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The Quantum and Classical Theories

A Crucial Difference of Theory-Type

Quantum Theory

Quantum theory (QT) has been with us for more than one hundred years, its earliest beginnings going back to the start of the twentieth century. It was then that Max Planck, after much effort to make theory fit fact, published his quantum hypothesis in order to provide some sort of basis for all that was then known experimentally about black body radiation.[1] Einstein's light corpuscle followed four years later to explain the photoelectric effect, and hardly two decades later, a mathematical quantum framework emerged whose predictive success was nothing short of spectacular.

Almost immediately, *quantum mechanics*—as this framework came to be known—yielded predictions of the known facts of spectroscopy, the Zeeman, Stark, and Compton effects, scattering phenomena, photo electricity, and the periodic table. The new "mechanics" promised to fill gaps in a classical theory that could not account for the specific heats of solids and the stability of the Rutherford planetary atom. Several decades later, theoreticians developed *quantum electrodynamics*—an electro-dynamical theory whose quantum-theoretic concepts of spin and resonance shed light on magnetism, chemical bonds, and more. Before long, QT was a scientific sensation as its predictions became more and more testable to a very high level of precision with ever more sophisticated experimental equipment.

Presently, QT is fully operative in solid state physics and therefore at the cutting edge of some of our cherished transistor, semiconductor, superconductor, and computer hardware technologies. It has found applications in laser, cryogenic, and genetic engineering as well as in theories of electrical conductivity, magnetic materials, and changes of state. More recently, it is providing the developmental basis for new technologies in quantum computing and cryptography involving some of the most arcane aspects of microphenomena. Only a few of the many possible examples of such applications are: *tunneling* for tunnel diodes, *superposition* at the level of atomic spin in order to vastly increase the number of simultaneous computing tasks, *phase entanglement* for correcting computer errors, and *decoherence* as a mode of control in quantum computing. There is also the application of *electron pairing* in superconductivity, in Bose-Einstein condensates, and in neutron beam thermometers. Some experiments even suggest the possibility of future micromachines using the ultrasmall Casimir force due to the pressure of virtual photons. And though cosmology has not yet systematically integrated with QT, the supplementation of general relativity theory with some quantum-theoretic rules vastly extends our reach into the elusive nature of black holes along with the possible origins and future of the universe. QT has thus figured crucially in modern physical theory from the microlevel of beta decay to the cosmic one of star formation.

But even more than all this, QT provides a contextual framework for quantum electrodynamics and quantum field theory now capable of encompassing the three nongravitational forces (weak, strong, and electrical) so basic to our understanding the causal dynamics of the physical world. Also noteworthy are the more recent efforts to bring the fourth basic force, gravity, into a final unification. These have resulted in various forms of *string theory*, still in unfinished states, but again developed as “quantum-type” or, as we shall call them, *quantumized* theories.[2] Finally, out of attempts to unify these forms, has emerged M-theory, presently only gestating, but with the promise of a vastly unprecedented explanatory scope. So, by all indications, QT is here to stay—at least for a long, long while. Indeed, its sweeping success in predicting microphenomena, together with its striking mathematical elegance, have earned it a top place among the most monumental of scientific creations.

Classical Theory

The landmark difficulties that beset classical theory almost a century ago—in special areas such as radioactivity, photoelectricity, black body radiation, specific heats, atomic spectra, and atomic structure—were certainly real and compelling signs that fresh approaches to the physics of nature were critically needed. Despite this crisis, however, classical theory—meaning by this, all of physical theory other than QT and *quantum-type (quantumized)* theories—remained (and continues to be) immensely successful in dealing with a vast range of phenomena including virtually all that happens in the familiar world of everyday life.

