the world; Maxwell's wave equations, which had unified the theories of electricity and magnetism into a coherent set of formulae, were held to be the capstone of this great project.

Obviously, classical physics' unproven loose ends and unexamined contradictions loom large in retrospect. The worldwide effort to detect and examine the luminiferous ether, which evaded experimenters precisely because it never existed, and the "ultraviolet catastrophe," a divergent theoretical artifact predicting that an ideal black body would emit radiation with infinite power, seem so glaring today because they were the strongest experimental hints of fundamental problems with the classical view of the universe. At the dawn of the twentieth century, these problems were neither unique nor frightening; they were merely stubborn.

Looking back, there were discoveries that foreshadowed the radical change to come, but their significance could not be – and certainly was not – recognized at the time. While Faraday, Lorentz, Planck, Poincaré, and Riemann each produced an important element of what would later be a new physics, none realized the power of his own discovery. It took the emergence of an unknown German Jew from Bern – whose time for pondering physical problems was restricted by his full time job as a patent clerk, his thus-far fruitless search for a proper academic position, and his practical obligations as a young member of the Swiss bourgeoisie – for someone to recognize the fundamental problems in the Newtonian problematic. In 1905, Albert Einstein, working alone, published three papers that would, in time, revolutionize physics. Initially, however, he had trouble getting anyone to read them.

Einstein's *annus mirabilis* was one of the greatest bursts of creative thought in human history. Though his three papers were short, they staked out radical new positions on Brownian motion, the quantum nature of light, and the electrodynamics of moving bodies that would force scientists to reformulate the existing conceptions of energy, space, and time. His new discoveries, which would mature into modern physics' two great theories of quantum mechanics and relativity, did not merely provide new explanations for phenomena that were already known; they showed how the Newtonian framework undergirding all scientific knowledge was just an approximation, an estimate of the universe as seen on the human scale. But Newtonian mechanics was ignorant of its limits, unaware of its perspective. Insofar as it aimed to describe the universe as an objective reality indifferent to the presence of its investigators, this obliviousness was necessary. But as a story told solely and unselfconsciously from the perspective of the human being, classical physics would never be able to see man or feel his wake.

As Europe's great scientific minds began to read the 1905 papers and attention turned to the young patent examiner, the problems with classical physics became impossible to ignore. But as the years wore on and others began to take up this new challenge to classical knowledge, Einstein lost control of his creation. Indeed, his transition from iconoclast to nostalgic conservative is one of the most fascinating aspects of the birth of modern physics. Once it became clear that of all his innovations, quantum mechanics was the most revolutionary, the intellectual center of mass shifted out of Einstein's skull and into the scientific world at large. While rival teams in Berlin and Copenhagen raced to understand the full implications of quantum mechanics, Einstein embarked on a strenuous, solitary, and ultimately fruitless quest to disprove the most radical implication of his theory: that the universe's fundamental randomness negates the strictly objective and deterministic reality of Newtonian mechanics.

By the late 1920s, the center of the physics world had shifted to Copenhagen, where Niels Bohr and Werner Heisenberg were formulating a set of quantum-mechanical concepts that describe a universe starkly different from the one understood by nineteenth century physicists. The Copenhagen Interpretation, which is still the most widely accepted explanation of quantum mechanics, rests on two foundational principles: Heisenberg's uncertainty (it is fundamentally impossible to simultaneously know all the dynamic information about any particular particle) and Bohr's complementarity (though all matter exhibits a wave-particle duality, a particular experiment can only show one or the other, not both). Together, these two principles produce a picture of the universe that is fundamentally random and can only be understood probabilistically.

In this new theoretical framework, irreducible chance replaces the usual deterministic certainty of Newtonian physics; this change has profound philosophical implications. As soon as fundamental randomness replaced simple determinism, it became impossible to maintain the narrative of a clockmaker God setting up the universe with a set of particular and decisive set of initial conditions. This instigated a crisis for physics as a science, which took the ability to predict the future and explain the past as its *raison d'être*. Bohr summed up the change: "It is wrong to think that the task of physics is to find out how nature *is*. Physics concerns what we can *say* about nature" (Isaacson 333).

