

WHAT IS QUANTUM THEORY TELLING US ABOUT HOW NATURE WORKS?

P. GOYAL

*Perimeter Institute for Theoretical Physics,
Waterloo, ON N2L 2Y5, Canada*

**E-mail: pgoyal@perimeterinstitute.ca
www.philipgoyal.org*

Quantum theory is an extraordinarily successful physical theory. But what does it mean? What implications does it have for the mechanical conception of Nature that underlies classical physics? Remarkably, some eighty years after the creation of quantum theory, we still lack clear answers to these questions. In this paper, we discuss the nature of the obstacles that stand in our way, and describe recent work to overcome them by attempting to *reconstruct* the mathematics of quantum theory from a small number of simple physical ideas.

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1. Introduction

Quantum theory is perhaps the most empirically successful theory in the history of physics. In the eighty or so years since its creation, it has provided us with precise mathematical models that account for a vast range of physical phenomena ranging from the principles of chemical bonding, the nuclear reactions that fuel the stars, exotic phenomena like superconductivity and superfluidity, and many others besides. In short, quantum theory has been the faithful companion of physicists for eighty years, and has consistently met the challenge of providing mathematical models of new physical phenomena.

Quantum theory also underlies much of the modern technology that fuels our lives. The transistor, the basis for the modern computer that underlies all information processing technology, requires quantum theory for its design and modelling. 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, for example), and many other

technologies. Yet more quantum technology (such as quantum computers and quantum cryptography) is waiting in the wings, promising to transform our lives still further.

The empirical successes of quantum theory leave little doubt that the mathematical rules of quantum theory—the *quantum formalism*—accurately capture fundamental features of the workings of the physical world. Since their formulation over 80 year ago, there have been very strong indications that these rules describe a physical reality that cannot be encompassed within the view of reality that underpins classical physics. However, the precise nature of the implications of the quantum formalism for our understanding of the material world remains obscure.

2. Classical Physics and the Nature of a Physical Theory

To understand better the nature of the problem and its importance, it is helpful to begin by considering classical physics. Underlying classical physics is a definite conception of the nature of reality, which traces back to the pioneering work of such figures as Descartes, Galileo, and Newton in the seventeenth century. The essential idea is 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 in precise accord with mathematical, deterministic laws of motion. And that, in principle, one can probe this matter as precisely as one wishes without disturbing its nature or its motion, and, through such probings, one can in principle discern the underlying laws of motion and thereby aspire to a theoretical model of physical reality that allows arbitrarily precise prediction of the behaviour of physical systems.

When mathematised in a fairly direct way, this conception leads to the *classical mathematical framework*, which forms the mathematical basis not only for Newtonian mechanics but for all of the theories of classical physics—chiefly electromagnetism (describing the phenomena of electricity and magnetism), thermodynamics and classical statistical mechanics (both describing the phenomena of heat and temperature)—that were built up during the two centuries after Newton.

Hence, classical physics has a clear bipartite structure: (i) a definite, clearly storable conception of reality (the mechanical view of material reality) that we are able to readily grasp without the aid of mathematics, and (ii) a mathematical framework which one can regard as a natural translation of this conception into the language of mathematics.

That classical physics has this bipartite structure has major consequences. Firstly, insofar as the development of classical physics is concerned, this bipartite structure imparted *flexibility*: if the mathematics in which Newton clothed the mechanical conception proved too restrictive, his intellectual descendants were able to refer back to the much broader mechanical conception for guidance on how to change the mathematics^a.

Second, this ‘clockwork universe’ view of the phenomenal world was also *readily graspable* by those who had no knowledge of the 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.

3. Quantum Physics

In contrast to classical physics, whereas quantum physics possesses a mathematical framework that can be used to model physical systems, it does *not* presently possess a clear conception of physical reality which, when suitably mathematised, leads to this mathematical framework. In order to understand how this situation arose, it is helpful to consider some history.

