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HEISENBERG'S CONCEPT OF MATTER AS POTENCY

Does the success of quantum mechanics require that we abandon the notion of complete scientific explanation? Or does it represent a breakthrough in the explanatory scope of physical theories? Ever since Werner Heisenberg formulated the theory of matrix mechanics in 1925,[1] this issue has been the topic of a continuing philosophical debate. In this essay I propose to explain Heisenberg's rejection of the mechanistic philosophy associated with classical physics and the significance of his return to Aristotle's concept of matter as potency.

I.

The central insight of Heinsenberg's matrix mechanics was that physics should deal exclusively with observable quantities, that each and every physical concept should be defined in terms of concrete measured results. Though this stipulation is logically impossible for any physical theory to achieve, as Dirac later demonstrated; it did inspire Heisenberg to define the properties

[1] Heisenberg, " Über quantentheorische Umdeutung kinematischer und mechanischer Beziehungen ", *Zeitschrift für Physik*, vol. 30 (1925), pp. 879-93.

of a physical system as linear algebraic operators, which, as Born and Jordan showed, could be represented as matrices.

*[A matrix Aij is simply a rectangular array of numbers (i indicates the number of rows and j the number of columns in the array). Matrices have certain interesting mathematical properties, the most important of which is that they do not commute under multiplication. Thus

$$AB - BA = n{:}\ n \neq o.$$

Though this mode of representation gave Heisenberg's theory a certain mathematical simplicity and did yield amazingly accurate predictions, it had startling theoretical consequences.

1) Where classical mechanics defines the state of a physical system by specifying exact values for conjugate variables (e.g., position in three dimensions and momentum in three directions), quantum mechanics requires only that the value of one conjugate be specified.

2) Where classical mechanics is able to calculate the state of a physical system at any arbitrary point in time, using laws of motion which implicitly define how state-variables are related through their time derivatives, quantum mechanics yields no observational description of a physical system between acts of measurement.

3) Where the state of a macrophysical system in classical mechanics is independent of any other system and is directly observable, the state of a microphysical system in quantum mechanics can only be inferred from its interaction with a macrophysical object, the measuring apparatus. To define the microphysical state, quantum mechanics uses a probability function known as the "probability amplitude".

Theoretically, this probability amplitude $<\chi|\phi>$ represents the change in a measuring apparatus from one macrophysical state $|\phi>$, the preparer, to a subsequent macrophysical state

* The part which follows in brackets contains technical explanations intended only for specialists. The reader who so desires may pick up the thread of the article again on page 28.

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$<\chi|$, the detector. Apart from these two macrophysical states of the apparatus, the microphysical state has no meaning. Observationally, the square of the probability amplitude $|<\chi|\phi>|^2$ yields a number P, a proper fraction which is the probability of finding the microphysical system in the macrophysical state $<\chi|$ having prepared it in the macrophysical state $|\phi>$. Mathematically, the probability amplitude corresponds to a complex number Re θ, whose magnitude R and phase θ—though they depend on the two macrophysical states of the measuring apparatus, the preparer and the detector—are neverthless two independent pieces of information about the microphysical system. The quantum mechanical state-description thus contains twice as much information as its classical analogue.

4) Where classical mechanics assumes that the physical state as measured corresponds to the state as theoretically defined, quantum mechanics assumes no such one-to-one correspondence. In quantum mechanics, the link between the probability amplitude (which defines the microphysical state) and the preparer and detector (the two macrophysical states of the measuring apparatus which are both directly observable) lies in the concept of symmetry.

A linear operator or matrix is said to be "symmetrical" if it is equal to its transpose, that is, if

$$Aij = Aji$$

The transpose of a matrix is simply its reflector or rotation about the main diagonal. Symmetrical operators have nice mathematical properties, including the fact that their Eigen values are all positive definite. But the real importance of symmetry lies in its physical interpretation.

