ON THE APPLICABILITY OF QUANTUM PHYSICS

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ABSTRACT: *Tony Leggett has suggested [1] that quantum theory cannot be applied to complex macroscopic objects. Many are exploring this limitation by seeking ways where entanglement can be extended to macro scales. This paper explores another aspect of this issue, by giving two specific examples of complex systems where quantum physics per se is inapplicable, namely feedback control systems and networks with adaptive selection. The key point is the essential nature of the quantum measurement process, which cannot be described by standard quantum theory evolution equations (none of the alternatives proposed for this process gets round this limitation, in practical terms). One can indeed describe quantum action in specific complex systems – but only if one includes in the description, macro entities that are not described in quantum theory terms. This result—in effect a restatement of the Copenhagen interpretation -- is part of the larger theme of the ubiquitous occurrence of top-down causality in physical systems - the key process whereby genuine complexity emerges from the underlying physics.*

1: INTRODUCTION

Among the many controversies concerning quantum theory is an implicit debate on the domain of applicability of the theory. Dirac famously stated that once the principles of quantum physics were in place, determination of chemistry was just a question of calculation, and to a large degree this has been realized through various approximation schemes. However there is an ongoing debate as to whether specifically quantum effects such as tunneling and entanglement have any direct impact on biology in general, and on the brain in particular. On the physics side extraordinary progress has been made in extending entangled states and EPR effects to scales of many kilometers, but those engaged in quantum computing struggle to contain and minimize the effects of decoherence. All these enterprises implicitly acknowledge the restricted domain of applicability of quantum principles as regards the macroscopic world. And of course this understanding is profoundly present in the Copenhagen interpretation of quantum theory, with it strict separation of the macro and micro world at the heart of the quantum measurement process.

On the other hand, there is a group of theoreticians, primarily from the quantum cosmology side, who proclaim that quantum physics is directly applicable at all scales, with its Hamiltonian evolution (implied perhaps by the Wheeler de Witt equation, and solved via path integrals) determining everything that happens. The whole history of the universe, past and future, is said to be implied by the wave function of the universe [2]. Julian Barbour [3] makes explicit that this viewpoint is intended to apply *inter alia* to all biology, including the human mind, so that (according to that theory) the appearance of the passage of time in the brain is an illusion.

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This view appears to be in direct contrast with the other quantum physics themes just mentioned. This paper[2] will support the view that such equations cannot describe the behavior of truly complex systems, by giving specific examples where quantum theory *per se*, while determining the behavior of the components, cannot deal with their interactions in a complex network. Yes quantum theory can be applied to non-linear contexts: but apart from some special cases, only if the system description includes classical elements that are NOT reduced to, or indeed reducible to, quantum mechanical descriptions. This "Copenhagen" interpretation is implicitly built into most papers on quantum theory and quantum field theory.

1.1 THE HIERARCHY OF COMPLEXITY. 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 at all levels of this hierarchy. Indeed, it is sometimes claimed that through the concept of `the wave function of the universe', a quantum state description in principle determines all that happens in the entire universe at all levels of complexity [2,3].

Level 8	***Sociology/Economics/Politics***
Level 7	***Psychology***
Level 6	***Physiology***
Level 5	***Cell biology***
Level 4	***Biochemistry***
Level 3	***Chemistry***
Level 2	***Atomic Physics***
Level 1	***Particle physics***

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: what levels can really be described by quantum theory? In the following we give specific examples of physical systems from the biochemistry level up whose evolution cannot be

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[2] The paper is an extended version of an FQXI Essay for their 2009 competition: see http://www.fqxi.org/community/forum/category/31416.

fully described by present day quantum theory. Only some radical alteration of our understanding of quantum physics can change this conclusion.

2: QUANTUM THEORY AND NETWORKS.

