On the limits of quantum theory: 
Contextuality and the quantum-classical cut

George F R Ellis
Mathematics Department, University of Cape Town.
February 2, 2013

Abstract

This paper is based on four assumptions: 1. Physical reality is made of linearly behaving components combined in non-linear ways. 2. Higher level behaviour emerges from this lower level structure. 3. The way the lower level elements behaves depends on the context in which they are imbedded. 4. Quantum theory applies to the lower level entities. An implication is that higher level effective laws, based in the outcomes of non-linear combinations of lower level linear interactions, will generically not be unitary; hence the applicability of quantum theory at higher levels is strictly limited. This leads to the view that both state vector preparation and the quantum measurement process are crucially based in top-down causal effects, and helps provide criteria for the Heisenberg cut that challenge some views on Schrödinger’s cat.

Contents

1 Quantum theory and classicality 2
2 Foundations 3
   2.1 Basic dynamics 3
   2.2 The measurement problem 5
   2.3 A basic standpoint 7
   2.4 The context: the hierarchy of the structure and causation 8
   2.5 Inter–level relations 9
3 Linearity, non-linearity, and quantum theory 10
   3.1 The essential linearity of QM 10
   3.2 Essential non-linearities of QM 12
   3.3 Allowed and non-allowed non-Linearity in QM 13
   3.4 When is quantum mechanics valid? 15
The classical to quantum relation is a key issue in understanding how quantum theory applies to the real world. In order to make progress in understanding this relation, it may well be profitable to consider firstly the way complexity emerges from the underlying physical relations, and secondly the way the operation of underlying physical processes is contextually determined. This paper will make the case that examining these issues of emergence and contextuality helps clarify the nature of the classical-quantum cut, also known as *Heisenberg’s cut* ([151]:15), and hence the way that non-quantum macro behaviour can emerge from underlying quantum systems.

The basic viewpoint taken here is that physical theory must explain not only what happens in carefully controlled laboratory experiments, but also the commonplace features of life around us, for which we have a huge amount of evidence in our daily lives. We will set out this viewpoint in more detail in Section 2 below, after first setting out the fundamental quantum dilemma. Further sections will explore the ways that quantum behaviour might emerge at higher levels of the hierarchy of complexity; will suggest contexts where this will almost certainly not be possible; and will explore the way contextual effects may help throw light on the quantum measurement problem.

This paper is structured as follows: Section 2 lays the foundations for the rest of the paper, setting out the context for the discussion and presenting a basic viewpoint which is then developed in the following sections. A key aspect is the proposal that higher level effective dynamics emerges out of lower level dynamics. Section 3 considers linear and
non-linear aspects of quantum theory, leading to some criteria for when quantum physics will be valid, based on the essential linear aspects of the theory. Section 4 considers when the requisite linearity can emerge at higher levels in the hierarchy of complexity from lower level linear theories, and when it cannot emerge. Section 5 looks at the converse feature of how contextual effects from higher levels may influence lower level dynamics, giving a number of examples of top-down causation in the context of quantum physics. Section 6 looks at the issue of state vector reduction in the context of top-down causation from the local physical environment. Section 7 looks at implications of the discussion for the classical quantum cut and Schrödinger’s cat. Section 8 reviews the viewpoint presented, and considers issues that arise from the discussion as suitable subjects for further investigation.

A major issue that arises out of the discussion in Section 5 of top-down influences in physics is the origin of the arrow of time. This is discussed in a companion paper [45].

2 Foundations

This section sets out the basic foundations for the rest of the paper. Section 2.1 sets out the basics of quantum dynamics, Section 2.2 the elements of the measurement problem, and Section 2.3 sets out a basic standpoint that underlies what follows. Section 2.4 sets out the context of the hierarchy of structure, and Section 2.5 the viewpoint that both bottom-up and top-down causation take place in this hierarchy.

