Deciphering Quantum Theory

Philip Goyal*
Perimeter Institute, Waterloo, Canada[†]

(Dated: April 2010)

Quantum theory poses deep challenges to the mechanical conception of reality that underlies classical physics. Yet today, over eighty years after its creation, its implications for our picture of reality remain enshrouded in uncertainty. In view of the current search for a more comprehensive theory of physics, it is vital that these implications be clearly elucidated. In this article, I describe the nature of the challenge posed by quantum theory, and outline efforts that have been made to better understand its non-classical features, such as non-locality. In particular, I discuss the informational perspective, which, through the study of quantum information processing, has provided deep insights into the nature of quantum reality, and has also revitalized the long-standing quest to reconstruct the content of the rather mysterious mathematical formalism of quantum theory from a set of crisp physical principles. Finally, I indicate some implications of recent reconstructive work for the search for a theory of quantum gravity, and, more broadly, for our picture of physical reality.

INTRODUCTION

Quantum theory is perhaps the most empirically successful theory in the history of physics. In the eighty-five years since its creation, it has proven itself capable of accounting, to a high degree of precision, for a vast range of physical phenomena such as the principles of chemical bonding and chemical reactions, the nuclear reactions that fuel the stars, and exotic phenomena like superconductivity. Much of the modern technology that fuels our lives is underpinned by quantum theory. The transistor; the basis for the modern computer that underlies all information processing technology, requires quantum theory for its design and modeling. The same holds true for the laser and the light-emitting diode, which jointly provide the basis for optical communication networks (the backbone of the telecommunications industry) and optical data storage (in the form of CDs and DVDs). Yet more quantum technology, such as quantum computers and quantum cryptography, is waiting in the wings, promising to transform our lives still further.

However, ever since its very beginnings, quantum theory has been of great interest for quite another reason. Taken at face value, quantum theory challenges many of the key tenets of the mechanical conception of reality. That picture of reality, which was developed by Descartes, Galileo, and Newton (amongst others), underpinned the development of physics—what is now called classical physics—for approximately three hundred years. So successful was this enterprise that it spawned the so-called mechanical world view, which had a profound effect not only on other scholarly disciplines, but also on the general culture. Thus, quantum theory forces reconsideration of not only a view of reality of interest to physicists, but also of a world-view that has guided the development of Western society for more than two centuries.

For physicists, the challenge posed by quantum theory is, at a minimum, to develop an intuition for the reality that it describes which is sufficient to be able to discover, explore, and harness the phenomena it encompasses, and, at best, to develop a conception of physical reality which takes quantum theory fully into account, to develop a conception which is as coherent and compelling as the mechanical conception of reality, and which is capable of guiding further development of physics. For the philosopher and thinker, the broader challenge is to develop a conceptually coherent and plausible world-view that fully takes the content of quantum theory into account.

In this article, I shall attempt to sketch the degree to which the challenge to understand quantum theory has been met and the means by which this has been done, and to give some sense of the road that lies ahead.

CLASSICAL PHYSICS

To understand the challenge posed by quantum theory, it is helpful to begin by considering classical physics.

Underpinning classical physics is a mechanical conception of reality. This conception is multi-faceted, but its essential *attitude* is that all particular events that occur in the physical world are, in their finest details, manifestations of general principles of nature. The promise is that, by careful study of particular events, we, in spite of our limitations as finite beings, can discover these general principles by a process of generalization.

More precisely, the mechanical concept posits that the totality of all that exists in the phenomenal world (namely that aspect of the world registered by our senses or instrumental extensions thereof such as microscopes or telescopes) is *matter* moving on the *fixed stage of space* in step with a *universal time.* That is, all that exists in the physical world is matter in motion, the manner in which it moves being completely governed in quantitative detail by *universal laws of motion.* These laws

---

*Electronic address: `philip.goyal@gmail.com`
[†] Corresponding author.

thus, as it were, stand outside the Universe dictating all that happens within it, but are left unaffected by what happens.

It is further posited that, in principle, agents can probe this matter as precisely as one wishes without disturbing its nature or its motion. Thus, in principle, agents have a "God's eye" view of reality: everything, in its finest details, is open to their gaze. Moreover, reality is so constructed that, even though agents are necessarily restricted to studying *parts* of the universe, they can nonetheless in principle come to learn the nature of the universal laws of motion, and thereby aspire to a theoretical model of physical reality that allows arbitrarily precise prediction of the behaviour of the entire physical universe.