Perhaps the best way to understand the physical significance of symmetry is to think of quantum mechanical properties (e.g., position, momentum, energy, time, etc.) as distinct operations performed on a microphysical system. Thus, if a particle is prepared in the state $|\phi>$, and the probability of its being detected in the state $<\chi|$ is independent of some operation R(u), and that independence is true for any state of detection, the particle prepared in the state $|\phi>$ is said to be symmetrical with respect to the operation R(u). If, for example, one prepares a particle in a state of good momentum (symmetry with respect to the operation position) then detecting the particle's momentum at some future state remains unaffected by changes in the particle's position.

The only properties that quantum mechanics attributes to a microphysical system are symmetry properties. Position is symmetry with respect to momentum, and vice versa. Energy is symmetry with respect to time going on, and vice versa. Spin is symmetry with respect to angle, and vice versa. It is because each of these properties is symmetrical with respect to its conjugate that quantum mechanics in able to define a microphysical state in terms of one conjugate variable. When a state-variable is symmetrical, its complementary conjugate becomes trivial.

5) Where classical mechanics uses a causal theory to define the state of a physical system and calculate its time evolution and a separate statistical theory to predict its actual occurrence, quantum mechanics combines these two logically distinct functions into one and the same mathematical formalism.]

One must remember that classical physics is not a single theory or even a collection of theories but the mode of scientific inquiry common to Galileo, Newton, Maxwell, Faraday, Lorentz, and Einstein. It was known as "classical" physics because for more than two centuries its outstanding success in organizing and predicting an ever increasing range of physical phenomena had made it the paradigm of rigorous scientific thinking. Classical physics achieved this reputation because its state-descriptions and its laws of motion enabled physicists to give a precise and seemingly complete account of the behavior of physical systems.

Until the early part of the twentieth century no one seriously challenged the claim that classical physics was the unique mode of physical science, though admittedly there were problems with hydrodynamics and with Maxwell equations. Then, as Heelan points out, there arose a number of problems which no classical theory could cope with. The Compton effect, and the Zeeman effect due to electron spin, remained complete mysteries. Pauli's exclusion principle forbade the duplication of bodies for no apparent reason. Bohr's old quantum theory allowed the electron to violate well established laws. Furthermore, Bohr's theory, which gave good results when applied to the hydrogen atom, failed completely when applied to the hydrogen molecule. It was in the light of these seemingly insoluble puzzles that Heisenberg undertook his reconstruction of physics.

The most important feature of Heisenberg's matrix mechanics was that it explained and predicted with singular accuracy those very phenomena which classical physics had found utterly anomalous. Yet Heisenberg had succeeded by changing the rules that had governed physics for more than two hundred years. Critics argued that Heisenberg's predictive success had been achieved at the cost of abandoning the principle of causality, imposing an arbitrary limit on the accuracy of measurement, and, above all, relinquishing the goal of complete scientific explanation. The issue was as much a philosophical one as a scientific one, for clearly the significance of the quantum revolution is not that it has added a new theory to physics but that it destroyed a world-view that since the time of Copernicus had come to dominate both science and philosophy.

II.

For Heisenberg classical physics had its philosophical counterpart in a mechanistic determinism whose origins he traced to the atomistic philosophy of Leucippus and Democritus, and later Epicurus.[2] Atomism contained all the elements for a thoroughly naturalistic account of the universe. An infinity of atoms explained multiplicity. The homogeneity of atoms preserved the unity of phenomena which Parmenides and the Eleatics had made the criteria of nature's reality as well as intelligibility. For the atomists, all atoms are identical except for position, shape, and purely numerical differences. Quantitatively distinct configurations of identical atoms accounted for qualitatively distinct sense properties, thus effectively reducing quality to

[2] For Heisenberg's view of atomism and classical physics see Heisenberg's *Philosophical Problems of Nuclear Science*, New York, 1952; *The Physicist's Conception of Nature*, New York, Harcourt Brace, 1958; and *Physics and Philosophy*, New York, Harper and Row, 1958.

quantity. Empty space, the void, provided atoms with a place to move; and blind necessity, ἀνάγκη, explained the law-like recurrence of natural phenomena. What for Plato would become an errant cause and for Aristotle a deprivation of perfection was for the atomists the source of nature's intelligibility. Natural events happen by necessity, respecting neither the will of men nor of gods.