^aFundamental changes were indeed made on several occasions. First, whereas Newton believed that all that exists is atoms in motion (with necessarily finitely [or countably infinitely] many degrees of freedom), Faraday and Maxwell introduced the idea of dynamical *fields* with continuously many degrees of freedom. Second, whereas Newton believed that everything that exists changes in step with a universal time and moves on the fixed stage we call space, Einstein (in his theory of general relativity) introduced the view that spacetime is itself a dynamical entity. In spite of these developments, the essential features of the mechanical view of reality (such as the deterministic and reversible nature of change, and the in-principle complete accessibility of the state of a physical system by means of suitable measurements) remained largely stable during the course of the development of classical physics. Perhaps the singular exception was the threat posed by the assertion of the second law of thermodynamics that certain physical processes are irreversible, and assertion that conflicted with Newton’s assertion in the fundamental reversibility of all dynamical processes.

3.1. *Historical Development of Quantum Theory*

By the 1890s, classical physics was in a highly developed state. Newtonian mechanics precisely accounted for both the motion of bodies on the Earth and detailed astronomical observations of the orbits of the planets, moons, and comets; Maxwell's electromagnetism provided a comprehensive understanding of electric and magnetic phenomena (including a quantitative explanation of light phenomena), and thermodynamics provided a detailed understanding of the phenomena of heat and the process by which heat is converted into useful mechanical motion ('work'). However, there were some clouds on the horizon—curious experimental facts which stubbornly resisted explanation within the framework of these theories. 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 theory did not come into existence in a straightforward and principled manner. On the contrary, the path by which it came into being is a tortuous, which is difficult to adequately summarise. In essence, the creation of the quantum formalism was guided by heuristic ideas (such as de Broglie's idea 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. Remarkably, even though the conceptual basis was patchy, and did not amount to a coherent picture of reality, it was somehow enough (in the hands of Heisenberg and Schroedinger) to give rise to an empirically-valid mathematical formalism.

To illustrate the *ad hoc* nature of the building up of the quantum formalism, I shall give one example. One of the striking features of the quantum formalism is the assertion that, in contrast to the situation in classical physics, when a measurement is performed on a quantum system, the measurement outcome is not wholly determined by the state of the system. Rather, the *probability* of the outcome is determined by the state of the system, but which outcome will actually be obtained is essentially undetermined. That is, the measurement outcome that is obtained cannot be wholly be accounted for by reference to the state of the system immediately prior to the measurement. Now, given the importance of this feature, it is remarkable that, in the building up of the quantum formalism, there was no

real inkling that the formalism had to possess this probabilistic feature. In fact, when Schroedinger, one of the founders of the theory, wrote down his famous quantum mechanical equation for the electron, he believed that it could be interpreted as simply a new kind of classical field equation that is fully deterministic. It was only afterwards that it was realised that such an interpretation could not possibly stand, and that Schroedinger's equation had to be interpreted in a probabilistic manner^b.

The process, then, by which quantum theory came into being led to a situation where, by 1925–6, although a well-defined empirically-adequate mathematical framework had been constructed, the physical origin and meaning of many of its features was obscure.

3.2. Immediate Implications of the Quantum Formalism

Once the quantum formalism was created, many implications were quickly drawn from it which suggested that the world of quantum phenomena it described violated fundamental tenets of the classical mechanical conception of reality. For example, as previously mentioned, one of these classical tenets is that it is possible, in principle, to perform a measurement on a system that reveals everything about its physical state without causing any disturbance to the system. In contrast, the quantum formalism implied that this is not the case—a measurement can, in principle, only give partial information about the state of a system, and necessarily causes disturbance to the system. Moreover, as already mentioned above, whereas the mechanical conception implies that all measurement outcomes are determined by the state of the system, the quantum formalism implied that measurement outcomes are *not* wholly determined by the state of the system, but have an inherently indeterminate element. These implications seemed to radically undermine key tenets of the mechanical view of classical physics.