In the hands of Descartes, Galileo, and Newton, this conception was mathematized in a fairly direct way. In Newton's mechanics, the first comprehensive theory of classical physics, published in 1683, matter is composed of particles represented by geometrical points in Euclidean space, moving in geometrically precise trajectories determined by a set of equations of motion in step with a universal time. The dynamics are such that all information about any time in the past is contained in the present. This theory was enormously successful, accounting in a unified way for the known regularities of the solar system (codified as Kepler's laws) and the precise trajectories of projectiles (such as canon balls) on the surface of the Earth, and also making new predictions (such as the arrival of Halley's Comet in 1758).

Over the subsequent two hundred years, theories of electricity and magnetism (Electromagnetism), and of heat and temperature (Thermodynamics), were developed and were similarly successful. These theories stretched the mathematical framework established by Newton. For example, whereas Newton believed that all that exists is particles in motion, which means that it requires only a finite (or countably infinite) number of parameters to fix the state of these particles, Faraday and Maxwell introduced the idea that there exist dynamical *fields* which require *continuously* many parameters for their specification. However, these modifications did not fundamentally challenge the mechanical *conception* of reality of classical physics [12].

It is important to note that this 'clockwork universe' view of the phenomenal world was also readily graspable by those who had no knowledge of mathematics. Consequently, this view was not confined to the physics community, but propagated to other areas of science (such as chemistry, biology, psychology, economics, and sociology) which were able to adapt this view to their own domains of enquiry and often also able to successfully adapt the mathematical techniques developed by physicists. More broadly, this view also propagated beyond the sciences to areas such as philosophy and theology, where it had a profound impact which, in the more than 300 years since Newton announced his mechanics, has played a vital role in the radical transformation that has occurred in our understanding of our place in the world.

QUANTUM PHYSICS: BEGINNINGS AND EARLY IMPLICATIONS

By the 1890s, classical physics was in a highly developed state. However, there were some clouds on the horizon—curious experimental facts which stubbornly resisted explanation within the framework of the existing theories of classical physics. One of these facts concerned the frequencies of light given off by heated bodies. The classical theories were unable to account even *qualitatively* for the experimental data. The tentative explanations of these stubborn facts, initiated by Max Planck, would, over the next 30 years, bring about the development of quantum theory—an entirely new theoretical foundation for physical theories that would replace the mathematical framework of classical physics.

Quantum physics did not come into existence in a straightforward and principled manner. Unlike the mathematical framework of classical physics, it was not arrived at by mathematization of some clear conception of reality. Rather, it arose through a rather tortuous path consisting of rather *ad hoc* modification of classical physics, guided by heuristic ideas (an example of such idea, due to de Broglie, is that each particle has an associated 'guiding wave') and by ingenious mathematical guesswork about what aspects of the existing mathematical structures of classical physics needed to be changed and what aspects could be retained.

The first quantum theory was non-relativistic quantum mechanics, developed in distinct forms by Schroedinger and Heisenberg in 1925–6. Its key achievement was accounting in quantitative detail for the light spectrum of hydrogen in a variety of different circumstances. Over the course of the subsequent few years, a general and rather beautiful mathematical formalism—the *quantum formalism*—emerged, which provided a new mathematical framework (replacing the mathematical framework of classical physics) within which to build physical theories.

Early Implications

Owing to the indirect process by which the quantum formalism was created, the physical origin of many of the mathematical aspects of the formalism was not clear. Nonetheless, some physical features could be safely read off the formalism which were sufficient to establish (within a few short years after its creation) that it departed radically from the framework of classical physics.

The Measurement Process.

As mentioned above, in the classical framework, an agent is afforded a God's eye view of physical reality. Thus, an agent can perfectly and completely access the goings on (or the *state)* of a physical system, and furthermore can do so without disturbing it to any significant degree. In contrast, the quantum formalism posits a new model of the measurement process which has three distinct features:

1. *Probabilistic Outcomes.* The outcomes of measurements performed on systems are only predictable on a probabilistic level.

2. *Complementarity.* A single type of repeatable measurement only yields information about some aspect of a system, at the expense of some other aspect of it.

3. *Discreteness.* Measurement outcomes can be discrete, being finite in number or countably infinite.