Except for the concept of shape and the need for hooks to connect atoms to one another, Leucippus and Democritus had assembled all the elements essential for mechanistic materialism. All that was needed was the notion of interaction, a concept of force and a mathematical expression for blind necessity. Classical mechanics would provide them all.

Though classical physics began with Copernicus' attack on Ptolemaic astronomy, the man most responsible for the classical mode of scientific explanation was Galileo. Copernicus was at best a reluctant revolutionary, seeking only to replace the earth with the sun at the center of an Aristotelian universe. Kepler, who was caught up in neo-Platonic mysticism, had failed to recognize the physical meaning of his own laws. Galileo on the other hand, was well aware of what was at stake. It was not the content of Aristotle's theories but the Aristotelian mode of scientific explanation that constituted a positive barrier to discovering the truth.

Galileo's science of motion rested on two independent philosophical assumptions. First, the intelligibilitiy of nature can only be expressed mathematically. Gone were Aristotle's material, efficient, and final causes. Only formal causality remained and that merely in a vestigial sense. Galileo had identified form with mathematical relation. His second philosophical assumption involved the distinction between primary and secondary qualities. The former: extension, motion, and their ideal derivatives, in short, the mathematical description of the object, represent physical reality as it really is. The latter: color, shape, taste, sound, etc., correspond to what is perceived, to the physical object as related to a knower's sensibility. Whereas primary qualities are objective, real, and thus valid for all knowers, secondary qualities are subjective and unreal, the effects of a moving, extended object on a knower's sense consciousness.

Classical mechanics came to maturity both as a physical theory and as a mode of explanation with Newton's theory of gravity, which brought together Kepler's laws of planetary motion and Galileo's law of free falling bodies. Newton began with the notion of gravity as a non-contact interaction between bodies which requires a mutually acting force. At the same time, he broke completely with the past by defining natural motion as any state which is uniform with respect to mass, speed, and direction. This made uniform rectilinear motion an observable, logically equivalent to rest, enabling Newton to relate the concept of force to acceleration, i.e., changes in natural motion. With his invention of the calculus Newton was able to calculate precisely the effect of any force on a moving body. His results were so impressive that for the next two centuries Newtonian mechanics was the paradigm not only for physics but for all of science.

Newton's own philosophical views were more affected by his theological predilections than by the mechanistic assumptions of his gravitational theory. Nevertheless, it was he who provided all the components for mechanistic materialism: an infinity of mass points moving through Euclidean space and time, subject to invariant physical laws which took the form of differential equations. The classical viewpoint was mechanistic as well as deterministic. It presumed that given the initial state of a physical system one could calculate—within the limits of experimental accuracy—the state of the system at any arbitrary point in time.

Mechanism added to this determinism the implicit assumption that there is a one-to-one correspondence between the state-as-measured and the state-as-defined, and that therefore in principle phenomena should obey causal laws just like the physicist's state-descriptions. In effect, mechanistic determinism assumed that ultimately only classical laws are valid and that statistical laws are merely the measure of our present state of ignorance. The ultimate goal of classical physics was conceived of as eliminating probability by showing that random events are in fact subject to causal laws. The epitome of the classical viewpoint was Laplace's daemon, who, knowing all the laws of the universe, and the state of every system at a point in time, would know the complete history of the world process, past as well as future. Until the twentieth century no one seriously challenged these classical assumptions.

In overthrowing classical physics, quantum mechanics virtually destroyed the mechanistic philosophy which historically had been associated with classical mechanics. At the same time, the quantum theory raised new epistemological questions for which there were no ready answers. There were, first of all, the uncertainty relations,[3] which ruled out classically complete state-descriptions. They are built into the logical syntax of the theory and cannot be eliminated without changing the fundamental assumptions of the theory. And, as Von Neumann showed, they cannot be improved upon without destroying the predictive power of the theory. Furthermore, Heisenberg had defined the quantum mechanical state by means of a probability function which meant that, while it was necessary to use classical concepts to interpret the results of a measurement, it was impossible to give a classical account of what happens to a microphysical system between acts of measurement.