2.1 Basic dynamics

The basic expansion postulate of quantum mechanics [107, 121, 78, 67] is that before a measurement is made, the state vector \( |\psi\rangle \) can be written as a linear combination of unit orthogonal basis vectors

\[
|\psi\rangle = \sum_n c_n |u_n(x)\rangle, \tag{1}
\]

where \( u_n \) is an eigenstate of some observable \( \hat{A} \) ([78]:5-7). The evolution of the system can be completely described by a unitary operator \( \hat{U}(t_2, t_1) \), and so evolves as

\[
|\psi_2\rangle = \hat{U}(t_2, t_1) |\psi_1\rangle \tag{2}
\]

Here \( \hat{U}(t_2, t_1) \) is the standard evolution operator, determined by the evolution equation

\[
i\hbar \frac{d}{dt} |\psi_t\rangle = \hat{H}|\psi_t\rangle. \tag{3}
\]

When the Hamiltonian \( \hat{H} \) is time independent, \( \hat{U} \) has the form ([78]:102-103)

\[
\hat{U}(t_2, t_1) = e^{-\frac{i}{\hbar}\hat{H}(t_2-t_1)} \tag{4}
\]

which is unitary ([78]:109-113):

\[
\hat{U} \hat{U}^\dagger = 1. \tag{5}
\]

Applying this to (1) with \( \hat{U}(t_2, t_1)|u_n(x)\rangle = |u_n(x)\rangle \) (an invariant basis) gives

\[
|\psi_2\rangle = \sum_n C_n |u_n(x)\rangle, \quad C_n := \hat{U}(t_2, t_1)c_n. \tag{6}
\]
Immediately after a measurement is made at a time $t = t^*$, however, the relevant part of the wavefunction is found to be in one of the eigenstates:

$$|\psi_2\rangle = c_N|u_N(x)\rangle$$

for some specific index $N$. This is where the quantization of entities and energy comes from (the discreteness principle): only eigenstates can result from a measurement. The eigenvalue $c_N$ is determined by the operator representing the relevant physical variables, and hence is unrelated to the initial wave function (1). The data for $t < t^*$ do not determine either $N$ or $c_N$; they merely determine a probability for each possible outcome (7), labelled by $N$, through the fundamental equation

$$p_N = c_N^2 = \langle e_N|\psi_1\rangle^2.$$

One can think of this as due to the probabilistic time-irreversible reduction of the wave function

$$|\psi_1\rangle = \sum_n c_n|u_n(x)\rangle \quad \longrightarrow \quad |\psi_2\rangle = c_Nu_N(x)$$

This is the event where the uncertainties of quantum theory become manifest (up to this time the evolution is determinate and time-reversible). It will not be a unitary transformation (6) unless the initial state was already an eigenstate of $\hat{A}$, in which case we have the identity projection

$$|\psi_1\rangle = c_Nu_N(x) \quad \longrightarrow \quad |\psi_2\rangle = c_Nu_N(x)$$

Hence it is unclear how this experimental result can emerge from the underlying quantum theory, which leads to (6) rather than (7). It is also unclear how classical behaviour can emerge from the underlying quantum behaviour, which will generically show (a) entanglement between different entities so that they do not have distinct individual states, and (b) only probabilities of different values of physical variables rather than specific determinate values.

This discussion presents the simplest idealized case of a measurement ([115]:542-549). More generally, one has projection into a subspace of eigenvectors ([78]:136; [151]:10-12) or a transformation of density matrices ([78]:137), or any other of a large set of possibilities ([151]:8-42), but the essential feature of non-unitary evolution remains the core of the process. Thus there is a deterministic prescription for evolution of the quantum state determining probabilities of outcomes of measurements, but indeterminacy of the specific outcomes of those measurements, even if the quantum state is fully known. Examples are radioactive decay (we can’t predict when a nucleus will decay or 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 [52, 67]).

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 \[116\] and so influence the course of evolutionary history on Earth, and they have changed the course of structure formation in the universe \[42\]. Thus quantum implications are not confined to the micro realm.

