Eight Oxford Questions: Quantum Mechanics Under a New Light

N. Ares [1]

A. N. Pearson [1]

G. A. D. Briggs [1]

Email andrew.briggs@materials.ox.ac.uk

[1] Department of Materials, University of Oxford, Oxford, OX1 3PH, UK

Abstract

Conceptual and experimental advances are opening up possibilities for addressing new questions in quantum theory. What is changing is the potential for relating conceptual and theoretical developments to foreseeable experimental tests. It is becoming feasible to rule out certain interpretations, maybe even to look for new ones, as well as addressing the various open questions in quantum mechanics, such as the role of gravity. We set out eight questions as a manifesto for future study and research.

Keywords

Quantum
Foundations
Collapse
Macroscopic

1. Background

Apart from violations of inequalities of the type of Bell's, which have been implemented to stunning precision [1, 2, 3, 4, 5, 6, 7, 8, 9], until recently it was, for the most part, doubted that experiments could ever discriminate between different variants and interpretations of quantum theory (QT). However, we now believe that avenues for such experimental tests are opening up. The steady improvement of experimental techniques [10, 11] for manipulating quantum systems might even allow us now to explore the post-quantum territory.

Fundamentally different theories of quantum reality, such as Everettian QT [12, 13], collapse-variants of QT [14, 15, 16, 17, 18], the pilot-wave theory [19, 20, 21] and Quantum Bayesianism [22], disagree on crucial issues like locality, reversibility, universality, completeness and determinism. For each variant there are different interpretations for entities appearing in the theory—for instance, concerning the reality of the wave function (which motivated the so-called ontological models framework [23]). It might be argued that since the empirically accessible part of quantum theory is the same for different interpretations/variants of QT, we should not worry about the above differences, but the key point is that differences may become testable in the near future.

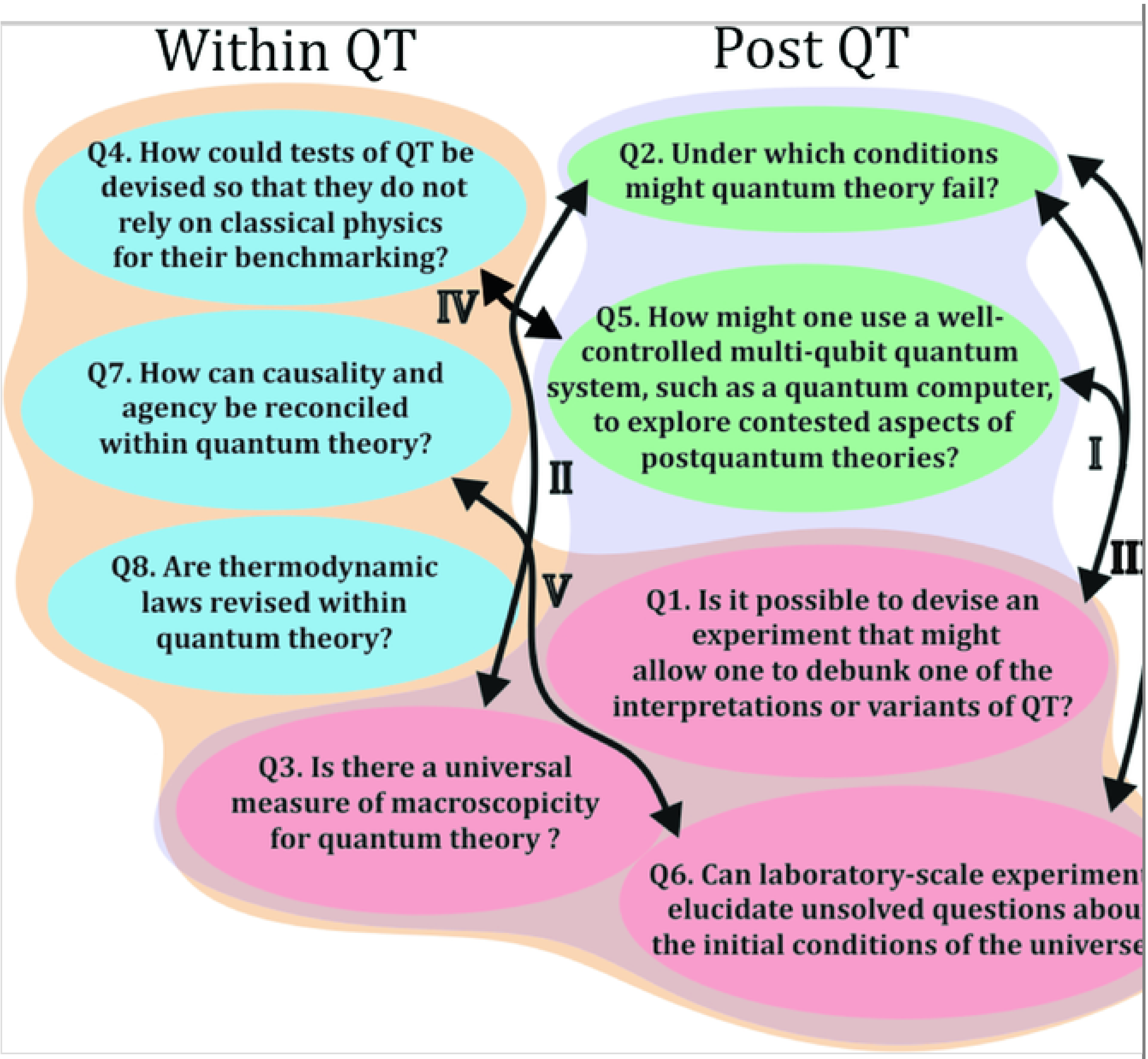
Looking for post quantum theories, a good place to start would be where gravitational effects are important. The problem of integrating general relativity (GR) with QT remains open. Loop quantum gravity [24] and string theory [25] are the two pre-eminent approaches that have been taken to studying such issues. GR and QT—the best available fundamental theories in their own domains of applicability—clash with one another at the fundamental level. Different quantum physical realities, even if empirically equivalent, may suggest different ways of going about reconciling QT with GR, of searching for the successor of QT, and of designing new experiments for QT. For example, a local, deterministic theory might be easier to reconcile with GR than a non-local, stochastic one.