We have, here, a level of success that has, time and again, been nothing short of spectacular. In this regard, some all too familiar examples still bear mention, namely, the prediction of the existence of Neptune and of its orbit in the mid-nineteenth century (before astronomers physically discovered the planet), or the spectacle of wireless communication at the start of the twentieth century—all on the basis of classical principles. Indeed, quite apart from the thunderous technological impact of quantum physics in some basic areas, the vastly major portion of present day macrotechnology from computing to space science, continues to be classically based. Also to be noted, in this regard, are the dramatic successes of relativity in both applied and theoretical contexts. They have been awesome, especially given some of the intuition-straining content and predictions of the theory. (From the standpoint of the present discussion, we regard relativity theory as essentially classical.)

The "Unfinished" Quantum Theory

None of this glorious classical history, however, has been quite as stunning as the success of QT—a success that has seemed utterly magical. The reason for the uncanniness, paradoxically and curiously enough, is what some see as an "unfinished" state of the theory. When compared to most great scientific theories, QT is missing something—something traditionally deemed important for any theory of nature to have in order to explain the facts of experience. What QT has not yet found itself is a universally accepted interpretation, and this means that there is no generally settled opinion on the kind of existential subject matter or, if you like, ontology to commit to, in order to provide the theory with explanatory power.

On reflection, however, it need not be so surprising that finding an interpretation of QT, especially one structured for explanation, is problematic. To begin with, the nature of scientific explanation is a controversial issue in the philosophy of science with disagreements reflecting widely differing philosophical orientations, for example, positivist, realist, etc. But more than this, the formalism of QT is itself, in some respects, remarkably resistant to physical interpretation. QT is irreducibly statistical. It is not about what will actually happen to any concrete physical system. It is about *possible* states (quantum states) in which not all the constitutive variables have determinate values on the basis of which to explain, or even just predict, any definite happening, that is, one involving individual physical entities. More specifically, what the theory defines and predicts is no more than the probabilities of such *possible* quantum states—probabilities grounded on expected relative frequencies in the outcomes of measurement.

Adding to this bleakness is the somewhat disconcerting fact that the results of a long history of investigations seem to block, in principle, any possibility of remediation by supplementing QT with additional subject matter, namely, additional variables. These would be variables on the basis of which (1) to give determinate and intelligible physical accounts of what is happening behind the statistical appearances, and (2) to recover, by averaging methods, the statistical predictions of QT. It has been variously shown on the basis of what are known as "no-go theorems" that such a "hidden variable approach"—as it is called—is not possible without violating both a reasonable measure of basic realism and some rock-bottom requirements of commonsense intelligibility. That is, no such interpretation of QT could possibly satisfy certain restraints required by any realism of the kind insisted upon by Einstein throughout a good part of his lifetime and, one may add, also required by the standards of ordinary commonsense intelligibility.[3]

Still other obstacles hamper agreement on any interpretation. The statistical predictions of QT regarding the data we get in quantum experiments are indeed remarkably accurate and refined. The moment we try to explain these results in terms of some underlying reality, however, we come up with bewildering scenarios. These are so vastly counterintuitive and so violating of common sense that even the most distinguished contributors are unable to come to terms on any universally acceptable existential framework for "grasping" what is going on behind the experimental appearances. Add to this the further hobbling of any agreement not only by differing philosophical attitudes but also by the logical impasses we have mentioned, and the issue of interpretation seems to become virtually irresolvable.

The question that remains therefore is: How do we define (describe, characterize) quantum subject matter? Obviously, the answer that will inform our grasp must be one framed in minimally understandable terms, that is, in terms of the familiar concepts that *consistently* structure what ordinarily counts as "real" and intelligible. Things don't simply go in and out of existence; they change in causal contexts, and they never present simultaneously incompatible traits.

