

On the applicability of quantum physics *George Ellis, University of Cape Town*

ABSTRACT:

Tony Leggett has suggested [1] that quantum theory cannot be applied to complex macroscopic objects. This essay supports that idea by giving two specific examples of complex systems where this is true, because of the essential nature of the quantum measurement process, which cannot be described by standard quantum theory (none of the alternatives proposed in the end get round this limitation, in practical terms). I then place this result in the larger context of the ubiquitous occurrence of top-down causality in complex systems, which is the key process whereby genuine complexity emerges from the underlying physics. The implication is that the ability of physics to comprehend the dynamics of complex systems, such as life, is strictly limited: physics underlies and strongly constrains what happens, but in the end does not determine the unique outcome that actually occurs. This is determined by autonomous emergent higher level dynamics.

INTRODUCTION

The physical existence of complex systems such as life is based in the hierarchy of causation and complexity: physics underlies chemistry, chemistry underlies biochemistry, biochemistry underlies cell biology, and so on (see Figure 1). As quantum theory is the basic theory at the foundation of physics, a common opinion is that together with suitable equations describing interactions, it determines (with a modicum of uncertainty, unimportant at macro scales) all that happens. Indeed there is common talk of 'the wave function of the universe', the quantum state description that in principle determines all that happens in the entire universe at all levels of complexity.

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|----------------|--|
| Level 8 | <i>Sociology/Economics/Politics</i> |
| Level 7 | <i>Psychology</i> |
| Level 6 | <i>Physiology</i> |
| Level 5 | <i>Cell biology</i> |
| Level 4 | <i>Biochemistry</i> |
| Level 3 | <i>Chemistry</i> |
| Level 2 | <i>Atomic Physics</i> |
| Level 1 | <i>Particle physics</i> |

Figure 1: *The hierarchy of structure and causation for life.* This figure gives a simplified representation of this hierarchy of levels of reality (as characterised by corresponding academic subjects) for living beings. Each lower level underlies what happens at each higher level, in terms of structure and causation. For a more detailed description of this hierarchical structure, see <http://www.mth.uct.ac.za/~ellis/cos0.html>.

A key issue then, is whether this is indeed so: can quantum theory really describe arbitrarily complex physical systems? Nobel Prize winner Tony Leggett suggests, in a fascinating article [1], that the answer is 'no'. This essay supports that view by giving specific examples of physical systems whose evolution cannot be fully described by present day quantum theory. Only some radical alteration of our understanding of quantum physics can change this conclusion.

QUANTUM THEORY AND NETWORKS

Interrelated basic features of quantum theory are (see e.g. [2-7]),

- quantization of entities and energy (the discreteness principle),
- wave-particle duality, leading to an intrinsic uncertainty in the properties of quantum entities,
- the superposition principle for quantum states, leading to interference between quantum entities and the development of entanglement,
- a deterministic prescription for evolution of the quantum state determining probabilities of outcomes of measurements,
- but indeterminacy of specific outcomes of measurements, even if the quantum state is fully known.

The superposition principle, central to quantum behaviour, is the key element we focus on here. Leggett states ([1]: 98), "it is quite conceivable that at the level of complex, macroscopic objects the quantum mechanical superposition principle simply fails to give a correct account of the dynamics of the system". If this is the case, then higher-level emergent dynamics are the true determinants of what happens at macroscopic levels, and quantum physics *per se* is simply unable to determine outcomes at those levels.

Why should one think this to be the case? Superposition is a consequence firstly of the fact that the quantum state lives in a vector space, with its linear structure appropriate to probability measures, and secondly of the fact that the evolution equations for the quantum state vector are linear first-order differential equations in time, and so respect this linear structure. However complex systems are based in networks of interactions (such as gene networks, protein networks, and neural networks) that involve non-linear structural and causal relations between constituent elements [8], so superposition surely would not be expected to hold in them. Note that ordinary quantum theory allows a certain degree of non-linearity in that it allows non-linear potentials to be source terms for the linear time-development equations. It is the linearity of the time development equations that matters there, and that is what is violated in generic networks: the higher-level structure of the system, which cannot be represented in terms of lower level variables, introduces non-linearities such as network motifs that control the dynamics [8].

Thus a genuinely complex system is made up of simple systems, each of which in isolation obeys linearity, but when assembled together in a causal network their combination does not, the elements being combined thus precisely in order to allow non-linear interactions such as positive and negative feedback. This would seem a priori to prevent superposition of states being a stable situation (if it were true to begin with, it would not remain so).