Interrelated basic features of quantum theory are (see e.g. [4-9]),

- 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. Superposition, based in the linearity of the Schrödinger equation, is at the core of quantum theory, e.g. Ghirardi [10] states:

"*Let us recall the axiomatic structure of quantum theory: 1. States of physical systems are associated with normalized vectors in a Hilbert space, a complex, infinite-dimensional, complete and separable linear vector space equipped with a scalar product. Linearity implies that the superposition principle holds: if* |f> *is a state and* |g> *is a state, then (for* a *and* b *arbitrary complex numbers) also*

|K> = a|f> + b|g>

is a state. Moreover, the state evolution is linear, i.e., it preserves superpositions: if |f,t> *and* |g,t> *are the states obtained by evolving the states* |f,*0*> *and* |g,*0*>*, respectively, from the initial time* t=0 *to the time* t*, then* a|f,t> + b|g,t> *is the state obtained by the evolution of* a|f,*0*> + b|g,*0*>*. Finally, the completeness assumption is made, i.e., that the knowledge of its statevector represents, in principle, the most accurate information one can have about the state of an individual physical system.*"

The crucial nature of this principle in applying quantum theory to physics and chemistry is made clear in remarks on the centrality of superposition to quantum theory by Rioux [11]. However Legett 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 physic*s 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 normed vector space, with its linear structure appropriate to probability measures [12], and secondly of the fact that 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 [13], 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 operator in the equations that matters, 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 [13].

2.1 SCHRÖDINGER'S EQUATION: The probabilities of experimental outcomes for some observable **A** are determined by an operator $\tilde{\mathbf{A}}$ 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:

$$\Psi_1(x) \rightarrow \Psi_2(x) = U(t_{12})\, \Psi_1(x) \qquad (1)$$

for some unitary operator U(t). It results from the equation of motion for the quantum state, which we here take to be Schrödinger's equation (we later comment briefly on the Dirac and Wheeler-de Witt equations). This can be written:

$$i\hbar\frac{\partial}{\partial t}\Psi(x,t) = \hat{H}\Psi(x,t) \qquad (2)$$

where $\hat{H}$ is a linear operator acting on the wavefunction Ψ to produce the wave function $\hat{H}\Psi$. This equation is then linear in Ψ: if $\Psi_A(x,t)$ and $\Psi_B(x,t)$ are solutions, then so is $a\Psi_A + b\Psi_B$, where a and b are any complex numbers. This superposition property is what leads to the key quantum effects of interference and entanglement.

This equation applies spectacularly well to individual particles but not to complex systems. It also does not tell you what happens in genetics, neuroscience, or evolutionary theory. In general in applying such an equation to complex contexts, first all the terms in the equation must be meaningful in the intended context, and second the equation must be shown to be applicable to that context.

Just because one writes down something like |**Ψ**> or |**up**> or |+> or |**cat**> or |**universe**> or |**multiverse**> does not necessarily mean it is a meaningful symbol, it may or may not be so: consider also the cases |**toothfairy**> and |**unicorn**>, or try |**God**> or |**soul**> . The corresponding entities may or may not exist; if they do, the further question is if a wave function description makes any sense for them. The issue is whether or not the square of that state vector gives a probability for suitable experimental results, which may be performed, allowing one to detect the signatures of the entities' existence (by measuring its specific properties).

And when $|\boldsymbol{\Psi}>$ does mean something, one additionally has to establish the circumstances where the context is such that linear equations like **(1)** and **(2)** in fact characterizes the relevant dynamics. This may be true in some restricted cases but not in all, e.g. in the case of interaction networks it may apply to the individual components but not to the way they are interlinked together to form a complex system with feedback control loops, or where non-linear processes like adaptive selection are taking place. In brief: one has to determine the macro situations where the equivalent of **(2)** holds, and the variables that may thereby be predicted. 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.

2.2 NON-LINEAR VERSIONS OF THE SCHRÖDINGER EQUATION: Why is the above argument not vitiated by the existence of nonlinear versions of the Schrödinger equation (`NLS')? Since the equations themselves are nonlinear, the solutions can't be superposed in general. There are exceptions: plane wave solutions exist for the nonlinear Schrodinger equation [14], as well as for non-abelian fields [15], and these can be superposed in special cases, but this is not possible generically, e.g. you can't superpose two plane waves with different propagation directions. NLS equations don't describe the evolution of a general quantum state, because they only obey the superposition principle for very special cases; hence they do not describe generic situations of either interference or entanglement, which are central to quantum theory, rather they are classical field equations for fiber optics and water waves.