The first of these features is that, in contradistinction of the fundamental attitude of the mechanical view of reality, it is *not* true that every detail of every event is determined by universal laws. Instead, the quantum formalism asserts that only the *probability* that a measurement will yield a particular result is predictable; the outcome that will be obtained in a particular run of an experiment, in general, is not.

The quantum formalism, as classical physics, considers measurements which are repeatable—that is, measurements which, when immediately repeated, yield the same outcome with certainty. If one considers such measurements, then it follows as a direct consequence of the fact that measurements are probabilistic that, in general, they *disturb* the state of the system upon which they are performed. In fact, they disturb it almost completely—almost no trace of the pre-measurement state of the system is left in the post-measurement state.

The second feature, complementarity, can be precisely expressed in a number of different ways. Perhaps the simplest is to say that, unlike the situation in classical physics, one cannot perform a repeatable measurement on a system which yields information about *all* of the degrees of freedom of the state of the system [13].

Taken together, these two features severely constrain an agent who wishes to learn about the unknown state of a physical system. First, due to complementarity, an agent cannot rely upon one type of measurement, but must use more than one type of measurement. Second, due to probabilistic outcomes, an agent must perform many measurements on identical copies of the system. Yet, after a finite number of measurements, the agent's knowledge about the state will still be imperfect. It is only in the unattainable, idealized limit of an infinite number of measurements where the agent's knowledge of the state becomes complete. Therefore, there is almost always an *informational gap* between the theoretical description of the underlying reality—the quantum state of the system—and the agent's knowledge of that state.

The third feature of the measurement process, discreteness, is that, when certain measurements are performed on physical systems, the number of possible outcomes can be finite (or countably infinite) in number [14]. This stands in contrast to the assumption of the classical framework that all physical quantities (such as the position of a particle) can take a continuum of possible values. Hence, discreteness challenges the classical idea that the continua of space and time are the fundamental bedrock of physical reality.

Non-decomposability

One of the basic premises of classical physics is that one can conceptually *decompose* the whole of physical reality into spatially disjoint *parts,* describe each of these parts separately, and then combine these partial descriptions together to form a description of the whole. This premise is required in order that an observer, who is necessarily restricted to studying the physical universe one piece at a time, can nonetheless aspire to a complete description of reality. However, the quantum formalism asserts that physical reality is *not* constituted in this way.

For example, considers the simplest case of physical system consisting of two spatially separated subsystems. The quantum formalism asserts that almost all of possible states of the system *cannot* be specified by giving the state of each subsystem separately. Such a non-decomposable state is technically referred to as an *entangled* state, a name coined by Schroedinger.

More generally, quantum theory implies that a physical system becomes entangled with other systems as it interacts with it. Consequently, one can expect that a typical physical system as it is found in nature is generically entangled with many other physical systems, including those at great distance from it. However, an agent studying that system has no way of determining the nature of these entanglements by studying the system alone.

Entanglement also has another important ramification. In classical physics, it is assumed that a system can only affect another system through influences that propagate through space at some finite speed (the speed of light), an assumption known as *locality.* However, Schroedinger showed that, according to the quantum formalism, if an entangled state of two subsystems is shared by two parties, Alice and Bob, then Alice can instantaneously affect—or *steer*—the state of Bob's subsystem by performing a measurement on her subsystem, an effect whose strength is moreover independent of how far away Bob's subsystem happens to be! Thus, the quantum formalism also appears to undermine the classical assumption of locality in a fundamental way. However, the situation is not as simple as one might expect: as Schroedinger also showed, Alice cannot use steering to instantaneously *signal* to Bob. Thus, locality is preserved at the level of signaling.

The Measurement Problem

In classical physics, a measurement performed upon a physical system can be regarded as an essentially passive registering of information about the system: in the ideal case, information is gained without in any way affecting the system. In contrast, as described above, the process of measurement according to the quantum formalism is an active intervention in the world: in general, the state of a system will be changed as a result of a measurement being performed upon it.

One immediate consequence of this difference is that, in the quantum formalism, a physical system can undergo two *kinds* of physical process, mathematically described in quite different ways. The first is deterministic temporal evolution, which is familiar from classical physics, and represents the change in the state of the system as a result of the passage of time while being in some 'environment' (consisting of other physical systems) with which it is interacting. The second is an indeterministic (probabilistic) change due to a measurement being performed upon it. But, now the question arises: what kind of interaction with a physical system should be treated as a deterministic evolution, and what kind of interaction should be treated as a measurement?