Many of the founders of quantum theory, such as Bohr, Heisenberg and Pauli, believed that the above-mentioned implications of the formalism had to be taken seriously, and that the classical mechanical view needed 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 concepts in the existing philosophical literature or to

^bMore precisely, in Schroedinger's equation, the wavefunction $\psi(\mathbf{r}, t)$, was initially interpreted by Schroedinger to be a field much like the fields of classical physics. Later, it was realised, principally by Born, that this interpretation could not stand, and that $\psi(\mathbf{r}, t)$ actually encoded the probability that a measurement of position would yield a particular result.

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 had 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 From his point of view, the impossibility in quantum theory of performing a measurement that provides complete knowledge about a physics 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 the well-known double slit experiment.^{3,4}

3.3. Development of New Conception of Nature

The ideas explored and developed by Bohr, Heisenberg, Pauli and others were important first steps in developing a new, non-mechanical conception of reality to underpin quantum theory. However, after their pioneering efforts, the development of a non-mechanical conception along the lines they envisaged was not continued in any kind of sustained way by the mainstream physics community.

As a result, today, more than 80 years after quantum theory was created, physicists possess a well-defined mathematical formalism in which (following its successful application to a vast number of physical systems) they have an enormous confidence, but lack a clear underpinning conception of reality with which to make sense of it.

The lack of such an underpinning conception impacts the development of physics in several ways. First, if one wishes to discover new quantum phenomena or to harness quantum physics in new technology, then, given the counter-intuitive nature of its predictions, one needs some guidance as to what interesting and useful quantum phenomena might follow from the quantum formalism. A clear conception of an underlying reality has the potential to provide such guidance; conversely, the lack of such a conception impedes the rate at which new phenomena are discovered and the rate at

which quantum physics is harnessed.

Second, when attempting to apply the quantum formalism to new physical domains, a clear conception of reality becomes especially important to guide one's intuition. For example, an outstanding problem in theoretical physics is the construction of a theory of quantum gravity—a theory that somehow unites the insights of quantum theory and general relativity, the two great pillars of modern physics. In carrying out such a project, it is important to know what assumptions about the physical world lie implicit in the quantum formalism. For example, is the formalism implicitly dependent upon the structure of spacetime? If so, what is the nature of that dependency? More broadly, how does the quantum formalism depend upon the fundamental concepts of classical physics such as matter, energy, momentum, and locality? At present, since we do not have a clear conception of reality that underpins the quantum formalism, we do not know what features of the physical world the quantum formalism depends upon. So, we do not have clear answers to any of these questions.

More broadly, from an interdisciplinary standpoint, the lack of a clear conception of reality underpinning the quantum formalism means that the core essence of quantum theory (whatever that may be) cannot properly disseminate to other areas of science and, more broadly, into other areas of academia and, beyond that, into the general intellectual discourse of society.

3.4. *Deciphering Quantum Theory*

Historically, various attempts have been made to decipher the physical content of quantum theory. The primary methods of doing so which have borne fruit have been to interpret it (often by first reformulating the quantum formalism in some way) or to prove that it possesses particular physical features.

As an example of the latter, it has been shown that quantum theory possesses such non-classical features as non-locality,⁵ contextuality,⁶ and no-cloning,⁷ each of which strongly suggests that quantum physics is at odds with the mechanical view in fundamental ways. For example, non-locality is the feature that implies that, if a pair of quantum systems are 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 on any so-called 'local hidden variable model' of the supposed underlying reality. In short, one is driven to the idea that there is in fact *some kind of connection* between physical systems that have interacted in the past which endures irrespec-

tive of their distance and which enforces subtle but very real correlations between them. If so, 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. If true, non-locality fundamentally alters the status of space, and with it another key element of the mechanical view: space is no longer the entity which mediates all interactions between material bodies; instead, there are also an ever-changing web of connection between systems that are inherently non-spatial.