While this argument is strongly suggestive, it is hardly solid proof of the claim made. I now aim to provide strong arguments for the claim made by giving specific examples where the nature of quantum measurement plays a key role.

QUANTUM MEASUREMENT.

The key feature of quantum measurement is the foundational unpredictability of its outcomes, expressed in the famous quantum uncertainty relations (see e.g. [3, 6]). Examples are radioactive decay (we can't predict precisely when a nucleus will decay and what the velocities of the resultant particles will be), and the foundational two-slit experiments (we can't predict precisely where a photon, electron, neutron, or atom will end up on the screen [6]).

It is a fundamental aspect of quantum theory that this uncertainty is unresolvable: *it is not even in principle possible to obtain enough data to determine a unique outcome of quantum events* [5,10]. This unpredictability is not a result of a lack of information: it is the very nature of the underlying physics. This uncertainty is made manifest when a measurement takes place, and only then - without measurements, there is no uncertainty in quantum processes. Here we mean by a measurement, a process whereby quantum uncertainty is changed into a definite classical outcome that can be recorded and examined as evidence of what has happened; it is not necessary that an observer actually takes any measurements. For example it happens when a photon falls on a physical object such as a screen, a photographic plate, or the leaf of a plant, and deposits energy in a particular spot on the object. In more technical terms, it generically occurs when a general wavefunction collapses to an eigenstate of an operator (see the Appendix). And this is not a side effect in quantum theory: it is absolutely central to its real world applications:

“.. it is the act of measurement that is the bridge between the microworld, which does not by itself possess definite properties, and the macroworld, which does. .. the concept of measurement, prima facie at least, is absolutely central to the interpretation of the quantum mechanical formalism” ([1]: 87).

However the process of determining experimental results - a measurement – cannot be represented by the standard quantum state evolution equations, such as the Schroedinger and Dirac equations, for those are predictable (they obey existence and uniqueness theorems) and time reversible. They simply don't have the kind of nature that can lead to an unpredictable result when the initial state is fully known; but that is what happens in quantum measurements, which do not obey linearity and hence violate the superposition principle.

This is the *measurement paradox*: the process of measurement [3:591-619; 4:53-62; 5:175-188; 6:215-243; 7:80-102 & 491-556; 10:225-296) cannot be described by standard quantum dynamics. Indeed, Leggett states it thus:

“the problem is that quantum mechanics absolutely forbids a measurement to take place in a nutshell, in quantum mechanics events don't (or don't necessarily) happen, whereas in our everyday world they certainly do ” ([1]: 87, 89).

Now this has been disputed by many, and alternative descriptions have been proposed that try to get around this fundamental limitation. For example, the many-worlds view (see e.g. [4,5]) initially appears to involve only unitary processes; but the selection of the specific world which any particular observer experiences in their actual history, which indubitably exists in practice, is an unpredictable non-unitary process. The effective equations describing the physical happenings (as set out in the Appendix) remain, as is the case also with hidden variable theories [4,5]. And decoherence [5,6] does not solve this problem either, as some claim: it effectively removes entanglement (by diagonalising the density matrix), but the diagonalised density matrix still does not determine a unique outcome for a specific physical situation. All we get for that physical outcome is a probabilistic prediction. None of the proposed alternatives solves the measurement paradox in a way that changes the fundamental lack of predictive capacities of quantum theory: these proposals have no cash value. As far as real physical experiments are concerned, what happens is described by equations (1)-(5) in the Appendix.

The fact that such unpredictable measurement events happen at the quantum level does not prevent them from having macro-level effects. Many systems can act to amplify them to macro levels, including photomultipliers (whose output can be used in computers or electronic control systems). Quantum fluctuations can change the genetic inheritance of animals and so influence the course of evolutionary history on Earth [11]. Thus quantum implications are not confined to the micro realm.

The implication of the above is that if one can find a macroscopic complex object whose dynamics essentially depend on the quantum measurement process, its dynamical evolution will even in principle be undetermined by quantum theory. Rather than a unique physical outcome, a diverging set of probabilistic predictions are the most that can be attained from quantum physics, even though in real-world practice, a unique outcome arises. I now give two specific classes of example where this is the situation.