Secondly, when canonically quantized, the NLS equation describes bosonic point particles with delta-function interactions, and the related Gross–Pitaevskii equation describes the ground state of a quantum system of identical bosons. Thus they deal with very particular physical cases, not related to the context of interaction networks that I deal with here. In the latter case the non-linear Gross–Pitaevskii equation is not an equation for a quantum mechanical wave function, even though it is often called the wave-function of the condensate; it is an equation for a classical field having the meaning of an order parameter.

Thirdly, it has been claimed by some that the Ghirardi-Rimini-Weber (`GRW") collapse theory entails a non-linear version of the Schrödinger equation that allows interference and entanglement. However, firstly, the present paper is concerned with standard quantum theory, not such extensions of the theory, where the situation might be different. Secondly, the summary of GRW theory by Bassi and Ghirardi [16] makes clear that, contrary to these claims,

(i) they are not proposing a non-linear version of the Schrödinger equation, but rather an additional collapse operation not based in the Schrödinger equation ([16]: 41-42);

(ii) this extra operation will not satisfy the superposition principle, and hence in fact will not describe interference and effects arising from quantum entanglement.

3: QUANTUM MEASUREMENT.

The key feature of quantum measurement is the foundational unpredictability of its outcomes, expressed in the quantum uncertainty relations. 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 [4,5,8]). 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* [7,17]. 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. If a measurement of an observable $\boldsymbol{A}$ takes place at time $t = t_*$, initially the wave function Ψ (x) is a linear combination of eigenfunctions $u_n(x)$ of the operator $\tilde{\boldsymbol{A}}$ that represents $\boldsymbol{A}$:
for $t < t_*$, the wave function is

$$\Psi_1(x) \; = \; \Sigma_n \, \Psi_n \, u_n(x). \tag{3}$$

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

$$\Psi_2(x) \; = \; a_N \, u_N(x) \tag{4}$$

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

$$\mathrm{Prob}(a_N;\psi) = |\Psi_N|^2. \tag{5}$$

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

$$\Psi_1(x) = \Sigma_n \Psi_n u_n(x) \rightarrow \Psi_2(x) = a_N u_N(x) \qquad (6)$$

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. [7,12]), as in the many-histories approach [2] and in the case of open quantum systems [9]. That projection process is non-unitary. 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).

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 ([18]: 260-263). Invoking a many-worlds description (see e.g. [6,7]) will not help (see [12]: 289-294]): in the actually experienced universe in which we make the measurement, N is unpredictable. Thus the initial state **(3)** does not uniquely determine the final state **(4)**. 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 **(6)** from **(3)** to **(4)**) 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 **(4)** 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 **(3)** at times $t < t_*$: the set of quantities ψ_n are not determined by the single number a_N**.**

Finally, two notes are appropriate. First, 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. Standard quantum theory cannot handle this, even when decoherence is taken into account; indeed Hartle [2] states "The most general objective of quantum theory is the prediction of the probabilities of individual members of sets of coarse-grained alternative histories of the closed system". This already makes clear that quantum physics is unable to deal with the prediction of unique outcomes of individual histories that we are concerned with in the macro world, and that macro physics, chemistry, and molecular biology is able to handle with some degree of success.

Secondly, the recently discovered process of weak quantum measurement proceeds somewhat differently to what is stated above. However it is not the generic case, and is unlikely to occur in complex systems. In any case, it is sufficient for my argument that the above *sometimes* describes what occurs in quantum measurement processes.

3.1 THE MEASUREMENT PARADOX. However the process of determining experimental results - a measurement – cannot be represented by the standard quantum state evolution equations, such as the Schrödinger 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 [5:591-619; 6:53-62; 7:175-188; 8:215-243; 9:80-102 & 491-556; 17; 18:225-296) 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. [6,7]) 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 above) remain, as is the case also with hidden variable theories [6,7]. And decoherence [7,8,19] 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 [2]. None of the proposed alternatives solves the measurement paradox in a way that changes the fundamental lack of predictive capacities of quantum theory for specific individual systems. As far as real physical experiments are concerned, what happens is described by equations **(3)-(8)** above.