However, the question which most troubled Heisenberg was the epistemological significance of probability. Does probability actually explain the world, or does it merely mask our ignorance of what actually occurs? And if, as Heisenberg was convinced, probability is genuine knowledge, what is the ontological status of indeterminacy? Do the uncertainty relations imply that the world is indeterminate, or merely our knowledge of the world? And if it is only our knowledge, is indeterminacy a permanent or temporary feature of knowing? Like most of the pioneers of quantum mechanics, Heisenberg spent considerable time and effort wrestling with such problems. His own philosophy shows the influence of diverse viewpoints. By background and temperament Heisenberg was inclined to a neo-Pythagoreanism. On the other hand, two of his colleagues at Leipzig, Carl Friedrich and Grete Hermann, convinced him of the power of neo-Kantianism. In deference to Bohr, to whom he owed so much of his own success as a physicist, he adopted the 'principle of complementarity.' He became in fact a leading advocate of

[3] Heisenberg, " Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik ", *Zeitschrift für Physik*, vol. 43 (1927), 177.

Bohr's 'Copenhagen Interpretation.' Nevertheless, to solve the problem of probability and indeterminacy, Heisenberg eventually turned to Aristotle's concept of matter as potency.

III.

The world of Heisenberg is not the world of Aristotle. Not only twenty-four centuries but essentially different attitudes toward mathematics and the nature of scientific explanation separate the two. Yet there is a common insight which is more than simply an interesting point of comparison. There is in Aristotle's concept of matter as potency a key to understanding what quantum mechanics reveals about science and its relation to the physical world.

For Aristotle the task of physics, the philosophy of nature, was to explain why things change.[4] With those who denied that individuals are real or that they change, he saw no point in arguing. The fact of change is self-evident. Yet, unlike most of his predecessors, who explained change as the transition from one state to its opposite, Aristotle was perhaps the first to recognize that the process of change requires a subject which undergoes the transition. Not only that, but there must be some aspect of the subject which endures through change. Aristotle called that enduring aspect the substratum or substance.

Aristotle's principle of substance could explain not only why a subject maintains its identity through change but also why predication is possible—because substance has a hylomorphic structure. For Aristotle what makes a substance intelligible is form, μορφή, the principle of specification. Form explains what a thing is, why it acts the way it does, and how it is related to other substances. What makes a substance an individual is matter, ὕλη, the principle of individuation. Matter explains why individuals are unique.

Within the framework of Aristotle's physics, the concept of matter has two fundamentally distinct connotations. Neither is

[4] For Aristotle's account of matter as potency see *Aristotle's Physics*, translated by Richard Hope; Lincoln, University of Nebraska Press, 1961, especially Book Beta.

related to the atomistic concept of matter as the indivisible building-blocks of the universe, for to Aristotle's way of thinking such building-blocks already possess form. As a principle, the first connotation of Aristotle's matter is essentially negative, the concept of matter as privation, στέρησις, matter as incomplete. Since Aristotle considered incompleteness as a kind of non-being, matter as privation partakes of nothingness; and, as such, it perishes by its very nature. This is as far as most of Aristotle's predecessors went—the juxtaposition of being and non-being. But Aristotle recognized that matter is only incidentally incomplete. In essence, matter is potentiality for change. As potency, matter is uncreated and imperishable, the ultimate subject or substratum of things, on which their origin and continued existence depends.

For Heisenberg, as for Aristotle, matter designates the world as potentially intelligible. In discussing the proliferation of elementary particles Heisenberg points out that:[5]

> All elementary particles are made of the same substance which we may call energy or universal matter; they are just different forms in which matter can appear.
>
> If we compare this situation with the Aristotelian concepts of matter and form, we can say that the matter of Aristotle, which is mere "potentia," should be compared to our concept of energy, which gets its "actuality" by means of the form when the elementary particle is created.

While not identical, the two concepts of matter have a certain dimension in common. For Aristotle, the concept of matter as potency made it possible for him to progress beyond the simple juxtaposition of being and nonbeing and to explain change as the transition from potency to act. For Heisenberg, the concept of matter as potency provided an ontological basis for indeterminacy in physics which in turn justifies the incorporation of probability into the syntax of quantum mechanics.