On this question, the quantum formalism is silent. The formalism itself talks of 'measurement' purely in the abstract, leaving the physicist to decide when to describe an interaction as a measurement. In *practice*, this ambiguity in the rules of application of the formalism is rarely a problem: an experimental physicist sets up an experiment, which, if it is to provide information about what is going on, necessarily contains some kind of a measurement device such as a photographic screen or similar detection device, and this device demonstrably produces outcomes. However, as a matter of *principle,* this ambiguity is troubling, and has produced sufficient disquiet so as to become known amongst physicists as 'the measurement problem'.

Quantum Theory and Our View of Physical Reality

In the period shortly after the formulation of quantum theory, physicists responded to the above-mentioned non-classical features of quantum theory in essentially two distinct ways.

The first view, held by many of the founders of quantum theory, such as Bohr, Heisenberg and Pauli, was that the non-classical features of the formalism, such as the statistical nature of its predictions, had to be taken seriously. That is, these features reflected the very structure of physical reality, and the classical mechanical view of physical reality had to be replaced by something fundamentally new.

In order to illuminate these non-classical features of the quantum formalism, some of these physicists attempted to identify related concepts in the existing philosophical literature or to develop new concepts of which these features could be regarded as particular instantiations, thereby placing these non-classical features in a broader philosophical light. For example, Bohr developed the concept of complementarity, which he expressed as meaning that the process of coming to know anything about some aspect of reality unavoidably has the effect of bringing into existence some aspect of it at the expense of simultaneously rendering inaccessible some other aspect of it [1]. Bohr believed that this concept had general validity beyond the field of physics itself, in areas such as psychology and sociology, for instance [2]. In his view, the impossibility in quantum theory of performing a repeatable measurement that provides complete knowledge about a physical system (but only one property of it at the expense of another) was simply a special case of the general principle of complementarity. Similarly, Heisenberg and Pauli both suggested that the Aristotelian notions of potentiality and actuality could be useful in understanding the relationship between the state of a system and the outcomes of measurements performed upon the system, and in understanding why the classical mode of thought led to inconsistencies when applied to such simple experimental situations as Young's double slit experiment [3, 4].

The second view, held by Einstein and some other physicists, maintained that notwithstanding the manifest non-classical features of quantum theory, the classical mechanical view of reality did not require the revision of its fundamental tenets. Einstein, for instance, argued that the statistical nature of quantum predictions was simply an indication that the quantum description of reality was incomplete, and spent a significant part of his later life searching for a classical field theory that was capable of underpinning quantum theory. de Broglie, in particular, supported this point of view by showing that the quantum theory of an ensemble of particles could be re-written in a form closely akin to classical mechanics, albeit with some curious non-classical features.

It may seem surprising that such different viewpoints could be taken based on the same evidence. However, it should be borne in mind that, at its core, a physical theory is simply a set of mathematical equations, and rules for their application. A theory does not "tell" us anything about the nature of reality itself. Every statement one makes on the basis of a physical theory about the nature of reality itself is an extrapolation, and is strongly dependent upon the metaphysical inclinations of the individual. Thus, in the face of quantum theory, it was perfectly rational for physicists to adopt quite different viewpoints as to its implications for our view of physical reality.

DECIPHERING QUANTUM THEORY

Today, some eighty years after the early efforts to understand quantum theory, there is still no broad agreement on what conclusions about the nature of reality we ought to draw from quantum theory. Nonetheless, in the interim, a number of important advances have been made. Two of the most striking developments have been the exploration of quantum non-locality, and the development of the *informational* perspective on physical reality.

Non-locality

As mentioned above, Schroedinger's work on entanglement showed that, at the level of theoretical description, two subsystems cannot in general be regarded as separate entities. This finding *suggests* that physical reality is non-local in the sense that an experimenter performing a measurement on one subsystem can instantaneously affect the state of the subsystem with which it is entangled, even if the subsystems are widely separated in space. But, it *could* be that the non-separability one sees in the quantum formalism is simply an artifact of the formalism, and not a reflection of physical reality itself. This latter possibility is supported by Schroedinger's demonstration that two entangled subsystems cannot be used to send instantaneous *signals*. However, at the time of Schroedinger's work, given that it did not appear to be possible to experimentally *test* for the existence of non-locality, it was difficult to choose between these two possibilities.