Indeed, the Copenhagen Interpretation forced physicists to study the distinction between what "happens" "objectively" and what we can say that we know. By explicitly reducing the domain of physics to knowable, the act of measurement and the (physical and philosophical) position of a particular observer gain primary importance. Instead of yielding the familiar classical data (the position and momentum of a particle), a quantum mechanical measurement produces a probability function ($|\Psi(\vec{r},t)|^2$), "which represents the experimental situation at the time of the measurement, including even the possible errors of the measurement. This probability function represents a mixture of two things, partly a fact and partly our knowledge of a fact" Heisenberg 87). Whereas Newtonian physics imagined itself to be transparently reporting on the state of a fully independent and objective external reality, the Copenhagen Interpretation treats measurement as a real action that cannot extract information about a system without irreversibly effecting it (without causing the collapse of the wave function, to use the technical parlance).

As the imagined Bohr of Michael Frayn's *Copenhagen* insists, quantum mechanics requires the existence of man to formulate its version of the universe. This man, who takes the position of the "observer" in technical literature, must not aspire to have the infinite knowledge that captivated the classical physicist. He must not because he cannot; the man of the Copenhagen Interpretation is a modern man, in the rigorous Foucauldian sense. He is acutely aware of his finitude, his fundamental inability to construct a full representation of the world. This finitude is not a problem of precision in experimentation that might be solved with more finely tuned optics or more securely insulated laboratories. Heisenberg's Uncertainty Principle formulates an absolute and fundamental lower bound for man's relation to the universe that no amount of technical refinement can ever solve. Because this error is intrinsic to the relation of knowledge the scientist seeks to establish with his object of study, the question of whether quantum physics is objective must be reformulated.

Whereas classical physics intended to parse the objective world so that its data might represent the system's reality between a scientist's peeks, Heisenberg insists that "the transition from the 'possible' to the 'actual' takes place during the act of observation. If we want to describe what happens in an atomic event, we have to realize that the word 'happens' can apply only to the observation, not to the state of affairs between two observations" (93). With this gesture, he exploded classical physicists' endless tables containing bits of knowledge about a fully independent universe that continued to move identically whether or not anyone was watching. These tables are relics of classical physics' origins in the observatories of Nicolaus Copernicus, Galileo Galilei, and Tycho Brahe, astronomers who deduced the geometric laws that replaced the harmony of Ptolemy's geocentric spheres as the dominant explanation of natural laws. After the Copenhagen Interpretation forced physicists to consider the exact nature of their empirical relationship to the universe, these tables – which never abandoned their astronomical provenance even as physicists started to probe the inner workings of the atom – had to be abandoned as artifacts of a previous age.

In *The Order of Things*, Foucault argues that man's epistemological appearance marked a "profound upheaval" that was the transition from the classical to the modern episteme. In this "archaeological mutation, man appears in his ambiguous position as an object of knowledge and as a subject that knows: enslaved sovereign, observed spectator, he appears in the place… from which his real presence has for so long been excluded" (Foucault 312). This epistemic shift – which he tracks through the parallel transitions of natural history to biology, the analysis of wealth to economics, and the analysis of discourse to the science of philology – is a threshold between two fundamentally different ways of ordering thought about the world. It is largely an issue of language, or rather the evolving manner in which language attaches itself to its objects: "The threshold between Classicism and modernity… had been definitively crossed when words ceased to intersect with representations and to provide a spontaneous grid for the knowledge of things" (Foucault 304). Man, as a figure of knowledge, appears in the wake of this fracture.