More generally, what we have in mind here are such "reality features" as substance stability or conservation, continuity of change, causality, and objectivity or mind-independence. To this we might add a measure of observer independence on the basis of the doctrine that one can, at least in principle, correct for any disturbance of the observed subject matter by the act of measurement. These, then, are the sort of "reality attributes," in terms of which one might want to frame any account of quantum subject matter. The idea is that such an account would be encompassing and coherent enough for making sense of the often astounding predictions of QT—predictions that experiment so remarkably confirms. Indeed, absent anything like such a framework or interpretation, the predictions of the quantum formalism, however accurate, remain stubbornly and opaquely puzzling.

As we intend it here, our notion that an interpretation of QT, in order to make sense of its predictions, must incorporate intelligibly structured physical subject matter, is not a bald claim about any "ultimate metaphysical status" of physical reality (mentalistic, materialistic, or other). Rather, it is a purely epistemic requirement about the sort of properties and relational attributes in terms of which we can say that we understand QT. Similarly, our subject matter requirement is independent of any distinction some might wish to draw between so-called quantum and classical modes of description. Our requirement is something prior to such a distinction; it is intimately tied to what we ordinarily have in mind whenever we say that we understand a subject.

None of this, however, means to suggest that quantum theory, though bereft of an explanatory ontology, has, as it stands, no physical content whatever. Obviously, the theory must be firmly linked to solid experimental ideas, or else it can predict nothing. Thus, for such quantities as position, momentum, energy, time, mass, charge, and spin as well as notions such as particle and wave, to have physical significance, they must to be tied to measurement. And, of course, measurement is what conveys information to the senses by means of appropriate observational (and usually "amplifying") systems—systems that translate alleged microscopic happenings into the macroscopic ones that experimenters actually observe, grasp, and record.

Indeed, what physicists predict and finally end up seeing as a result of measurement, even in the most arcane quantum experiments, is communicable only in terms of ordinary familiar experiences such as clicks, scintillations, vapor trails, meter readings, patterned shadings on photographic plates, and so on. These are all fully coherent, discrete, and classically describable, familiar experiences. Moreover, as every quantum experimenter knows, the devices (colliders, scatterers, detectors, absorbers, reflectors, computers, etc.) to which these experiences are tied in any quantum measurement are all familiar and accessible things that obey strictly classical principles.

QT, however, does much more than merely correlate raw data via classically rendered measurement setups. The fact that it arose in the very midst of real experimental issues makes it the heir of a rich patrimony of reality (ontological) concepts such as microparticles, spin, waves, and so on. QT, it seems, held to some classical moorings with implicit and often not so implicit references to an underlying subject matter that seemed at least analogous to the original classical one.[4] Indeed, the legacy of classical physics to QT runs even deeper. The quantum-theoretic categories of physical description remain given in terms of both status and change, and these, in turn, are specified in terms of location and momentum—the coordinates that physicists use in classical description. Unsurprisingly, therefore, the expression for the total energy (the "classical Hamiltonian") of a physical system figures centrally in the very formulation we call "quantum mechanics."[5]

But at the same time, QT, with its successful and often surprising predictions, seriously strains the relationship between the classical and quantum worlds. If the theory suggests anything at all about some quantum substrate, what it suggests is not stable and coherent enough to provide a basis for explaining the details of what the theory predicts—certainly not in any philosophically satisfying sense of "explaining." There are too many gaps and too many perplexities.

Indeed, in not providing such a coherent reality model or ontology, QT draws nettlesome ontic and semantical questions from the objective realist sector. This is a sector whose philosophical outlook is the one that still dominates at virtually all levels and branches of natural science. Are there, in fact, such "things" as microparticles and microstates? And how shall we understand pervasive terms such as: "physical wave," "particle," "charge," "field," "empty space," "virtual," "real," "possible," "objective," "determinate," and so on?

The phenomena that QT predicts are paradoxical enough from any classical or even commonsense viewpoint, but the structure and content of the theory itself, as we shall see, presents its own set of enigmas. As a result of both these aspects of QT, the characterization of quantum reality has been and remains a stubbornly resistive issue. This is the issue of interpretation, and it virtually defines the history of the foundations of quantum mechanics.