To help make progress with such deep, long-unsolved problems, it is useful to find some specific key questions which could be addressed in the shorter term, rather than simply revisiting a familiar cycle of arguments which have now been around for decades. Fresh pieces of evidence are of the essence. We therefore ask where one should look for that evidence, and what kinds of new experimental (and theoretical) tools are needed to look for it? Although the realisation of experiments that would shine light on some of the long-standing problems will be challenging, the mere exercise of trying to pose the appropriate questions stimulates the intellectual environment and may hopefully create a fertile territory for scientific breakthroughs. This was the fundamental motivation for the questions which follow, which we have collected during a conference on Experimental Tests of Quantum Reality. This conference followed a conference on Quantum Physics and the Nature of Reality that led to *The Oxford Questions on the foundations of quantum physics* [26].

These new questions aim for a productive interplay between theory and experiment. Our questions reinforce the conviction that experimental tests are of the essence in discerning which foundational theories to accept and which to reject. We expect that the interplay between experimental and theoretical tools will in turn lead to the development of new ideas. The questions are charted in Fig. 1. The questions pertain to two territories: one, within QT and the other, post-QT, and some overlap between them.

Fig. 1

The questions relate to two territories: within QT and post QT, with questions 1, 3 and 6 having bearings both within and post QT. Arrows indicate links between questions. (I) highlights the link between certain interpretations of QT being disproved and a more radical failure of quantum theory. It also links these questions with the possibility of advancement of our understanding enabled by the use of quantum technologies to look beyond our current formulation of QT. (II) brings out the question whether at a certain level of macroscopicity QT will fail and give way to classical physics. (III) shows that experiments on the early conditions of the universe might point to a breakdown of QT. (IV) links questions 4 and 5: the development of a quantum computer will allow for new tests of QT looking beyond the benchmark of classical physics. (V) draws on questions that are raised about the initial conditions of the universe, specifically with regards to measurement, when considering causality and agency



2. The Questions

1. **Is it possible to devise an experiment that might allow one to falsify one of the interpretations or variants of QT?**

The quantum realities described by the variants of QT show profound differences from one another. For example, **Everettian quantum theory (EQT)** is universal [13], *deterministic* and *reversible*, and non-probabilistic, in that it does not have the Born Rule axiom. Moreover, the theory is deemed to be *local* by some [27], and non-local by others [28].

Collapse variants of QT (CQT) are stochastic and prescribe that there be an *irreversible evolution of the wave function* (the *collapse*), whenever a measurement is completed. EQT implies the existence of the Multiverse, where the probabilistic predictions of the Born Rule are recovered via the decisiontheoretic approach to probability [13, 29] (there is an ongoing debate in regard to that approach, see e.g. Ref. [30] for a critique). According to CQT, there is instead a single, irreversibly (although this is challenged in Ref. [31]) and stochastically evolving universe.

Bohmian mechanics is deterministic, non-local and avails itself of an additional equation of motion [32] but it is limited in that it has not fully been extended to relativistic quantum field theories of the Standard Model.

Other relational interpretations of QT such as **QBism** [33] and **Contexts, Systems and Modalities** [34, 35] redefine what is meant by/how one assigns probabilities and how physical properties are attributed to a system. For an overview of how these different interpretations compare to each other see Table 1. We have not included interpretations which may be from distinguished thinkers in the field but which have not been widely taken up by others, such as cellular automata and superdeterminism [36, 37].