Though Foucault concentrates his archaeological energies on the emergence of life, labor, and language in the sciences of biology, economics, and philology, I argue that emergence of measurement as a primary concern in the birth of modern physics is the same kind of revolutionary moment in epistemological history. Indeed, the transition from Newtonian mechanics to the Copenhagen Interpretation of quantum theory can be placed alongside Foucault's other three as an important, if somewhat late, trajectory along which we can track the birth of man at the threshold of modern thought.

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> The profound vocation of Classical language has always been to create a table – 'a picture': whether it be in the form of natural discourse, the accumulation of truth, descriptions of things, a body of exact knowledge, or an encyclopedic dictionary. It exists, therefore, only in order to be transparent… it has not yet acquired the multiple existence about which we question ourselves today; in the classical age, discourse is that translucent necessity through which representations and beings must pass – as beings are represented to the mind's eye, and as representations render beings visible in their truth. The possibility of knowing things and their order passes, in the classical experience, through the sovereignty of words: words are, in fact, neither marks to be deciphered (as in the Renaissance period) nor more or less faithful and masterable instruments (as in the Positivist period); they form rather a colorless network on the basis of which beings manifest themselves and representations are ordered.
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> *Michel Foucault,* The Order of Things*, (311)*

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It might be best to judge Newtonian physics by its aspirations. Spurred on by their success with astronomical predictions, classical physicists endeavored to deploy their discipline over the entire universe. According to theory, one *merely* needed to know the simultaneous positions and momenta of all matter in the universe (which was falsely assumed to be a static, closed system) and everything past and future would be determinable. Obviously this dream could never be realized, but it remained a theoretical possibility, if only at the limit of the science. In a quantum mechanical framework, however, achieving this knowledge is not only practically but *theoretically* impossible; the uncertainty relations between momentum and position and between energy and time prevent any physical state from being fully specified, i.e. measured. Because classical physicists predominantly worked at a macroscopic scale, these uncertainties were never manifested, but in the atomic realm uncertainty is a continual barrier to fully knowing a system. Physicists' aspirations to infinite knowledge died just as a cohort of European Jews gave birth to quantum mechanics.

Using this contrast as a point of entry, we can retroactively label Newtonian physics a thoroughly classical regime of knowledge. While Foucault worked out his epistemic divisions by tracking the developments of biology, economics, and philology, he was able to set out a number of characteristics of the classical episteme. Indeed, he opens his epic chapter "Man and His Doubles" with a glancing reference to physics: classical knowledge, he writes, "is rationalistic, since Galileo and Descartes… it has accorded an absolute privilege to Mechanism, it presupposes a general ordering of nature, it accepts the possibility of an analysis sufficiently radical to discover elements or origins" (Foucault 303). Though he continues by explaining the ways in which this definition captures the changes in his signal disciplines, the description seems tailor-made for describing the salient features of the Newtonian problematic. The resemblance grows more convincing as Foucault goes on to discuss the "fundamental arrangement" of classical thought, the conditions of possibility for such a determined, rationalistic form of knowledge. This rigidity is possible due to "the entire system of grids which analyzed the sequence of representations, arresting its movement, fragmenting it, spreading it out and redistributing it in a permanent table" (Foucault 303-4). For physicists, this table was not a metaphorical arrangement of data; the tables of constants and trajectories awaiting completion at the end of the nineteenth century were not designed to represent any play. The only uncertainty in this arrangement was the number of years until every answer would be available in the stacks of Berlin's great science libraries.

Though Foucault works equally hard to demonstrate the epistemological breaks in all three of his representative disciplines, it is clear that he accords the greatest weight to the birth of philology. This is not only because his own work tends toward the linguistic; as a philosopher working in the midst of the (post-)structuralist revolution (he repeatedly disputes this label, but I refuse to take him at his word), he ascribes a primary importance to language. It does not transmit preformed thoughts. For Foucault, thinking is inseparable from language. Thus, *The Order of Things'* linguistic analysis overflows the banks of his study of philology and comes to occupy a central position in his broader archaeological investigation.