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 [20]. Thus quantum implications are not confined to the micro realm.

4: SPECIFIC EXAMPLES

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.

4:1 SIMPLE CONTROL SYSTEMS. The first example is simple feedback control systems with fixed goals, such as a thermostat. Such systems are ubiquitous in engineering [21] and in biology [22]. 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.

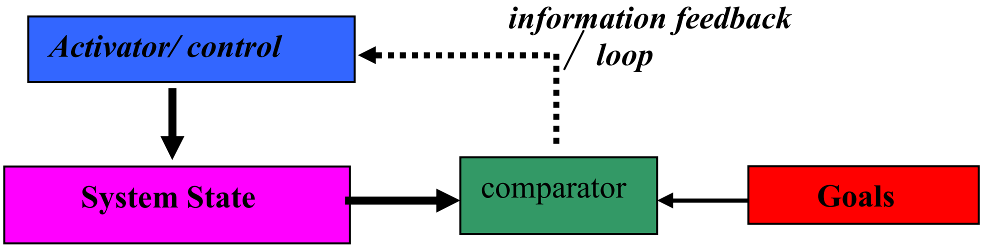

Figure 2: ***The basic feedback control process.*** *The goals tend to lead to a specific final state via a specific mode of physical action. The initial state of the system is then irrelevant to its final outcome, provided the system parameters are not exceeded.*

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 [23].

Suppose we could describe the temperature by a quantum state |**Temp**>. The dynamics of a feedback control loop are such that for an initial state |**Temp_1**>, we find |**Temp_1**> → |**Temp_goal**>, where |**Temp_goal**> is the desired output temperature. For a different initial state |**Temp_2**>, we find |**Temp_2**> → |**Temp_goal**>. Superposition requires that that if input ***A_1*** produces response ***X_1*** and input ***A_2*** produces response ***X_2*** then input (***A_1*** + ***A_2***) produces response (***X_1*** + ***X_2***). This simply does not happen when we consider a feedback control system. You therefore can't describe what is happening by writing down a Schrödinger equation for |**Temp**>, so standard quantum theory does not apply to such feedback systems.

So is the problem any worse in the case of such networks of interactions than it is in the standard measurement problem? Yes, it is. The point is that in the case of those loops, *one feeds the result of the measurement process back into the system in order to determine its future micro evolution*. You can't do that in terms of a theory involving unitary evolution alone, because that can't handle the measurement issue except in statistical terms: but we want to predict the unique behaviour of a specific system. In the standard measurement case on its own, macro results are already unpredictable on the basis of the microphysics, but this further problem does not arise: the measurement result resides in the macro world and does not get fed back into the micro world. You can handle the present case in terms of a combined classical and quantum description broadly in the spirit of the Copenhagen interpretation, i.e. you add in to the system some elements not covered by standard unitary quantum evolution rules. You can make the relevant models, but only by adding in non-quantum elements into the theory. We are back at the issue of how that can possibly make sense, if macro objects are based in quantum physics at the micro level.

What about the growing field of quantum networks [24] obtained by assembling a number of elementary quantum circuits into a network and resulting in quantum channels. Does not that counter my thesis? No it does not, because that theory only applies to networks with no cycles ([25]:5). These can be represented by Directed Acyclic Graphs, and so do not include the feedback loops I consider here.

And what about the rapidly growing field of quantum control [26,27] ? In any quantum control process, the result of a measurement is used to determine the future evolution of the system. Such devices can be constructed and function beautifully; but just like the Copenhagen interpretation of any ordinary measurement, their operation can only be understood through a mixture of classical and quantum theory, because the measurement part of the operation can't be described by the Schrödinger equation. The theory of quantum feedback control shows how the effect of the measurement changes the master equation for the system state (equations (4) and (5) in [25]) but not how the measurement takes place. There is to be sure a phenomenological equation for the measurement process (equation (7) in [25]) but that equation is not linear: hence it does not satisfy the superposition principle, and is not derivable from the Schrödinger equation. This is where the non-quantum aspect of the process is implicitly introduced. This is true even when continuous measurement takes place, because (see [27]) such measurements involve first a unitary measurement between the system and an auxiliary system, and then a von Neumann measurement of the auxiliary system. It is the latter event that is not described by standard quantum theory.