Table 1

An overview and comparison of the variants of QT mentioned in the text

Everettian quantum theory	**Universal, deterministic and reversible. Debateable whether local [27] or non-local [41]** **The wave function is ontic**	**Everett [12] and Wallace [13]**
Measurement collapse variants of quantum theory	Non-universal, stochastic, irreversible, non-local and violates energy conservation The wave function is epistemic	Ghirardi et al. [14, 15, 16] and Bassi [17, 18]
Dynamical collapse variants of quantum theory	Universal, stochastic, irreversible, non-local and violates energy conservation The wave function is ontic	Ghirardi et al. [14, 15, 16] and Bassi [17, 18]
Pilot Wave Mechanics	Universal, deterministic, reversible and non-local It is proposed that the wave function is ontic, either (quasi) material or nomological	Dürr [19], Bricmont [20], Norsen [21], Dürr et al. [42]
QBism	Piece-wise universal (there's nothing, from one's own perspective, with the exception of one's own experiences which QT does not apply to) and local The wave function is doxastic	Fuchs et al. [33]

Despite being so remarkably different, it is usually thought that these interpretations cannot be told apart by means of experimental tests. However, new technologies might unlock the potential to do so. A thought experiment, originally suggested by Deutsch [38], can discriminate collapse variants (CQT) from Everettian quantum theory (EQT). While EQT prescribes a universal reversible unitary evolution, CQT requires an irreversible change in the descriptor of the physical state, i.e. the wave function collapse. This leads to empirically testable different predictions, **provided an observer can undergo a coherent unitary evolution**. We can distinguish between the question whether this is conceptually self-consistent, and the question whether in practice a wave function for such an observer could be determined. Similar considerations apply to QBism in so far as it depends on assumptions about the observer, such as whether a belief requires consciousness. Since there is even less consensus about consciousness than about interpretations of quantum theory [39, 40], we shall not follow that path.

Deutsch's thought experiment can be described schematically as follows: a spin ½ particle is prepared in an eigenstate $|\uparrow\rangle$ of, say, the *z*-component of the spin. This is an equally weighted superposition of the eigenstates $|0\rangle$ and $|1\rangle$ of the *x*-component of the spin, X. An automaton is then coupled with the particle **so that in the EQT interpretation it would undergo a unitary evolution that corresponds to its measuring the observable X**. The automaton is programmed so that once the measurement is complete, it writes on a piece of paper that the measurement is indeed complete and that it sees a definite outcome, *without writing down which value it sees*. According to CQT, the particle and the automaton's register by this point have undergone an irreversible collapse, ending up in either the pure state $|00\rangle$ or the pure state $|11\rangle$, with probability ½ each. In the case of EQT, the composite system of the automaton and the spin is now in an equally weighted superposition of $|00\rangle$ and $|11\rangle$: the spin and the automaton are entangled. Then one applies the time-reversal of the unitary transformation that implemented the reversible measurement of the automaton on the spin—acting on the spin and the automaton's register only, but *not* on the piece of paper; finally, the *z*-component of the spin is measured. In the case of CQT, the prediction is that the outcome 'up' or 'down' is observed, each one with probability ½. According to EQT, since the above was an interference experiment, the outcome will be invariably $|\uparrow\rangle$. The fundamental irreversibility of CQT therefore makes the difference, and this difference can be empirically tested in this scenario.

This experiment touches on several of the problems mentioned below—chiefly, **macroscopicity** (see Q3) and **the role of the observer**. Implementing such an experiment might require technology beyond current capabilities; but understanding what technologies would be needed, and which kinds of approximations to that experiment could be currently conceived is a productive line of enquiry. Tests of CQT are discussed in more detail in Q2.

Another interesting line of experimental tests are **non-local hidden variable ‘super-deterministic’ theories**, as proposed by Hossenfelder [43]. She proposes searching for evidence for correlations generated by non-local hidden variables via a time-resolved single-photon double-slit experiment and a Stern-Gerlach type experiment in a spatial loop, at low temperature and with minimal sources of noise. This should probe regimes where the corrections to quantum theory predicted by those hidden-variable models become relevant.

Concerning **the reality of the wave function**, the problem is whether the quantum wave function encodes our knowledge of a quantum system (the so-called ‘psi-epistemic’ view), or whether it describes something objective about reality, irrespective of us (the ‘psi-ontic’ view). New, general no-go theorems provide the theoretical inspiration for experimentally testing the difference between ontic and epistemic views of the wave function: the Pusey-Barrett-Rudolph (PBR) [44] theorem, further advanced in the Barrett-Cavalcanti-Lal-Maroney (BCLM) [45], and Branciard theorems [46]. **These theorems have started to be tested experimentally with the results all favouring the psi-ontic view** [47, 48, 49, 50]. In addition, recent experimental work by S. Simmons and co-authors (private communication) ruled out ‘maximally psi-epistemic’ models using a single electron-nuclear two-spin system in isotopically purified silicon, achieving the low degree of errors required by the BCLM test. For an overview of testable theorems and their experimental status see Table 2.