In classical thought, discourse operates according to the rule of representation, which views "natural discourse" as a transparent tool for "the accumulation of truth" (Foucault 311). Make no mistake: this tool *was* potent. "The power of discourse" was its ability to filter the vastness of the phenomenal world "in so far as it represents – language… names, patterns combines, and connects and disconnects things as it makes them visible in the transparency of words" (Foucault 311). For all of this forcefulness, classical language was able to examine its object without performing any action; it was epistemologically intransitive.

In this representational scheme, language did not accrue meaning or power through the continuing action of signification. Instead, words worked by finding a site within an infinite circulation of meaning. Thus, "the profound vocation of classical language has always been to create a table – a picture: it exists, therefore, only in order to be transparent" (Foucault 311). Determining the precise substance of "language" is one of the most important tracks along which physics developed as into a true theoretical science, but it is safe to say that Newtonian physics treated both written language and mathematics as ways to directly represent reality.

This function was crucial to its overarching but unseen epistemological approach, which took its scientific researches to be unobtrusive, neutral studies of the universe *as it was*. Knowing full well that planets' motions remain unchanged wherever astronomers trained their telescopes, classical physicists treated observation as the weightless intermediary between the really existing universe and the more or less accurate data composing their accumulated knowledge. In this program, observation need not be repeated every moment, since the reality of demonstratively accurate data was just as robust as that of the really existing planets: One only needed to interpolate in order to determine where an object has been between two observations. Classical language was the "*common* discourse of representation and things" (Foucault 311). The classical physicist's concern for his measurements was on the same register as that of a realist painter: he would slave for slight improvements in precision, for nearly imperceptible refinements of detectors and insulation. He was concerned more with methods of data analysis than with teasing out the epistemological implications of his measurements. Always, the goal was a more accurate correspondence between the rhythms of the universe and their mathematical representations.

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> It has been stated in the beginning that the Copenhagen Interpretation of quantum theory starts with a paradox. It starts from the fact that we describe our experiments in the terms of classical physics and at the same time from the knowledge that these concepts do not fit nature accurately. The tension between these two starting points is the root of the statistical character of quantum theory. Therefore, it has sometimes been suggested that one should depart from the classical concepts altogether and that a radical change in the concepts used for describing the experiments might possibly lead back to a nonstatistical, completely objective description of nature.
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> This suggestion, however, rests upon a misunderstanding. The concepts of classical physics are just a refinement of the concepts of daily life and are an essential part of the language which forms the basis of all natural science. Our actual situation in science is such that we *do* use the classical concepts for the description of the experiments, and it was the problem of quantum theory to find theoretical interpretations of the experiments on this basis. There is no use in discussing what

> could be done if we were other beings that we are. At this point we have to realize, as von Weisäcker has put it, that "Nature is earlier than man, but man is earlier than natural science." The first part of the sentence justifies classical physics, with its ideal of complete objectivity. The second part tells us why we cannot escape the paradox of quantum theory, namely, the necessity of using the classical concepts.
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> *Werner Heisenberg,* The Copenhagen Interpretation of Quantum Theory*, (94-5)*

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For anyone doing intellectual work in the classical episteme, the challenge was how he could best represent the world's infinite richness: Whereas bare perception might be able to apprehend the world in its full depth, thought required one to confine oneself to words. This was certainly true of Newtonian physics, which sought to parse complex physical systems with relatively simple analytical tools. As discussed above, this requires that language "transform the sequence of perceptions into a table," but it also assumes that it "cuts up the continuum of beings into a pattern of characters" (Foucault 311). Though Foucault argues that language no longer functions as a tabular sorting device in the modern episteme, it is this second assumption that is most directly and unequivocally rejected by the Copenhagen Interpretation. According to the quantum theory of Heisenberg and Bohr, there is no longer a direct correspondence between mathematical formulae and "real" atomic events. One's formalism does not represent the other's physicality. Indeed, this distinction between reality and representation is no longer tenable.