This deadlock was broken in extraordinary fashion in 1964 by John Bell [5]. Bell showed, that, if a pair of quantum systems is allowed to interact and are then separated by an arbitrarily great distance, the outcomes of measurements performed on each of them separately can be *correlated* in a way that cannot be accounted for if we assume that reality behaves in accord with the mechanical conception of classical physics (being deterministic and local, in particular). In short, Bell showed that entanglement indeed leaves an experimentally detectable fingerprint which cannot be accounted for on a so-called 'local realistic' picture of reality.

Bell's theorem strongly suggests that there is *some kind of connection* between physical systems that have interacted in the past, a connection that endures irrespective of their distance, and that enforces subtle but very real correlations between them. This connection is of a type never seen in classical physics. Unlike the forces of gravity, electricity or magnetism, the connection is unattenuated by distance, and is specific to the systems which previously interacted.

Nevertheless, Bell's theorem rests on a number of assumptions, and one can rationally question the validity of some of these assumptions, and thereby avoid the conclusion that there is some kind of non-locality in nature.

In recent years, as we shall describe below, the conclusion of Bell's work has been bolstered by the demonstration that entanglement is a powerful physical resource that can be used to carry out various processes that are impossible or very difficult according to classical physics. If true, non-locality fundamentally alters the status of space, and with it a key element of the mechanical view: space is no longer the entity which mediates all interactions between material bodies; instead, bodies also interact via an ever-changing web of inherently non-spatial connections.

Information Physics

The concept of information is an intrinsic part of our everyday experience. Each of us is an agent immersed in a physical world, and our knowledge of that world (including the knowledge possessed by other agents) is necessarily limited. Consequently, we must constantly ask questions of the world and use our sensory systems in order to gather more information about it, and make inductive inferences about the world based on limited information.

Yet, despite its ubiquity in everyday experience, the concept of information is conspicuously absent in the theories of classical physics (such as classical mechanics and electromagnetism). The reason for this is two-fold. First, in the classical framework, the universe evolves *deterministically* and *reversibly*—the past fully determines the future and, conversely, the future determines the past, so that no information is lost or gained over the passage of time. Second, agents can always, in principle, perform measurements that yield perfect and complete information about the state of reality. Therefore, every agent in principle has the same "God's eye" view of reality. If an agent lacks knowledge about the state of reality, then that is the result of contingent circumstances (such as due to limited access to experimental devices) rather than reflecting a fundamental feature of reality and the agent's relation to it. For these two reasons, the concept of information is essentially redundant in classical physics.

However, as mentioned earlier, the quantum formalism posits a new model of the measurement process, from which it follows that there is almost always an informational gap between an agent's knowledge of the state of a physical system and the state itself. Furthermore, when an agent performs a measurement to obtain information about a system, the state of the system is, in general, irrevocably altered. Hence, there is, in general, no information gain without disturbance. Thus, in conceptualization of the quantum formalism, the concept of information naturally occupies a central role.

Over the last few decades, these non-classical features of quantum theory, together with developments in theories of inference (information theory and probability theory) and the rise of information technology in everyday life and the concomitant rise of computer science as a discipline, have given rise to the belief amongst many physicists that the concept of information may have a critical role to play in our understanding of quantum theory.

More broadly, in recent years there has been considerable interest in the program, perhaps best articulated by John A. Wheeler under the slogan *"It from Bit"* [6, 7], of providing an information-theoretic foundation for the two major pillars of modern physics, namely quantum theory (our framework for theories of the microscopic world) and general relativity (our best theory of the macroscopic world). One of the major stimuli for this program arises from the discoveries in black hole physics in the early 1970s, which have revealed a deep connection between the geometry of a black hole and its entropy (a measure of the information about the matter inside the black hole which we cannot access). Over the last few decades, this work has given rise to the striking notion that the outcomes of length and area measurements of space are inherently discrete, and that the information that can be stored in a region of space is intrinsically limited.

The informational viewpoint has generated at least two important strands of development which have impacted our understanding of quantum theory. First, the investigation of information processing within the context of quantum theory, which has given rise to the fields of quantum information and quantum computation. Second, the investigation of whether the quantum formalism itself can be characterized in terms of information-theoretic principles, and thus whether quantum theory can be understood as essentially a theory of information processing.