SIMPLE CONTROL SYSTEMS

The first example is simple feedback control systems with fixed goals, such as a thermostat. Such systems are ubiquitous in engineering [12] and in biology [13]. Their feedback control process demands a determination of the current state of the system, in order to give the information used to feedback a control signal to the controller (Figure 2). In other words, the functioning of such systems demands a specific experimental outcome that is then utilized to uniquely determine the further dynamics, and this outcome can only be obtained in conjunction with collapse of the wave function -- which is not describable by present day quantum theory, as just discussed.

Thus if a physicist tries to give a complete quantum-theory description of the dynamics of such a simple feedback control system, they will be unable to do so. The outcome is determined by the goal of the feedback control system - a higher level property that is not reducible to lower level entities, or even describable in lower level language [14].

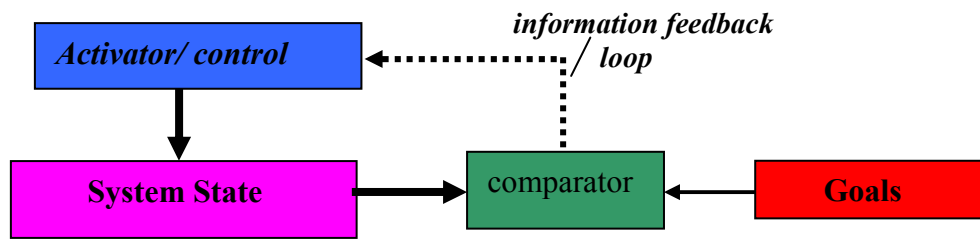


Figure 2: The basic feedback control process. The goals tend to lead to a specific final state via a specific mode of physical action. The initial state of the system is then irrelevant to its final outcome, provided the system parameters are not exceeded.

ADAPTIVE SELECTION

The second example, fully appropriate in the year of Darwin's centenary, is the process of adaptive selection, ubiquitous in biology, but also occurring in digital computers, for example in artificial neural networks and genetic algorithms [14].

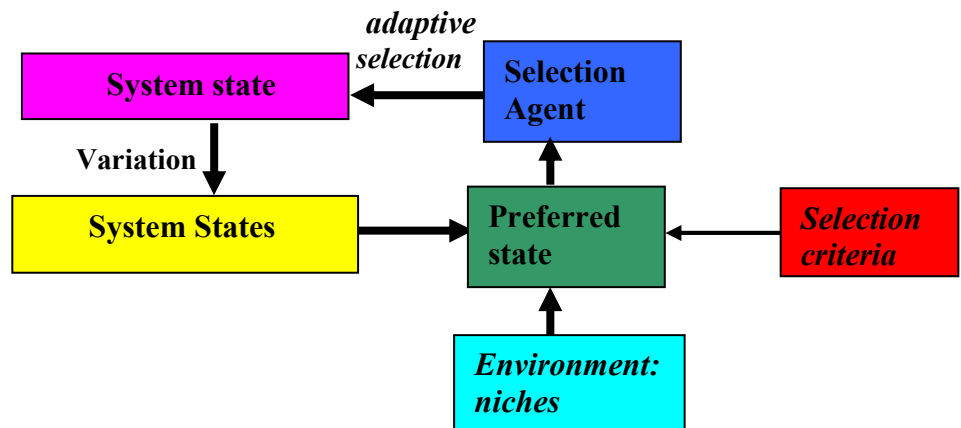


Figure 3: Adaptive selection. The meta-goals embodied in the value system do not lead to a specific final state: rather they lead to any one of a class of states that tends to promote the meta-goals. Thus the final state is not uniquely determined by the meta-goals; random variation influences the outcome by leading to a suite of states from which an adaptive selection is made in the context of both the value system and the environment.

This also demands an effective collapse of the wave function, as the selection process takes place on the basis of the specific outcomes of the variations that underlie such Darwinian processes (see Figure 3). This is in effect a measurement process that selects an eigenstate of the selection operator, and so again these dynamics will not be describable in quantum physics terms: they crucially depend on specific outcomes that determine the further dynamics.

The importance of this process is that it is the way new information enters the physical world in a way that is unpredictable on the basis of the underlying physics; it does so on evolutionary, developmental, and functional timescales, thereby enabling the emergence and functioning of true complexity [14].

TOP-DOWN ACTION

Placing this in a larger context, these are both examples of top-down causation in the hierarchy of complexity (see Figure 4). Such causation, in conjunction with bottom-up action, is the key to emergence of complexity from underlying physics (for a full discussion and many examples, see [14]). These examples suggest that generically, situations where top-down causation is important may be where we can expect quantum physics to give an incomplete dynamical description of events.