Table 2

Theorems used to test aspects of QT, with their underlying postulates and experiments performed to date

Theorem	Postulates	Experimental status
Bell	Correlations are **locally explicable** and no causal influence can travel faster than light [51][a]	The inequality has been violated [1, 2, 3, 4, 5]

[a] In Bell’s original 1964 treatment [51] the existence and determinism of underlying hidden variables was derived from the conjunction of locality with the existence of perfect (anti-)correlations for parallel measurements on a singlet state. In later discussions (e.g. 1976, 1981, 1990 [175]) he relaxed the perfect correlations assumption, whilst retaining the idea that correlations ought to be explicable, even if only probabilistically

Theorem	Postulates	Experimental status
Leggett-Garg (Bell type inequality for time)	**Macrorealism per se**—A macroscopic object, which has available to it two or more macroscopically distinct states, is at any given time in a definite one of those states **Noninvasive measurability**—It is possible in principle to determine which of these states the system is in without any effect on the state itself, or on the subsequent system dynamics [52]	The inequality has been violated in microscopic systems leading to the conclusion that “All accurate descriptions of systems of this type must include a concept similar to that of quantum superposition, and/or an exotic notion of measurement similar to that of wavefunction collapse” [7, 8, 9] **but tests using a macroscopic system have yet to be carried out**. It should be noted that this conclusion has been debated philosophically [53]
Bell-Kochen-Specker	No non-contextual hidden variable theorem (i.e. one in which the values of the physical observables are the same whatever the experimental context in which they appear) can reproduce the predictions of quantum theory [54, 55]	The inequality has been violated in microscopic systems showing that the observed phenomena cannot be described by non-contextual models [56, 57]. In addition it has been shown experimentally that there is a monogamy relation between the violation of either a Bell inequality or a Bell-Kochen-Specker inequality [58]
PBR/BCLM/Branciard	The quantum state is not purely epistemic (informational) [44, 45, 46]	Bounds have been put on maximally psi-epistemic models but further tests are needed to rule out partially psi-epistemic models [47, 48, 49, 50]

[a] In Bell’s original 1964 treatment [51] the existence and determinism of underlying hidden variables was derived from the conjunction of locality with the existence of perfect (anti-)correlations for parallel measurements on a singlet state. In later discussions (e.g. 1976, 1981, 1990 [175]) he relaxed the perfect correlations assumption, whilst retaining the idea that correlations ought to be explicable, even if only probabilistically

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2. Under which conditions might quantum theory fail?

The **continuous spontaneous localisation (CSL)** model [14, 15, 16] is one of many theoretical efforts to explain wave function collapse [17, 18]. In this model, the wave function collapses spontaneously, and *the collapse rate is* *proportional to the mass*, hence certain superposition states of macroscopic objects (e.g. involving a localised mass being in a superposition of significantly different positions) are very difficult to observe.

In order to distinguish the effects of CSL from decoherence stimulated by interactions with the environment, a system in which noise induced by the environment is minimised is required. Potential phenomena due to CSL include:

1. ***the decoherence of a superposition state*** [59, 60, 61],
2. ***the linewidth broadening*** [62] ***and heating of a mechanical oscillator (i.e. a violation of energy conservation due to the collapse of the wave function)*** [63, 64, 65],
3. ***diffusion in free space*** [66, 67].

It might be that the most practical way to test for CSL is to look for thermally induced delocalisation due to the collapse process. A detailed analysis has been evaluated for an experiment to detect the heating due to CSL of a trapped nanosphere [68] and also of a charged macroscopic object in an ion trap [69]. Of all the possible causes of unwanted decoherence, the dominant ones are likely to be mechanical and electrical noise and molecular collisions. The calculations suggest that although the practical demands exceed what has already been achieved, the experiment should be within reach. Using a high quality factor cantilever, a nonthermal force noise of unknown origin which could be due to the CSL heating rate predicted by Adler has been recently detected [65].

Trying to create macroscopic quantum superpositions is another way of testing the ground where quantum mechanics might fail. See Q3 for a discussion on macroscopicity.

To perform *laboratory-scale* experiments of QT where gravity would be important, the challenge is to engineer quantum states of mechanical systems in which gravitational effects must be taken into account to describe the dynamics [70]. In such scenarios, QM may need to be modified in a yet unknown way in order to account for gravitational effects such as decoherence and gravitational self-interaction [71, 72, 73, 74], or on the other hand the gravitational force may be quantum coherent [75, 76].

In a quantum theory of gravity, quantum fluctuations in the underlying field that mediates the gravitational interaction between matter degrees of freedom may appear as an additional source of noise [77]. Such effects might be thought to be restricted to the Planck scale and thus seem unlikely to arise in table-top experiments. Surprisingly, proposals of Penrose [72] and Diosi [73], and later by Kafri et al. [78], amongst others [79, 80, 81, 82], would indicate that this is not the case and that, given sufficient quantum control over macroscopic mechanical degrees of freedom, gravitational decoherence might be revealed. Like CSL, the most accessible way to test for gravitational decoherence might be through sensitive detection of heating effects. Optomechanical systems might be a good platform for this goal, enabling us to measure minuscule heating rates [83].