Recall Heisenberg's claim that "the transition from the 'possible' to the 'actual' takes place during the act of observation" (93). Measurement is necessary for the physicist to say anything definitive about a particle. While a classical physicist would aim to calculate its determined trajectory from a set of dynamical data, quantum theory allows a modern scientist to formulate only a probability distribution, which "does not in itself represent a course of events in the course of time. It represents a tendency for events and our knowledge of events" (Heisenberg 93-4). Classical mechanics' kinematics equations are able to determine the trajectory of a baseball and predict its precise landing spot; were the identical experiment carried out a thousand times, the prediction would never change and the baseball would always land on the same patch of turf. This is not true in quantum theory. The probability distribution for a stream of electrons shot towards a target would suggest a range of possible outcomes. If the experiment were repeated many times (i.e. if one left the stream of electrons on) there would be many different "landing points," each occurring with the frequency suggested by the probability distribution. This is the result of uncertainty; on the atomic scale identical actions do not produce identical results.

But this example does not yet illustrate the full scale of what physicists affectionately call "quantum weirdness." Were one to reduce the stream's intensity until it was ejecting single electrons, one would not be able to say, before measurement, where exactly it was going. One would have to say that it was simultaneously following all of the possible paths and landing at all of the possible locations on the target with probabilities given by the aforementioned distribution function. One can only assign the electron to a particular path, one can connect the probability function "with reality only if one essential condition is fulfilled: if a new measurement is made to determine a certain property of the system"

(Heisenberg 94). At this moment of measurement, all the possibilities contained in the distribution function collapse: "The observation itself changes the probability function discontinuously; it selects of all possible events the actual one that has taken place" (Heisenberg 93). In this quantum realm, physicists are not innocently recording data from independently occurring events in the world. Atomic events cannot be rigorously said to have "happened" until they have been observed, and at that point something has changed.[1]

As physicists began to understand the implications of Einstein's 1905 paper, which established that the quantization of energy was an intrinsic feature of matter and not an artifact of measurement (as Planck had argued), it became clear that they could no longer treat the microscopic realm as a microcosm. The atom was no longer just a tiny solar system with a nucleus for a sun and electrons for planets. Breaking this similitude was both physically required and philosophically important. The "ancient notion" of the microcosm was an epistemological holdover from the sixteenth century that treated Nature as "closed in upon itself in conformity with the duplicated form of the cosmos" (Foucault 31). The crumbling of this "duplicated resemblance" corresponded to the fragmentation of scientific language as physics leaped across the threshold separating the classical and modern epistemes. Without a verifiable, concrete reality on the atomic scale, physicists were compelled to abandon both their tables of absolute data and their hopes of one day possessing infinite knowledge of a determined universe. Modern language, detached from classical representation, exists "only in a dispersed way" (Foucault, 304). The solidity of its meaning decayed along with the Newton's determinism.

After crossing this threshold, everything was difficult and confusing; attention to language was mandatory. Without the "unity of general grammar… language appeared in a multiplicity of modes of being, whose unity was probably irrecoverable." Whereas "philosophical reflection for so long held itself aloof from language," it now had to grapple with tools it thought were understood. This was difficult: "words had to be freed from the silent content that rendered them alien, or language had to be made more flexible and more fluid, as it were, from within, so that once emancipated from the spatializations of the understanding it would be able to express the [required] movement and temporality" (Foucault 304). Heisenberg clearly felt that uncertainty was not restricted to the motions of electrons. "We have to be very cautious about the wording of any statement concerning the behavior of atomic particles," he wrote (Heisenberg 89).