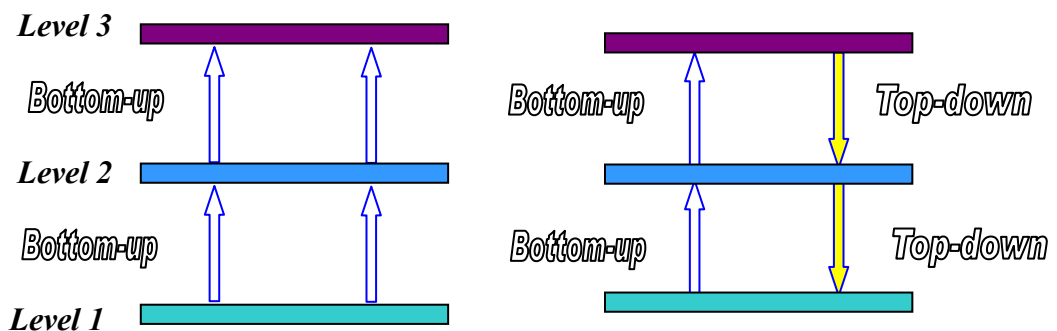


Figure 4a: Bottom-up causation only.

Figure 4b: Bottom-up and Top-down causation

Figure 4: Bottom-up and Top-down causation. *The fundamental importance of top-down causation is that it changes the causal relation between upper and lower levels in the hierarchy of structure and organisation.*

However there is another intriguing relation of all the above to top-down causation: there are various strands of evidence suggesting that top-down causation may be related in an essential way to the quantum measurement process. These items are as follows:

Firstly, the Copenhagen interpretation of quantum physics [3-5,10] explicitly envisages top-down action from the macro world (‘the observer’) to the micro world (the quantum system) as the key ingredient in quantum measurement. This involves an implicit statement that the macro-world is not subject to quantum laws (else the experimental apparatus could not deliver a specific outcome for an experiment). The discussion above suggests this apparently fundamental incompatibility may after all make sense.

Secondly, Zurek has proposed [15] that decoherence as a quantum system interacts with its environment can be regarded as a process of a Darwinian nature: environmental selection of specific system states (“einselection”) takes

place. This proposal of quantum Darwinism is a case of top-down action by adaptive selection, as discussed above.

Thirdly, a very interesting and innovative proposal by 't Hooft [16] envisages quantum theory emerging from an underlying deterministic theory based on a discrete spacetime structure. A core feature of his analysis is the causal effectiveness of equivalence classes of lower level processes in determining outcomes. But existence of such equivalence classes is a characteristic feature of top-down action [17]: so actually his proposal is one where top-down action underlies the fundamental nature of quantum theory.

Finally, the arrow of time problem is, how does a unique arrow of time emerge at the macroscopic level, as famously embodied in the Second Law of Thermodynamics, when the underlying fundamental physics is time symmetric? Virtually every viable solution proposed is in effect a suggestion of top-down action from boundary conditions at the cosmological level to local physical systems (see e.g. [18] and references therein). This process is associated with the passage of time, which is possibly based in the time-asymmetric process of collapse of the wave function when quantum measurement occurs [11]. Hence this too suggests that top down processes may be playing a fundamental role in quantum measurement. None of this is conclusive, but it suggests a line of enquiry for the future that may be fruitful.

CONCLUSION

There are sound reasons to believe that quantum theory (as presently conceived) cannot as a matter of principle be used to describe the dynamics of genuinely complex systems in a bottom-up way. This allows the higher level dynamics to have genuine causal power governed by the effective laws operational at each level. Consequently physics per se underlies these higher levels operations, but as a constraint: it cannot determine the unique outcomes that occur, which are determined by higher level causes [14]. This is one of the most important restrictions on what is possible through physics on its own. Indeed there are tantalizing hints that top-down action may play a significant role in quantum theory measurements.

The implication is that the ability of physics to comprehend the dynamics of complex systems, such as life, is strictly limited: physics underlies and strongly constrains what happens, but in the end does not determine the unique outcome that actually occurs. This is determined by autonomous emergent higher level dynamics, such as the processes of genetics, physiology, and neurology. Physics enables all of this, but is not sufficient to determine the outcomes, even if infinite computing power were available. The essential nature of these processes, as a matter of principle, lies outside the domain of applicability of physics.