Quantum Information and Computation

The classical theory of computation, formulated by Church and Turing in the 1930s, presupposes a classical conception of physical reality. All of our modern computers, however sophisticated, are based on this classical model of computation. The elementary unit of information is a bit (short for *b*inary dig*it*), which takes the value zero or one. Abstractly, a computation is a deterministic map from a string of bits to another string of bits. More concretely, in an abstract computing device proposed by Turing, the device acts on a tape divided into square spaces, in each of which a symbol is printed. The device has a 'head', which, at any time, is positioned opposite a particular space on the tape. At each time-step, the head either reads the symbol printed on the space, or erases and writes a symbol to the space; and the device moves the tape one unit to the left or right or leaves it in the same place. The device also has a discrete internal state, which is modified in a deterministic way at each time-step. The essential idealizations of classical physics are apparent here: there is no mention of quantum states and quantum measurements.

It is natural to wonder whether information processing fundamentally differs when embodied in quantum reality, and, in particular, whether new things are possible when the full richness of quantum reality is harnessed. It is also natural to wonder whether quantum theory imposes new constraints on how the information encoded in quantum systems can be manipulated.

The elementary unit of quantum information is not the bit but the qubit. Information is encoded in the state of the qubit, which can be visualized by a point on the surface of a sphere. According to quantum theory, a measurement performed on the qubit will yield only one of *two* possible outcomes. Thus, there is a strange disparity between the state of the qubit (which can take on a two-fold continuum of possible values), and the result of a measurement (which can take only two possible values). In particular, it follows from quantum theory that the state of a qubit cannot simply be 'read' as can that of a classical bit.

However, one might imagine that there exists a process which is capable of *copying* the state of a qubit without actually reading it. One of the most striking early findings of quantum information in the early 1980s is that, according to quantum theory, this is impossible [8]. That is, unlike a classical bit, there is no general device which, when fed a qubit in an unknown state, can output two qubits in the same unknown state.

But quantum information is not only about restrictions. Over the last thirty years, it has been found that, when information is embodied in quantum systems, it is possible to carry out information processing tasks which are impossible or very difficult using classical information processing. For example, one can in principle build a *quantum computer* which can quickly solve certain problems (such as the problem of factoring large numbers) which are of great practical importance and yet are intractable on classical computers. One can also carry out tasks using quantum information processing that are classically *impossible.* For example, using quantum theory in what is known as *quantum cryptography,* two parties can communicate a message encoded in qubits, and yet to be able to detect whether there is an eavesdropper listening in on their communication. This sensitivity to eavesdropping relies essentially on the fact that, in quantum physics, unlike classical physics, a measurement (the eavesdropping) is an *active* process that, in general, affects what is being measured.

Remarkably, most of the innovations allowed by information processing depend crucially upon the use of *entanglement.* For example, in quantum cryptography, it is essential that the two parties involved share entangled particles. For this reason, in quantum information processing, entanglement has come to be viewed as an indispensable resource. At a foundational level, this has stimulated the study of entanglement in its own right, and has persuaded many physicists that entanglement is a very real facet of physical reality.

Reconstruction of Quantum Theory

As mentioned earlier, the formalism of quantum theory was obtained in a rather ad hoc manner, as a result of which it possesses many mathematical features whose physical origin is unclear . Presumably, there are *physical* reasons for these features, but what are they? Until the 1980s, most progress to understand the nature of quantum reality has been made by taking most or all of the quantum formalism *as a given,* and then attempting to draw physical implications from it in various ways. The early interpretation of de Broglie, Bell's theorem of non-locality, and the discoveries of quantum information processing are all examples of this methodology. As a result of taking most of the formalism as a given, however, these approaches are intrinsically unable to account for the physical origin of the quantum formalism itself.

Over recent years, there has been an increasing realization that such a methodology is also intrinsically limiting in other ways. For example, it is now established that quantum reality has numerous non-classical features, such as the probabilistic nature of measurements, non-locality, and so forth. But, if we are to understand the nature of quantum reality as a whole, we need to understand how these separate features fit together as part of a single, overarching picture of reality. However, as long as the quantum formalism is taken as a given, we cannot know which of these non-classical features are fundamental and which are secondary or derived, and neither can we be sure that there are no other important non-classical features which remain to be discovered that are, in some way, essential to our understanding of quantum reality.