3. **Is there a universal measure of macroscopicity for quantum theory?**

Leggett used the term ‘macroscopic’ to—amongst other things—articulate how, in our ‘us-sized’ lives, we experience events and outcomes that are definite and predictable in a way that seems quite different from the mystery of quantum superposition [84]. ***He questioned whether (whereas Bohr assumed) there was some different kind of reality at the macroscopic level from that which is found at the quantum level***, and he sought to devise a rigorous test of this proposition in the form of experimentally measureable inequalities. What his inequalities actually put under test is, however, still under debate [53].

There could be many dimensions of *macroscopicity*. Does it lie in a greater number of atoms or photons, in a greater mass or spatial size, in greater complexity (if so how should this be quantified?), or in a greater number of dimensions in Hilbert space? Does it perhaps lie at the threshold where life begins [85]? Another quantifiable possibility may be that it depends on limits to the linearity of the system. ***If so, can we quantify the degree of non-linearity of dynamical evolution that would be required to prevent macroscopic superpositions or entanglement occurring, and can we characterise the kinds of contexts in which this limit would arise*** [86]? Are they for example related to the issue of thermalisation and heat baths that interact with quantum systems [87]? Each of these dimensions of macroscopicity needs to be explored in order to extend the tests of macroscopic realism.

The task of defining macroscopicity measures within quantum theory is confounded by a fundamental problem of an ad hoc selection of distinguishable observables. As Nimmrichter and Hornberger put it, ‘the more macroscopic [something is] the better its experimental demonstration allows one to rule out even a minimal modification of quantum mechanics, which would predict a failure of the superposition principle on the macroscale’ [88]. As that paper showed, the question of macroscopicity applies as much to collapse theories as to Leggett-type inequalities.

The issue of whether a *universal* measure of macroscopicity exists is central to our understanding of quantum reality. On the one hand, wave function collapse variants of quantum mechanics ***require there to be a limit to the domain of applicability of reversible unitary quantum theory, whence the necessity of specifying, quantitatively, where this limit exactly is***. On the other hand, if there is not such a fundamental limit to quantum coherence, a universal measure of macroscopicity would still be highly desirable in order to monitor technological progress, and compare results of different experiments. Indeed, the question of how far can we demonstrate quantum behaviour it is not only at the heart of foundations of QT but it is crucial for the development of new technologies. It has also big implications on how we understand complex systems and even life; for example, can macroscopic living entities make use of quantum coherence? The importance of quantum effects in biological processes has been highlighted for olfaction [89], magneto-reception in the avian compass [90] and photosynthesis [91, 92].

Finally, even if there is no universal measure of macroscopicity (see Ref. [93] for an outline of 14 different measures of macroscopicity), it is fruitful to ***search for measures of how hard it is to maintain a physical system in a given superposition or to implement a unitary gate to arbitrarily high degree of accuracy***—whence the modified question of what particular measures of macroscopicity might arise from operational/experimental considerations.

Theoretical proposals for creating superpositions of macroscopically distinct states include capacitively coupling a resonator to a superconducting qubit [94], flux coupling a nanotube to a superconducting qubit [95] and using an interferometer to optomechanically couple a mirror to a photon in a superposition [61, 96, 97]. On the experimental front, although yet to be fully realised, much progress has been made toward the goal of creating a superposition state in a micromechanical resonator coupled to a superconducting qubit [98, 99]. In millimetre sized [100, 101] resonators, the ground state has been reached, which is the first step towards creating a quantum superposition. Interference experiments have been carried out with molecules of up to 1×10^4 atomic mass units [102] and entanglement has been demonstrated between a single photon and a single collective atomic excitation in a 1 cm long crystal [103], as well as between two mechanical resonators [104, 105].

4. **How could tests of QT be devised so that they do not rely on classical physics for their benchmarking?**

Most tests involving QT over the past decades have been designed to corroborate the idea that QT largely violates our classical expectations. Indeed, QT's predictions have been tested against rival theories **sharing the common feature of** ***keeping one or the other basic principle of the classical physics intact***:

1. hidden-variable models involved in Bell-type experiments assign definite values to outcomes of unperformed measurements;
2. non-linear Schrödinger equations allow solutions with localised wave-packets to resemble classical trajectories;
3. collapse-type models restore macrorealism by suppressing superpositions between macroscopically distinct states.

While of great importance in the problem-situation of demonstrating fundamental differences between quantum mechanics and the classical world-view, such approaches to testing quantum reality may not be very fruitful when considering *different problems* that are now coming to the fore. A particularly prominent example of problems calling for experiments with a different benchmark than classical physics is the search for the successor of quantum theory: for a 'post-quantum' theory may be expected to break not only principles of classical but also of quantum physics. This is a case where interplay between experiment and theory promises to be particularly fruitful. There have indeed been a number of proposals for theoretical frameworks for thinking of viable post-quantum theories, against which QT could then be tested. These frameworks could thus be the source of such new tests.