Aristotle's concept of matter reflects his insight that the physical world can never be fully circumscribed by human intelligence—not because it is supra-intelligible but because it

[5] Heisenberg, *Physics and Philosophy*, p. 160.

consists of individuals; and, for Aristotle, the individual *qua* individual is unintelligible. Particular times, particular places, unique circumstances as such—what modern scientists sometimes refer to as the residue of reality—are purely factual. They are an inevitable component of our experience but as particulars they cannot be understood. Within an Aristotelian framework, one can predict how a physical object will behave to the extent that one understands its cause, αἰτία. Even so, Aristotle recognized that prediction can never be fully reliable because causal sequences are susceptible to the nonsystematic intervention of other causes. Physical objects do not always act according to their natures, and Aristotle ascribed this deviation to the limitations of matter. Thus matter, the principle of individuation, is the intrinsic source of indeterminacy in nature and in knowledge.

Heisenberg, too, recognized that microphysical systems, to the extent that they can be considered as sequences of ideal states, are subject to causal laws. One can calculate any future state of a physical system by knowing an initial state. Yet Heisenberg also realized that causal determination is never complete. Not because causality is defective but because the system-as-measured never conforms to the system-as-defined. Furthermore, the lack of any one-to-one correspondence is not simply attributable to experimental error or to some physical perturbation of the object by the measuring instrument. It lies rather in the logic of measurement itself.

According to Heisenberg, measurement in quantum mechanics is both the physical interaction of a microphysical system with a macrophysical instrument and the logical translation of an ideal state into an observable. Apart from the act of measurement, a state has a purely mathematical meaning. As a result of measurement, a state becomes a concrete object, subject to the material limitations of concrete reality. Hence, for Heisenberg as for Aristotle, predicting how an observable will behave is always subject to the non-systematic intervention of random events. Because he had no theory of probability to bring random events and diverging series of conditions within the purview of a scientific theory, Aristotle held that there could be no science of the contingent. On the other hand, Heisenberg was able to deal with non-systematic conditions by incorporating probability into the formal structure of his theory.

Quantum mechanics was the first physical theory to make a sharp distinction between causality (a formal relationship between the states of a physical system) and determinism (a necessary relationship between the measured states of the system). Heisenberg's matrix mechanics retains the classical notion of causality while discarding the classical concept of determinism in favor of a probabilistic connection between observable events.

Probability enters into the quantum theory as part of the act of measurement. Of course, probability was also part of classical mechanics but only as a separate theory of errors. No one ever expects a set of concrete data, which can only be measured with a finite degree of accuracy, to coincide with the infinitely precise values of a classically complete state-description. Instead classical physicists treat such states as ideal norms on which a random set of actual measurements would converge. In principle the ideal state was attainable; in practice the inevitable divergence of any actual measurement from the ideal norm was attributed to experimental error.

In quantum mechanics it is the probability amplitude, which defines the state, that evolves causally with time. Hence, it is possible, given an initial state of a system, to calculate in a strictly causal sense the probability amplitude (the quantum mechanical analogue of Artistotle's substantial form) for any future state of the system. But unless one makes a measurement, the system remains unobservable. On the other hand, the act of measurement, which translates the probability amplitude into a probability (which *is* observable), alters the causal development of the system and generates a new probability amplitude.

In short, the states of a quantum mechanical system are perfectly deterministic—so long as they remain abstract and unobserved. The moment the system is measured one encounters the indeterminacy of the concrete. As a result, the outcome of any measurement must be expressed as a probability. If a system has *not* been prepared in a state of good symmetry, it is treated as a statistical aggregate. But if the system has

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been prepared in a state of good symmetry, then the probability of its being detected in the predicted state at some future time can be calculated exactly. (These are the Eigen states of the function.) A deterministic prediction, then, depends on preparing the quantum mechanical system in a state of good symmetry.

Clearly probabilistic explanations are defective only if one clings to the mechanistic assumption that the physical object as observed is simply identical with the physical object as conceptualized. But this assumption, which is tantamount to asserting that a physical thing is identical with its form, has already been proven inadequate by the failure of classical mechanics. Having discarded it, we can now see that probability is what enabled quantum mechanics to deal effectively with the indeterminacy that is an intrinsic part of concrete reality, the indeterminacy which Aristotle ascribed to matter as potency.