4.2 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 [23]. 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. But another way to think of it is that it is really a case representable by non-unitary creation and annihilation operators – i.e. it resembles Quantum Field Theory.

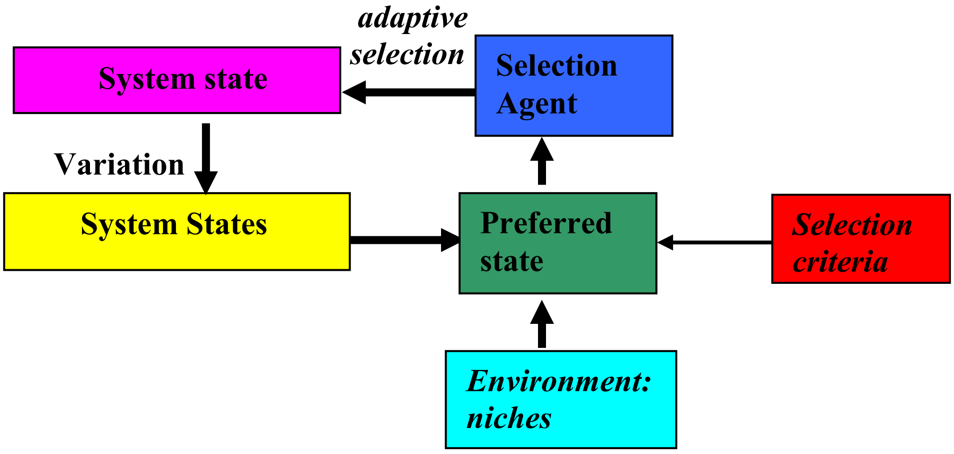

Figure 3: ***Adaptive selection***. *The meta-goals embodied in the value system do not lead to a specific final state: rather they lead to any one of a class of states that tends to promote the meta-goals. Thus the final state is not uniquely determined by the meta-goals; random variation influences 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.*

Suppose it makes sense to describe a situation of natural selection by standard quantum mechanics methods. Following Roederer's description of the physics of the Mach-Zehnder interferometer ([28], we can for example choose an initial state **|Ψ_insects>** = **(0 1)**, **|Ψ_dinosaurs>** = **(1 0)**, where we are assuming it makes sense to use such vectors to describe the probability of existence (or detection?) of the relevant entities[3]. Then the natural selection event that occurred is given by an elimination matrix **E_L** or **E_R** (with zeros in all places except one diagonal element: ([28]:60). The transformation from initial to final states is given by this matrix acting on the given initial values of |**Ψ_insects**> and |**Ψ_dinosaurs**>, and results in |**Ψ_insects**> = (**0 1**), |**Ψ_dinosaurs**> = (**0 0**). This is a non-unitary irreversible transformation that cannot be derived from a Schrödinger-type unitary evolution.

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 [23]. The process is directed by selection criteria and the environment, both higher order entities that are not describable in lower level terms.

5: 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. It is useful to compare this with the application of Newton's law of motion

$$\mathbf{F} = m\,\mathbf{a} \tag{7}$$

to macroscopic objects. Now at a macroscopic scale, **(7)** applies to everything (in its domain of validity, i.e. slow speeds relative to the speed of light and small gravitational fields so that space-time is almost flat in the region considered). It tells us everything we need to know about `point particles'. It tells us something useful about an amoeba or but very little about a cat or a human being. To be sure it tells us about the motion of the centre of mass of a cat or a human, but we may want to know about more than that. It applies to every component making up a human, so we can apply it separately to arms, legs, and so on. But it is not much help to a geneticist or a neuroscientist: while it is indeed working away there underneath things, it does not help determine the actual outcome of any initial situation in a cell or the brain.