One way forward is to take a few of the non-classical features of quantum theory that we think are fundamental to how nature works, and to try to *derive*—or reconstruct—the quantum formalism from these features in a systematic way. If successful, such a reconstruction would show that the non-classical features we started with are indeed sufficient by themselves to account for the full richness of quantum reality. Ideally, a reconstruction of the quantum formalism would distill the physical content of the quantum formalism into a set of clear, intuitively graspable statements expressed in natural (everyday) language, thereby rendering the entire content of the quantum formalism available to the kind of conceptual analysis that is necessary to develop an underpinning conception of reality. Thus, reconstruction is a powerful methodology that can be used to *test* any candidate understanding of quantum reality, and, by focussing our attention on just a small number of the non-classical features of quantum theory expressed in natural language, facilitate the building up of a conception of physical reality capable of fully underpinning it.

Information-based Reconstruction The fundamental role played by the concept of information in a discussion of the quantum formalism, together with the insights into the nature of quantum reality gained through an exploration of quantum information processing, naturally gives rise to the question of whether quantum theory can be reconstructed on the basis of information-theoretic principles.

One of the earliest investigations in this direction was carried out by Wootters [9], who showed that a fundamental prediction (Malus' law) of quantum theory could be derived by assuming that quantum reality is, in some precise sense, as good as it could possibly be for sending information via quantum systems from one party to another. Another early investigation [10] centers on the remarkable fact that, although quantum reality is non-local in the sense shown by Bell, quantum theory also implies that this non-locality cannot actually be used for instantaneous signaling. As physicists sometimes say, there is a peaceful coexistence between the properties of non-locality and no-signalling. Although this investigation concluded that this peaceful co-existence was not by itself sufficient to account for the structure of quantum theory, it was an important inspiration for later work.

Over the last decade, a number of detailed reconstructions have been presented, which proceed from diverse starting points. To illustrate the nature of a reconstruction in more detail, I will consider recent work in which I have recently shown how it is possible to reconstruct the core of the quantum formalism (namely Feynman's rules of quantum theory)[11]. By making use of elementary symmetry and consistency conditions, I have shown that it is possible to derive the complex nature of the quantum formalism directly from the probabilistic nature of measurement outcomes and complementarity. This reconstruction strongly suggests that the quantum formalism can indeed be regarded as a way to process information consistent with particular informational constraints.

This derivation takes place without making reference to more than one physical system, thus showing that features such as non-locality and no-signaling are *not,* in fact, essential to an understanding of the structure of the quantum formalism. That is, from the point of view of the derivation, features such as non-locality and no-signalling are not fundamental, but secondary. Moreover, the derivation makes no use of spatial locality, which suggests that the quantum formalism is in some sense more fundamental logically prior to space.

Implications for Quantum Gravity In the existing quantum theories of particles and fields, space-time is treated classically, while the particles and fields themselves are described using the quantum formalism. Thus, these theories are curious hybrids where particles interact via influences propagating through space, but can also interact non-locally via entanglement-mediated influences which bypass space. Is there some more fundamental way to unify local and non-local interactions?

As discussed in the preceding section, the quantum formalism can be derived without reference to space, which strongly suggests that the quantum formalism itself is inherently non-spatial. That is, quantum theory is neither non-local nor local; it is more fundamental than either notion. Nevertheless, the reconstruction also shows that entanglement *is* a basic feature of this formalism. This suggests that one should not regard locality (and thus space) and non-locality as primitive givens, but rather approximate features of the world, which jointly emerge from some more basic, pre-spatial, reality in which entanglement plays a central role.

If valid, this view suggests that, if one wishes to develop a theory of quantum gravity, one should not start with space as a given and try to describe it directly using the quantum formalism, but rather to try to find some more primitive pre-spatial structure, from which space will emerge as an approximation, perhaps at large-length and low-energy scales.

Implications for our Conception of Physical Reality If, as is suggested by the reconstruction, we accept indeterminacy and complementarity as a given, what conception of physical reality do they suggest? What are they telling us about how Nature works? A reconstruction of quantum theory, as the one referred to above, is an important stepping-stone to a new conception of nature in that it focuses our attention on just a small number of non-classical features. But it is still only a stepping-stone. How does one proceed beyond this point?