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[1] The precise physical reason for this discontinuity is, unsurprisingly, complicated. I will attempt to explain what exactly constitutes a measurement later in this essay. For now, consider how one might observe an electron orbiting an atomic nucleus. One might use a high-power microscope to pinpoint the particle's location. In order to resolve such small features, this microscope would have to use high-energy, low-wavelength gamma (γ) rays instead of ordinary visible light. In order to detect the electron, a γ photon (the fundamental particle responsible for the transmission of electromagnetic energy) would have to collide with the electron; the microscope would then be able to calculate its position from the photon's deflection. But like any collision, this interaction would have transferred some momentum to the electron, changing its motion. Most likely, the γ photon would have been strong enough to knock the electron completely out of its atomic orbit. Any subsequent measurements would not detect the electron in its original orbit but would instead find it speeding away from the atom. Because all detection requires some such interaction between the object of study and an external "measuring device," it is impossible for a physicist to gather any information without having an effect on the system and generating some uncertainty above the lower limit identified by Heisenberg. Of course, this is true for classical systems as well: one only knows the position of a baseball thanks to the photons that bounce off its surface and reach a retina. However, the difference in momenta between a baseball and a photon is so enormous that the baseball's path remains unchanged.

That flexibility and fluidity are not characteristics of the mathematical formulations of Newtonian mechanics should not be a surprise, for classical physicists were aiming to make unambiguous predictions in an apparently deterministic universe. Modern physicists faced the challenge of producing mathematical models that could account for uncertainty and other bits of quantum weirdness while maintaining some predictive value. Erwin Schrödinger, who in 1926 was working in Berlin while Heisenberg and Bohr were busy developing their twin pillars of the Copenhagen Interpretation, solved this problem by inventing wave mechanics, which relies on a quantity know as a particle's wave function: $\Psi(\vec{r},t)$.[2] The wave function is a notoriously confusing quantity. It signifies the evolution through time of a particle's quantum mechanical state but does not have any simple physical meaning. Squaring it ($|\Psi(\vec{r},t)|^2$) however, produces the all-important probability distribution, which can be interpreted as the relative probabilities for the particle to be in a certain place at a given moment in time.

Schrödinger's wave mechanics, which is reducible to other mathematical formulations including Heisenberg's matrix mechanics, meets the challenge of being both flexible and predictive. It is capable of analyzing both the multiplicity of possible quantum states and the discontinuous collapse of a system subjected to a measurement. Instead of representing the system in a simple, linear manner, wave mechanics is able to model the complexities and slippages of a system without the logical simplicity afforded by strict determinism. To use language rarely associated with mathematics, we can say that Schrödinger introduced a degree of *play* into the formal structure of quantum mechanics.

Wave mechanics' theoretical power is obvious in its treatment of the hydrogen atom, the exact problem Schrödinger was working on during its development. In 1913, Bohr used the immature version of quantum mechanics available at the time to develop a model of the atom in which electrons were said to orbit the nucleus on defined, planet-like paths. In this model, electrons could be said to be in definite places at definite times. Since Bohr used Newtonian mathematics, there was no uncertainty. Though it contained some essential characteristics of quantum mechanics and explained some experimental results, Bohr's early model was definitely classical. Later, the statistical power and flexibility of wave mechanics enabled Schrödinger to make a truly modern model that portrayed each electron as existing in a petal-like probability cloud called an orbital instead of simple circular orbits.

In the epigraph at the beginning of this section, Heisenberg articulates the necessity of using classical concepts in the elaboration of quantum theory. Classical ideas, he argues are "just a refinement of the concepts of daily life and are an essential part of the language which forms the basis of all natural science. Our actual situation in science is such that we *do* use the classical concepts for the description of the experiments, and it was the problem of quantum theory to find theoretical interpretations of the experiments on this basis" (Heisenberg 94-5). Indeed, one of the most challenging aspects of studying quantum theory is learning how to think about the physical significance of a whole slate of complicated mathematical constructions. Frequently, the best one can do is to make a classical analogy.