One logic, suggested by Dakic and Bruckner [106], is to reconstruct QT from a set of axioms (see, e.g., Hardy [107]; Clifton et al. [108]; Chiribella et al. [109]), and then weaken or drop some of the axioms to get broader theoretical structures, whereby we can conceive of QT's generalisations. This has led to **generalised probabilistic theories** [110]—generalisations of quantum theory, which permit phenomena such as interference, randomness of individual results or violation of Bell's inequalities, but in more extreme ways than quantum theory does.

Another approach is to define a set of theoretical possibilities designed so that they share with quantum theory (some of) its main features (and reproduce its testable predictions). For example, when the features are chosen to be quantum theory's information-theoretic properties, a *local*, *non-probabilistic framework* for generalisations of quantum theory can be accommodated in the recently-proposed **constructor-theory of information** [111, 112]. Other general frameworks that could provide tools to devise rivals against which to test QT are ontological models frameworks [23].

Quantum simulators, annealers and computers provide a playground for testing QT without relying in classical physics (see Q5).

5. **How might one use a well-controlled multi-qubit quantum system, such as a quantum computer, to explore contested aspects of postquantum theories?**

In his Nobel lecture, Robert B. Laughlin starts by saying that to deduce phenomena such as superfluidity from first principles is an impossible task; superfluidity, he says, is an emergent phenomenon, a low energy collective effect of huge number of particles that cannot be deduced from the microscopic equations of motion in a rigorous way and that disappears completely when the system is taken apart [113].

Could it be that new questions and new answers arise from **emergent phenomena in multi-qubit quantum systems** like quantum annealers, simulators, computers or different types of quantum networks? Can these systems help us to explore and formulate postquantum theories [114, 115, 116]? In the same way we use classical computers to calculate quantum (post-classical) predictions, could we use a quantum computer to calculate postquantum predictions?

Large quantum networks provide an appealing route to a scalable universal quantum computer, which is built by networking together several simple processor nodes (as opposed to a monolithic structure) [117]. Other applications are made possible via the network directly. One is so-called **blind quantum computation** [118], where a remote person can control a quantum computer which is run and maintained by another person, who nevertheless cannot know what particular computational task the computer is performing. This is crucial to preserve the privacy of a computation.

Other applications arise for quantum networks with some amount of computation at each node (as implementable by, e.g., the ion trap architecture being pursued at Oxford [119]). For instance, cryptographic applications beyond quantum key distribution; verifiable quantum computation (which allows a user to verify the results of a quantum computation with certainty) [120]; quantum homomorphic encryption (a form of encryption which allows operations to be performed on the encrypted data without access to the secret key) [121]; a quantum internet [122] which can distribute quantum software [123]; and even long baseline astronomy [124].

Large scale quantum computers—not necessarily universal ones—open up a new frontier because they are systems with large amounts of entanglement. In particular, when the internal entanglement of a system becomes sufficiently high, our ability to simulate the system with anything other than a quantum computer falls away, due to the apparent difference between the computational complexity classes P and BQP [125]. Experimentally demonstrating quantum algorithms which show a large advantage over the best classical algorithms (particularly in terms of provable advantages such as in the case of query complexity for search and collision algorithms) would provide further insights into a proof of clear separation between computation allowed by quantum physics and computations achievable by a classical computation model. Another notable phenomenon is the breakdown of thermalisation for open systems. Although we expect systems in a confined volume in contact with a heat bath eventually to reach a Gibbs distribution, it is known that the ground states of certain classes of local Hamiltonian are QMA hard to compute [126]; they cannot efficiently be reached by physical systems. Thus, existing conjectures about computational complexity [127] would imply the possibility of constructing systems which cannot thermalize in less than exponential time. This may bring about an important transition in our understanding of chemistry and condensed matter physics, implying that absolute energy structure is less important for understanding the behaviour of large quantum systems and materials.

Quantum machine learning might be another promising tool. In addition to quantum machine learning showing quadratic improvements in learning efficiency and exponential improvements in performance over limited time periods over classical machine learning [128] it is hoped that a quantum artificial intelligence may be able to recognize patterns that are difficult to recognize classically [129]. This could be a powerful tool for research into post-quantum theories.

6. Can laboratory-scale experiments elucidate open questions in the evolution of the universe?

About 400,000 years after the Big Bang, the *last scattering* occurred; photons decoupled from matter and travelled freely through the universe, constituting what we observe today as cosmic microwave background radiation. There is no good theory for how the quantum fluctuations arising during inflation get changed to classical fluctuations by the time of last scattering, when they become seeds for large scale structure formation. Any experiments that elucidate the classical to quantum transition as a real or effective physical process have the potential to help throw light on this. It has been proposed on the one hand that this may be due to decoherence [130] and on the other that this is related to variants of CSL [131, 132].