Although these methods have yielded important insights, their principal limitation lies in the fact that they take the quantum formalism as a *given*. Recall that, in classical physics, we possess a clear conception of reality which, when mathematised in a natural way, yields the mathematical framework of classical physics. However, the quantum formalism has a great deal of mathematical structure which is not present in the mathematical framework that underlies classical physics. For example, states of systems are represented by complex vectors that live in a complex vector space, and temporal evolution of states are represented by unitary transformations of these vectors. Presumably, there are *physical* reasons why this is so, but what are these reasons? By themselves, the above-mentioned efforts to decipher quantum theory do not answer this question.

3.4.1. *Reconstructing Quantum Theory*

In the last three decades, there has been a growing realisation that, if we are to make significant further progress, we must try to discover what *physical* ideas are implicit in the quantum formalism. That is, rather than taking the formalism as a given, we ought to try to formulate a set of simple physical principles from which the quantum formalism can be derived. Such a *reconstruction* of the quantum formalism would essentially distill the *physical content* of the quantum formalism into a set of clear 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.

Over the last thirty years, significant efforts have been made to reconstruct quantum theory (see Ref. [8] for details). As a result, we are in the extraordinary situation where there now exist many detailed proposed reconstructions of quantum theory based on a wide variety of different starting points. However, thus far, none of the existing reconstructions has been able to obtain the quantum formalism in its standard form without making

abstract mathematical assumptions of key importance.

4. Quantum Theory from Complementarity

In Ref. [9], I have recently shown how it is possible to reconstruct the core of the quantum formalism, namely Feynman's rules of quantum theory, directly from a single postulate:

Pair Postulate: each sequence of measurement outcomes obtained in a given experiment is represented by a *pair* of real numbers, and the probability associated with this sequence (which is all that one can learn about in the experiment) is a continuous, non-trivial function of both components of this real number pair.

By making use of elementary symmetry and consistency conditions, and without assuming that these real number pairs have any other algebraic structure, one finds that these pairs must be manipulated according to the rules of complex arithmetic. Furthermore, one finds that these complex numbers combine according to Feynman's sum and product rules, with the modulus-squared yielding the probability of a sequence of outcomes. The reader is referred to Refs. [9,10] for details.

The pair postulate, which is at the heart of the approach, expresses the simple idea that a measurement performed on a physical system is only able to yield information about *one-half* of the degrees of freedom of the system. This is a simple formalisation of the principle of *complementarity* originated by Bohr.¹

In classical mechanics, one assumes that one can simultaneously attribute exact values of position and velocity to a particle. However, the postulates of quantum theory imply that one can attribute either an exact value of position, or of velocity, but not both simultaneously. In order to understand this quantum restriction on a fundamental classical notion, Bohr developed the Principle of Complementarity.¹¹ According to this principle, any description of a physical phenomenon is indissolubly bound up with a particular experimental arrangement, and such an arrangement provides information about certain aspects of the phenomenon to the exclusion of other aspects that, in classical thinking, are equally necessary for a complete description of the phenomenon. This principle, which was partly inspired by the dialectical aspect of Kierkegaard's philosophical thought,² served to underpin the quantum restriction by treating it as a special case of a general philosophical principle, namely that our apprehension of reality involves bringing particular aspects of reality into consciousness by choosing to at-

tend to reality in a particular way and, in so doing, providing a perspective on reality to us that is inescapably incomplete.

By way of exploring the generality of the principle, Bohr and others pointed to analogous phenomena in the mental and organic realms. For example, Pauli developed an analogy between physical complementarity and the relationship of the unconscious and conscious aspects of mental experience:

On the one hand, modern psychology demonstrates a largely objective reality of the unconscious psyche; on the other hand, every bringing into consciousness, i.e. observation, constitutes an interference with the unconscious contents that is in principle uncontrollable; this limits the objective character of the reality of the unconscious and invests reality with a certain subjectivity.⁴

Bohr regarded complementarity as one of the most fundamental lessons of quantum phenomena for our physical world-view.^{1,11,12} What we have shown is that it is possible to construct a route that leads directly from the fundamental concept of complementarity to the formal structure of quantum theory (in the form of Feynman's rules).