To start with, we need to understand indeterminacy and complementarity. For example, it is one thing to accept that measurements are indeterministic as an operational principle (that is, as a summary of what we find in our experiments), but quite another to accept at a philosophical level that things happen without any cause whatsoever. How are we to get a philosophical handle on such an idea? In the case of complementarity, why is it that a measurement can access *one-half* of the degrees of freedom of the state of a system, and not some other fraction, for instance?

One of the important jobs of a conception of reality is to provide a unified understanding of the separate assumptions that underlie a reconstruction. In the above reconstruction, indeterminacy and complementarity have been postulated for essentially different reasons. So, in this case, we would like to find an overarching understanding of why Nature has *both* these features, and not just one or the other.

We must also face the measurement problem. In the above reconstruction (and also in almost all recent reconstructive attempts), the notion of measurement is taken as a given. Yet, as previously discussed, we do not know what kind of physical process constitutes a measurement. My own view is that the indeterministic, irreversible physical process we commonly refer to as "measurement" occurs constantly at the microscopic level of matter, and thus is an objective feature of reality's unfolding rather than (as one might suppose from the language of quantum theory) something that depends upon observers performing what we ordinarily think of as measurements. Accordingly, the challenge is to understand the conditions under which the dynamics of a system are dominated by deterministic dynamics (mathematically referred to as unitary dynamics), and when and why measurement dynamics (indeterministic, irreversible dynamics) occur.

Currently, all of these issues remain open, and are the focus of current research.

CONCLUSION

As described in the Introduction, quantum theory poses deep challenges to the classical view of physical reality, and, by extension, to the mechanical world-view. At present, there is no consensus on how to meet those challenges, no consensus on how to revise the classical view of physical reality or the mechanical world-view which it spawned.

Nevertheless, as I hope I have conveyed in the preceding pages, many vital insights into the nature of quantum reality have been obtained, chief amongst them the nature of entanglement and non-locality, and the role of information in the quantum realm.

Methodologically, the recent upsurge of interest in the reconstruction of quantum theory has the potential for unifying the insights that have been obtained thus far, and lead to the discovery of the key physical ideas that underlie the quantum formalism. Such a distillation of the physical content of the quantum formalism into a small number of simple physical ideas has the potential to provide the basis for developing a coherent conception of physical reality that takes account of the full physical content of the quantum formalism. Such a conception is probably vital for the future development of physics.

---

[1] N. Bohr. Causality and complementarity. *Philosophy of Science*, 4:289–298, 1937.

[2] A. Pais. *Niels Bohr's Times.* OUP, 1991.

[3] Werner Heisenberg. *Physics and Beyond.* 1971. Translated from the German original.

[4] W. Pauli. *Writings on Physics and Philosophy.* Springer, 1994.

[5] J. S. Bell. On the Einstein Podolsky Rosen paradox. *Physics*, 1:195–200, 1964.

[6] J. A. Wheeler. It from bit. In *Proceedings of the 3rd International Symposium on the Foundations of Quantum Mechanics, Tokyo*, 1989.

[7] John A. Wheeler. Information, physics, quantum: The search for links. In W. H. Zurek, editor, *Complexity, Entropy, and the Physics of Information.* Addison-Wesley, 1990.

[8] W. H. Zurek and W. K. Wootters. A single quantum cannot be cloned. *Nature*, 299:802–803, 1982.

[9] W. K. Wootters. *The acquisition of information from quantum measurements*. PhD thesis, University of Texas at Austin, 1980.

[10] S. Popescu and D. Rohrlich. Causality and nonlocality as axioms for quantum mechanics. In *Causality and Locality in Modern Physics and Astronomy: Open Questions and Possible Solutions*, 1997.

[11] P. Goyal, K. H. Knuth, and J. Skilling. Origin of complex quantum amplitudes and feynman's rules. *Phys. Rev. A*, 81:022109, 2010. arXiv:0907.0909.

[12] Perhaps the singular exception was the threat posed by the assertion of the second law of thermodynamics that certain physical processes are *irreversible*, an assertion that conflicted with Newton's assertion in the fundamental reversibility of all dynamical processes. This remains a contentious point today, but has been overshadowed by the challenge posed by quantum theory.

[13] In fact, if a system is in a so-called pure state, a repeatable measurement only accesses *one half* of the degrees of freedom of the state.

[14] For example, a measurement of the magnetic moment of a silver atom will yield one of just *two* possible outcomes.