In order to discriminate between such proposals, one can speculate on whether these proposals might make a difference to the expected classical fluctuations at the end of inflation. For example, might they be scale-dependent and hence cause a breakdown in the prediction of an almost scale-invariant spectrum of perturbations, affecting Cosmic Microwave Background and large scale structure observations at the present time [133]? Would they affect the usual assumption of Gaussianity of fluctuations at the end of inflation? If either were to be true these would be observational tests of such quantum theory variants [134]. Test of quantum theory variants can be devised as further bench-top experiments, enabling us to answer questions about the growth of structure in the Universe in the laboratory, as well as using data from cosmological phenomena to probe QT in extreme conditions [135, 136].

Finally, when considering the problem of the initial conditions of the universe one gets into the domain of quantum gravity (see also Q2). We are unable to access the required energies to test quantum gravity theories in colliders, and in the cosmological context inflation smooths out any pre-inflationary structures there might be, so we cannot see their cosmological outcomes either, although one avenue for exploring quantum gravity is Black Hole evaporation [137]. *String cosmology* suggests some inflationary potential on the basis of string theory, but this cannot be applied to the inflationary regime where the relevant energies are quite different.

The issues here are twofold. First, do the same principles of ordinary quantum theory apply to quantum gravity or do we need new foundational principles for the nature of space-time, or for some kind of (probably discrete) pre-spacetime structure, and hence for quantum theory? Loop quantum gravity [24] and string theory [25] are the two pre-eminent approaches that have been taken to studying such issues, but others such as causal set theory [138] provide more radical departures points, because they assume space-time structure is discrete. What justifies use of the same principles as those of ordinary quantum theory in these circumstances?

The more direct relation to the questions posed here arise as regards the second point: does the start of the universe in some sense correspond to a measurement event? How does the idea of measurement work out in quantum gravity theories, whatever they are?

7. How can causality and agency be reconciled within quantum theory?

Puzzling situations can arise where the causal order of events (in a fixed spacetime background) is not necessarily fixed, but is subject to quantum uncertainty. Could there be indefiniteness with respect to the question of whether an interval between two events is time-like or space-like, or even whether event A is prior to or after event B? Might, this correspond to the "superpositions of situations where, 'A is in the past of B' and 'B is in the past of A' jointly" [139]? This problem has bearings on quantum gravity studies: a theory unifying collapse-based variants of QT with GR, causal structure might plausibly be both be dynamic, as in general relativity, as well as indefinite, due to quantum features. A framework for the dynamics of quantum causal structures of something of this kind is given in Ref. [140].

Oreshkov, Costa and Brukner have put forward theoretical ***models where there is no fixed causal order and the dynamics is specified in terms of linear operators*** [141]. In 2017 an experiment was carried out in Vienna which implemented a measurement which was described as a superposition of causal orders [142], and subsequently a demonstration described as an entanglement of temporal orders [143] violating a Bell inequality for temporal order [144] (although it is not yet a loophole free test). The development of this inequality for temporal order allows for a quantitative method for investigating quantum aspects of space-time and gravity, and the demonstration of its violation could lead to the conclusion that nature is incompatible with a local definite temporal order. An improved experiment to render the causal order between operations indistinguishable by their spacetime location has yielded a causal witness 18 standard deviations beyond the definite-order bound [145].

Other approaches to investigating modified causal orders within quantum theory are based on the framework of closed time-like curves (see Ref. [139] for a discussion), and have recently inspired experimental simulations—see e.g. Ref. [146].

A special kind of causal order is that pertaining to events caused by the action of *agents*: things which react to environmental stimuli in flexible yet sensible ways, and to whose active powers we attribute many of the happenings around us. In this regard, there is an ongoing rich debate about how *attributable agency* can be incorporated within physics, and in particularly reconciled with quantum theory. In the case of collapse-endowed variants of QT, the problem, according to some (see Ref. [147] for a discussion of the problem of agency), is that there appears to be no room for attributable agency in the context of a stochastic theory; it is therefore a challenge to accommodate a prominent feature of physical reality, i.e., the existence of agents, within those variants of quantum theory. Progress has been made via a theoretical model of *projective simulation*, where the concrete outcome of a random process can be consistently attributed to an agent [147]. This has recently inspired a model for an implementation via measurement-based quantum computation [148]. Could the source of asymmetry between cause and effect be simply the act of intervention itself? Milburn and Shrapnel put forward the view that it is the temporally symmetric laws of physics that underwrite the agent-based interventions through which asymmetric causal relations are discovered [149].

An additional aspect to consider when discussing causality is the possibility of retrocausality; of events in the future being able to influence events in the past. Retrocausality would be one way of allowing for a Lorentz-invariant explanation of Bell correlations without action at a distance and it has been proposed that retrocausality follows directly from the quantization of light, provided that fundamental physics is time-symmetric and that one does not take an ontic interpretation of the quantum state [150, 151]. Of course, some models of QT are not time symmetric—the introduction of a collapse event for the wave function is said by some to introduce time-asymmetry, in which case retrocausality would not be introduced. The transactional interpretation introduces a form of retrocausality, although in this interpretation the future does not influence the past [152]. In this case the predictions of QT are interpreted to be due to an exchange of advanced and retarded waves, with the predictions of the theory being the same as standard quantum mechanics.