5. Implications for a Conception of Nature

The above reconstruction makes two key assumptions. First, the operational assumption of indeterminacy, namely that measurements are probabilistic in nature. Second, the physical assumption that complementarity holds true, namely that, in a given experiment, one can only access one half of the degrees of freedom needed to theoretically describe a system. Both of these assumptions are at odds with fundamental assumptions in the mechanical view of classical physics, namely determinacy (a measurement outcome is determined by the state of the system) and transparency (in principle, there exists a measurement which is capable of accessing all of the degrees of freedom of the state of a system).

If we accept indeterminacy and complementarity as a given, what conception of nature do they suggest? What are they telling us about how Nature works? A reconstruction of quantum theory, as the one sketched above, is an important stepping-stone to a new conception of Nature in that it focusses our attention on just a small number of non-classical features. But it is still only a stepping-stone. So, how does one proceed?

One of the important jobs of a conception 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 of indeterminacy *and* complementarity, and not just one or the other.

We would also like to understand indeterminacy and complementarity in themselves. For example, it is one thing to accept that measurement outcomes 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?

Currently, all of these questions remain unanswered, and some are the focus of current research. More broadly, it is still an open question whether one actually needs a new conception of nature in order to understand the indeterminacy and complementarity, or whether these can still be underpinned by a classical mechanical conception of reality.

My personal view is that the most fruitful way forward is the one which Bohr and Pauli long ago asserted, namely to accept complementarity and indeterminacy as fundamental features of reality, and to attempt to evolve our understanding so as to grasp their nature. That there is a deep psychological resistance to such ideas amongst physicists is clear—it could hardly be otherwise if one has grown up with classical physics and has had the mechanical conception of reality repeatedly reflected back to oneself within the attitudes and culture of the society in which one has grown up. However, there exist many philosophical resources that may be able to help us loosen the grip of these cultural conditionings, such as Whitehead's process philosophy.¹³ Several physicists, such as Bohm¹⁴ and Wheeler¹⁵ have, in recent time, attempted to develop novel conceptions of reality which take some of the non-classical features of quantum theory as fundamental.

The view of reality which one can dimly make out is one which is fundamentally *participatory*: agents have some irreducible freedom to choose what questions to ask of Nature through their measurements (the non-triviality of this choice been assured by complementarity), and Nature responds with an answer which is only partly determined by variables under experimental control. The answer in turn brings into a state of definiteness some aspect of reality at the expense of some other feature, which is rendered into a state of indefiniteness. Hence, the temporal trajectory of

reality is bound up inextricably with the choices that we make. In this conception, what exists is not in a state of complete definiteness, but is rather somewhere along a spectrum between complete definiteness and complete indefiniteness. As Heisenberg pointed out some time ago,³ there seems to be close connection here with Aristotle's concepts of potentiality and actuality, which he developed in response to Parmenides paradox of change.¹⁶

One startling feature of the above reconstruction is that no mention is made of space or its properties. This stands in sharp contrast to the manner in which the quantum formalism was obtained by Schroedinger and Heisenberg, where the classical notion of space was presumed at the outset. That is, the above reconstruction strongly supports the view that the quantum formalism is *independent* of space and its properties; that is, it is intrinsically *non-spatial*. This suggests that the classical mechanical view that what exists fundamentally is matter *in space* is incorrect, and that what exists is, in fact, *not necessarily tied to space*. This point of view is already suggested by the existence of Bell non-locality; the above reconstruction provides even clearer support of this view. This insight is of particular relevance to the programme of quantum gravity, and suggests that a theory should be sought in which spacetime is emergent rather than being posited at the outset.

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