Luckily, the Copenhagen Interpretation provides some structured help in the form of Bohr's Complementarity Principle. Unfortunately, it is not simple. In 1924, Louis de Broglie showed that all matter exists in a fundamental duality: Matter can be thought of either as a particle or as a wave. This was an extension of Einstein's original quantum

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[2] For the sake of completeness, here is the three-dimensional Schrödinger Equation:

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

mechanics paper, which asserted that light could be thought of in the same dual manner. Classically, wave-particle duality was impossible, since matter was made thought to be "made" of particles. But in quantum mechanics it is sometimes useful to think of electrons as particles, while other times waves make more sense. The discovery was driven by experimental results, since experiments produce effects that are either wave-like or particle-like, but never both. Heisenberg explains:

> These two pictures are of course mutually exclusive, because a certain thing cannot at the same time be a particle (i.e., a substance confined to a very small volume) and a wave (i.e., a field spread out over a large space), but the two complement each other. By playing with both pictures, by going from the one picture to the other and back again, we finally get the right impression of the strange kind of reality behind our atomic experiments (89-90).

This is Complementarity. And it is not limited to thinking about the wave-particle duality. Bohr showed how quantum theory could never cover over everything at once; experiments can never simultaneously show both sides of any duality. Some theories work best when working with particles and others are more intuitive when electrons are formulated as waves. This is a clear break from the representational discourse of the classical episteme. There can never be any fully satisfying picture, only snapshots that are provisional, metaphorical, and incomplete. When working with quantum theory, one must always be as attentive to the lacunae in any approach as one is to the things in focus. Indeed, Schrödinger's wave function can be mathematically reduced to yield the Newtonian dynamical variables of position and momentum but not without "break[ing] the determined continuity of the probability function by changing the knowledge of the system" (Heisenberg, 90). This is precisely what happens when one performs a measurement.

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> No doubt, on the level of appearances, modernity begins when the human being begins to exist within his organism, inside the shell of his head, inside the armature of his limbs, and in the whole structure of his physiology; when he begins to exist at the centre of a labor by whose principles he is governed and whose product eludes him; when he lodges his thought in the folds of a language so much older than himself that he cannot master its significations, even though they have been called back to life by the insistence of his words. But, more fundamentally, our culture crossed the threshold beyond which we recognize our modernity when finitude was conceived in an interminable cross-reference with itself. Though it is true, at the level of the various branches of knowledge, that finitude is always designated on the basis of man as a concrete being and on the basis of the empirical forms that can be assigned to his existence, nevertheless, at the archaeological level, which reveals the general, historical *a priori* of each of those branches of knowledge, modern man – that man assignable in his corporeal, laboring, and speaking existence – is possible only as a figuration of finitude. Modern culture can conceive of man because it conceives of the finite on the basis of itself. Given these conditions, it is understandable that Classical thought, and all the forms of thought that preceded it, were able to speak of the mind and the body, of the human being, of how restricted

> a place he occupies in the universe, of all the limitations by which his knowledge or his freedom must be measured, but that not one of them was ever able to know man as he is posited in modem knowledge. Renaissance 'humanism' and Classical 'rationalism' were indeed able to allot human beings a privileged position in the order of the world, but they were not able to conceive of man.
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> *Michel Foucault,* The Order of Things*, (318)*

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Complementarity is how Niels Bohr grappled with the problem of representation in the modern episteme. The complementary dualities – knowledge of the position of a particle and knowledge of its momentum, the energy of a particle and its position in four-dimensional spacetime of relativity, and the space-time description of atom events and their deterministic description – embody the untenability of the classical representational table in quantum theory. With this, we see physics seamlessly join Foucault's modern triad – biology, economics, and philology – insofar as "representation ceased, *ipso facto*, to have validity as the locus of origin of living beings, needs, words, [and matter] or as the primitive seat of their truth; henceforth, it is nothing more in relation to them than an effect, their more or less blurred counterpart in a consciousness which apprehends and reconstitutes them" (313). Before Einstein, physical order sprang from the representation of matter in the equations of Newton mechanics. This is why Planck could not accept the full import of his discovery when he realized that black bodies radiate heat in discrete units of energy (he refused to believe that energy was fundamentally quantized; he maintained his opposition to Einstein's 1905 claim for years by arguing that quantization was merely an effect of matter absorbing and radiating energy).