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APPENDIX

The probabilities of experimental outcomes for some observable A are determined by an operator \tilde{A} acting on the system state $\psi(x)$. Different states $\psi_1(x)$, $\psi_2(x)$ can be added, leading to interference effects. The state $\psi(x)$ normally evolves according to a linear process:

$$\psi_1(x) \rightarrow \psi_2(x) = U(t_{12}) \psi_1(x) \quad (1)$$

for some unitary operator $U(t)$. This is what leads to entanglement. If a measurement of an observable A takes place at time $t = t_*$, initially the wave function $\psi(x)$ is a linear combination of eigenfunctions $u_n(x)$ of the operator \tilde{A} that represents A : for $t < t_*$, the wave function is

$$\psi_1(x) = \sum_n \psi_n u_n(x). \quad (2)$$

(see e.g. [5]: 5-7). But immediately after the measurement has taken place, the wave function is an eigenfunction of \tilde{A} : it is

$$\psi_2(x) = a_N u_N(x) \quad (3)$$

for some specific value N . The probability of each different eigenstate being selected is given by

$$\text{Prob}(a_N; \psi) = |\psi_N|^2. \quad (4)$$

Immediately after a measurement the state of the system is known to be a specific eigenstate, and any immediate further measurements will give the same eigenstate and eigenvalue. Thus until sufficient time has evolved, the state is known and its outcome determined because the wavefunction has changed to an eigenstate. Thus the transition

$$\psi_1(x) = \sum_n \psi_n u_n(x) \rightarrow \psi_2(x) = a_N u_N(x) \quad (5)$$

is the measurement process (and also essentially the state preparation process). It cannot be described by a unitary process (1). More sophisticated measurement processes involve projection into a subspace of the full state space (see e.g. [5,7]), as in the many-histories approach and in the case of open quantum systems. That projection process is non-unitary.

The data for $t < t_*$ do not determine the index N ; they just determine a probability for the choice N . One can think of this as due to the probabilistic time-irreversible collapse of the wave function ([10]: 260-263). Invoking a many-worlds description (see e.g. [4,5]) will not help: in the actually experienced universe in which we make the measurement, N is unpredictable. Thus the initial state (2) does not uniquely determine the final state (3); and this is not due to lack of data, it is due to the foundational nature of quantum interactions. You can predict the statistics of what is likely to happen but not the unique actual physical outcome, which unfolds in an unpredictable way as

time progresses; you can only find out what this outcome is after it has happened. Furthermore, in general *the time t_* is also not predictable from the initial data*: you don't know when 'collapse of the wave function' (the transition (5) from (2) to (3)) will happen (you can't predict when a specific excited atom will emit a photon, or a radioactive particle will decay).

We also can't retrodict to the past at the quantum level, because once the wave function has collapsed to an eigenstate we can't tell from its final state what it was before the measurement. You cannot retrodict uniquely from the state (3) immediately after the measurement takes place, or from any later state that it then evolves to via the Schrodinger equation at later times $t > t_*$, because knowledge of these later states does not suffice to determine the initial state (2) at times $t < t_*$: the set of quantities ψ_n are not determined by the single number a_N .

Note: The decoherence option, ably put by Kiefer in [19], shows how classical looking predictions can emerge for an *ensemble of objects* through interaction with the environment (because of these interactions, the system itself no longer has a unitary evolution). But we want a theory can that can give a specific result for an *individual entity*. The way theoretical physics underlies biology must apply to unique individuals as well as to statistical ensembles.

Proviso 1: the recently discovered process of weak quantum measurement (see e.g. http://en.wikipedia.org/wiki/Weak_measurement) proceeds somewhat differently to what is stated above. However it is not the generic case, and is unlikely to occur in complex systems. It is sufficient for my argument that the above *sometimes* describes what occurs in quantum measurement processes.

Proviso 2: the argument, and perhaps even the conclusions of this essay, would have to be modified if some specific mechanism for the quantum measurement processes were to be added to quantum theory. But that would not then be quantum theory as we know it, it would be a revised theory: call it Quantum_Plus, including a specific proposal for collapse of the wave function, perhaps a variant of the proposals by Ghirardi, Pearle and Rimini, or that by Penrose. No such proposal has so far been agreed on by the quantum theory community; so the current situation is as presented here.

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