8. **Are thermodynamic laws revised in quantum theory?**

Standard thermodynamics offers a bird’s eye view of a system consisting of vast numbers of particles by describing it using a few parameters such as temperature, volume and pressure. Although this simplicity allows for an elegant approach when dealing with systems with large numbers of particles, the downside is that ***as the system size decreases the thermodynamic approach starts to lose accuracy as fluctuations of the parameters become relevant***. Stochastic thermodynamics can be used to describe fluctuations in the thermodynamic quantities due to thermal effects and to describe non equilibrium systems however, once quantum effects come into play we need a theory of quantum thermodynamics [153].

The famous Maxwell demon case, with regards to the second law, highlights the link between work and information. Using knowledge of the system the demon can extract work from the system without increasing its entropy, seemingly violating the second law. We achieve a neat resolution to this puzzle upon realising that the ***information (stored in the demon's memory, which is used to enable it to extract work) must also be accounted for thermodynamically, and achieving a thermodynamic cycle requires that this memory be erased, incurring a waste of energy as heat*** [154].

Early experiments to study non-equilibrium phenomena in nanoscale systems have been realized with molecules and soft matter at ambient temperatures [155, 156]. Heat-to-work conversion has been demonstrated with a dimeric polystyrene bead suspended in a fluid by measuring if the particle has moved up and, depending on the result, modifying an external potential to ensure the particle continues climbing. A micrometre-sized stochastic heat engine and a Carnot engine were realized with a single optically trapped particle as the working substance [157, 158]. A direct measurement of the entropy change along symmetry-breaking transitions for a Brownian particle in a bistable potential has also been achieved [159].

These experiments, however, do not provide an easy path towards incorporating quantum effects. A single-atom heat engine has been demonstrated in a single calcium ion in a tapered ion trap [159]. The study of quantum fluctuation relations with spin-1/2 system [160] and a trapped ion [161], as well as a demonstration of the Landauer principle in the quantum regime with a three-nuclear-spin molecule [162] and ultracold ions [163], were achieved. Very recently, spin heat engines were realised in an ion trap and a spin ½ system [164, 165]. The limitation in these cases is that either they are restricted to closed systems or the reservoir is not much larger than the system; reservoirs in the conventional sense are those of open systems and it is the study of open quantum systems that will answer the most pressing questions about energy harvesting, dissipation and thermalisation in quantum circuits.

A glimpse of the potential of solid-state circuits became evident when the Jarzynski equality, a Szilard engine and an autonomous Maxwell's demon were demonstrated with a single electron box [166, 167, 168]. A superconducting qubit has been used to demonstrate a quantum Maxwell demon [169] and an ensemble of nitrogen-vacancy centres in diamond has been used as a quantum heat engine [170]. A quantum heat valve [171], a quantum-dot heat engine [172] and a quantum-dot energy harvester [173] have also been realised in the solid-state.

The development of these experimental techniques opens the way for testing disagreements which are beginning to emerge about aspects of nonequilibrium thermodynamics in nanoscale quantum systems. To some extent these different viewpoints arise because of the different communities in which they originate, such as statistical physics, mesoscopic physics, quantum information theory, and many-body theory. Open questions include the definition of work, how quantum systems thermalize, and the efficiency and power of quantum engines [174]. We confidently hope and anticipate that experimental testing will serve to evaluate the validity of different approaches in different contexts, and will elucidate those concepts which are presently obscure.

3. Discussion and Conclusions

Thinking back to the first set of Oxford questions [26], these new questions, although sharing the same theme, are less focused on reconciling quantum physics with classical physics and ideas *and are more focused on experiments to test the boundaries of QT with post quantum theories*. With the development of new technologies it is important to continue to think of experiments to expand the boundaries of our understanding of the quantum realm.

With regards to collecting fresh evidence, good progress has been made even in the short period of time since the first set of Oxford questions. There has been further theoretical development of the *PBR theorem on the reality of the wave function* to the BCLM and Branciard theorems, with experimental tests pointing towards a psi-ontic interpretation [47, 48, 49, 50]. *A framework for indefinite causal order within quantum theory* has been developed including a Bell inequality for temporal order with the first experimental verifications being recently published [142, 143]. The most recent experiment of a CSL type heating effect has measured *a nonthermal force noise of unknown origin,* down to the level of the CSL heating predicted by Adler [65], although the authors are not willing to claim CSL heating until every other possible source has been ruled out. We are still some way off making sense of many of the aspects of QT, but as these experiments are improved and theoretical proposals are brought into realisation we can expect the murky waters of the foundations of QT to become clearer.

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