It is twentieth century physics' incorporation of quantum mechanics – in all of its radical weirdness, paradoxical confusion, and fundamental randomness – as a property of the universe that makes it a truly modern science, in the Foucauldian sense. After crossing the threshold of modernity, after dispersion of classical discourse, representation "is, for that empirical individual who is man, the phenomenon – perhaps even less, the appearance – of an order that now belongs to things themselves and to their interior law. It is no longer their identity that beings manifest in representation, but the external relation they establish with the human being" (Foucault 313). The necessity of Bohr's Complementarity is an indication that the Copenhagen Interpretation no longer confuses the object of its scientific knowledge (i.e., the representation of matter) with the real object itself. Heisenberg and Bohr can grasp the force of scientific knowledge because they understand that man, "with his power to present himself with representations, arises in a space hollowed out by living beings, objects of exchange, words, [and matter], when, abandoning representation, which had been their natural site hitherto, they withdraw into the depths of things and roll up upon themselves in accordance with the laws of life, production, language, [and measurement]" (Foucault 313). Man comes into existence at the center of this network of knowledges, and his relation to them is complex. He is at once the "source of order for the totality they form," but simultaneously "governed by labor, life, language, [and observation]" as if "it is possible to have access to him only through his words, his organism, the objects he makes, [and the observations he carries out]" (Foucault 313). These positive limits on knowledge are the things that allow man to know that he is a finite being, that he will never be able to hold everything solidly in mind at once.

But Foucault's caution forces him to judge this preliminary configuration unstable. One might imagine an overcoming of these obstacles and a return to the idealized possibility of infinite potential. For grounding, he searches "at the foundation of all the empirical positivities [for] everything that can indicate itself as a concrete limitation of man's existence"(Foucault 315). He finds a body ("irreducible spatiality"), desire ("a primordial appetite on the basis of which all things assume value"), and language ("in the thread of which all the discourses of all times, all successions, and all simultaneities may be given") (Foucault 314). To this we add a point of view, the irreducible position from which all observations are made and all knowledges are constructed. This is not only a position in time and space but also a scale; it is the point of view from which we refined the concepts of Newtonian physics, which Heisenberg argues we cannot, as humans, transcend ("There is no use in discussing what could be done if we were other beings than we are").

Though man's empirical existence is confined to an always-Newtonian "daily life," humanity has tried expanding this point of view in order to probe more deeply into the mysteries of the universe. We have built satellite telescopes that create an effective mirror larger than Earth itself, particle detectors assembled in caverns beneath miles of insulating rock and ice, and the biggest machine humanity has ever constructed – the Large Hadron Collider, a particle accelerator nearly thirty kilometers long – to escape the trap of our Newtonian reality. But according to the Copenhagen Interpretation, as hard as physicists try, they will never be able to return the act of observation to its classical weightlessness.

Thus, "we discover a finitude – which is in a sense the same: it is marked by the spatiality of the body, the yawning of desire, the time of language, [and the reality of a point of view]; and yet it is radically other: in this sense, the limitation is expressed not as a determination imposed upon man from outside (because he has a nature or a history [or insufficient data]), but as a fundamental finitude, which rests on nothing but its own existence as fact, and opens upon the positivity of all concrete limitation" (Foucault 315). Hemmed in by the fundamental limits of Uncertainty and Complementarity, modern man can no longer look without touching or know without changing. The future is unknowable not because he hasn't recorded enough about his present but because it hasn't yet happened. And he cannot harbor the illusion that the world he knows would be the same without him, for its possibilities become realities only when he opens his eyes.

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