Higher order emergent laws do that work, such as the Hodgkin-Huxley equations for action potentials or the biological principles underlying the reading of the genetic code. There is no way you can determine outcomes in these cases by applying **(7)** (which is why this equation does not occur in books on genetics or neuroscience – check it in the appendix!). Furthermore it does not help an evolutionary biologist determine the evolutionary dynamics at work – higher order principles do so (in this case, the principle of adaptive selection). Newton's law is working away there all the time, but does not by itself determine the relevant dynamics or outcomes.

Thus Newton's law **(7)** is of fundamental importance but only applies (as expressly stated in equation **(7)**) to very restricted real-world situations. There

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[3] For typographic reasons I'm representing a column vector by a row vector.

is a very beautiful theorem that is relevant here: if **(7)** applies to all the particles in a system, then it applies to the motion of the centre of mass of the system because by Newton's law of action and reaction, all the internal forces cancel out and make no contribution to the overall motion Symbolically,

{**(7)** applied to components} ➔ {**(7)** applies to C of M motion of whole} (8)

But this statement (and a few similar related to linear and angular momentum) are the exception: apart from them, one can't meaningfully apply **(7)** to the whole to predict macro-outcomes. By itself it throws no other useful light on the rest if the dynamics of cell division or of action potentials, for example. Similarly in the case of quantum theory, Ehrenfest's theorem shows that a quantum-mechanical wave packet obeys the equations of motion of the corresponding classical particle when the position, momentum, and force acting on the particle are replaced by the expectation values of these quantities [2]. This is a useful and important result, but a far cry from stating that quantum theory can be used to determine the outcomes of dynamics of complex macroscopic systems.

Placing this in a larger context, the examples given are both examples of top-down causation in the hierarchy of complexity, because the relevant controlling higher level variables are not expressible in lower level terms. Such causation, in conjunction with bottom-up action, is the key to emergence of complexity from underlying physics, through the effective action of equivalence classes of lower level states that represent a single higher level state (for a full discussion and many examples, see [23,29]). 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. This is indeed explicit in the Copenhagen interpretation of quantum physics [5-7,18] and its generalizations [12], which envisage top-down action from the macro world (`the observer') to the micro world (the quantum system) as a key ingredient in quantum measurement. This involves an implicit statement that the macro-world is not subject to quantum laws [12] (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.

Does this have any consequences? Not for most quantum theory and quantum field theory applications, which calculate energies of states and statistics of outcomes so successfully. But there is an area where it does matter: namely when the idea of the wave function of the universe [2] is utilized to give consequences for macro scales and the brain, claiming *inter alia* that time is an illusion [3]. These theories assume that quantum mechanical ideas can be applied to the universe as a whole, using some form of unitary evolution and without any process of collapse of the wave function being included in the description. This paper argues that this won't work when we wish to predict deterministically the behavior of individual macro systems, *inter alia* because feedback control loops exist in the real universe (e.g. in the human brain). To my considerable surprise this ends up supporting the Copenhagen view to some degree: it can be legitimate to suppose there are macro objects not described by standard quantum theory as exemplified by the Schrödinger equation [12].

The implication is that the ability of quantum physics to describe 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 [23], according to Anderson's famous dictum [30]: "*More is different"*. If true, then a significant task is to determine all the cases where such arguments are applicable: in what other case do similar kinds of considerations apply?

Two final comments are in order. Firstly, the above has dealt with quantum theory, rather than quantum field theory. Would there be any significant difference in the conclusion in that case? I believe not. Most quantum field theory texts assume the underlying probability interpretation as usual and say nothing explicit about the measurement, but implicitly assume the Copenhagen interpretation based on a macro/micro split (for example Feynman's book *QED* [4] explicitly represents macro apparatus such as photon detectors as "black boxes" whose internal workings are not under discussion).

Secondly, the argument, and perhaps even the conclusions of this paper, 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 [16,31] or Penrose [13]. No such proposal has so far been agreed on by the quantum theory community; so the current situation is as presented here. But a key task for the future is to extend quantum theory to give some proposal that does give a satisfactory description of the measurement process. Maybe the problem will look different in the light of such future theories.

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