2.2 The measurement problem

The measurement problem \[100\] \[148\] \[8\] or measurement paradox \([115]:782-815\) is a key issue for quantum theory. Measurement is the location of the unpredictability of outcomes, consistent with the quantum uncertainty relations (see e.g. \[107\] \[67\]); but it is not an outcome of standard quantum dynamics, although it is crucial to the theory.

It is a fundamental aspect of quantum theory that the uncertainty of measurement outcomes is unresolvable: it is not even in principle possible to obtain enough data to determine a unique outcome of quantum events \[54\] \[78\] \[114\]. 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 some component of a general wavefunction collapses to an eigenstate of an operator (eqn.(9) above). And this is not a side effect in quantum theory: it is absolutely central to its real world applications. As stated by Leggett,

“.. 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” \([93]: 87\).

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 do not have the kind of nature that can lead to an unpredictable result when the initial state is fully known \([115]:530-533\); 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 \([107]:80-102,491-556,591-619\]; \[121]:53-62; \[78]:175-188; \[67]:215-243; \[114]:225-296; \[151]:8-44\) cannot be described by standard quantum dynamics. Indeed, Leggett states it thus \([93]:87,89\):

“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”.

Aharonov and Rohrlich, considering a Stern-Gerlach apparatus with entangled spin states (11:122), express it this way:

“Clearly, our treatment of quantum measurements is incomplete, we cannot leave the measuring device in a superposition of states. But clearly quantum mechanics offers no way to reduce a superposition of pointer states to a definite position.”

Now this has been disputed by many, and alternative descriptions have been proposed that try to get around this fundamental limitation.

The **many-worlds view** [121, 78, 143, 144, 129] theoretically involves only unitary processes; technically it is based on the idea of a relative state, which involves a special basis of Hilbert space relative to which the splitting occurs (78:157-159). This approach arises out of assuming the Schrödinger equation (8) applies consistently to the physical universe at all scales, and taking the consequences seriously. However it will be the contention of this paper that the application of that equation is strictly limited (Section 7.1). I will here pursue the idea that some form of state vector reduction should be taken seriously.

In the **consistent histories approach** [71, 144], a Heisenberg formalism is used with unitary evolution of the projection operators but non-unitary projections taking place to define a branch state vector (71: eqn.(A.2)). Thus even though the operator evolution is unitary, this formalism does not get rid of the need for non-unitary projection operators, and some prescription as to when they should operate (see also comments in [3]).

**Decoherence** [78, 160, 67] does not solve the problem either, as some claim. The measurement problem involves two distinct steps. The first is the non-unitary elimination of the off-diagonal terms of the density matrix (decoherence). The result is a statistical ensemble. The second is the projection of one particular eigenvalue from that ensemble. Decoherence does not solve step 2. It effectively removes entanglement (by diagonalising the density matrix), but the diagonalised density matrix still does not determine or even represent a unique outcome for a specific physical situation. But we want a theory can that can at least *describe* a specific result for an individual entity, even if it can’t causally predict that unique outcome. The way theoretical physics underlies the real world, including biology, must apply to unique individuals as well as to statistical ensembles: for ensembles are made of individual entities.

None of these proposed alternatives solves the measurement paradox in a way that changes the fundamental lack of predictive capacities of quantum theory. As far as real physical experiments are concerned, what happens is described by the equations presented in section 2.1, this is what has to be explained. It took decades of theoretical exploration and experimental work to verify that this is the way things work; those results are not in doubt, and are what we have to deal with.

By contrast the **explicit collapse models**, for example those by Ghirardi, Rimini, and Weber [9, 62] and Penrose [114, 115], do offer a solution to the problem. However I am
here concerned with standard quantum theory; I will propose (Section 8.2) the possibility that such an effective collapse mechanism might arise as a local top-down effect from a measuring apparatus. I will not deal with hidden variable theories, except to comment that the same issues of interacting scales will occur in those theories too.

There are of course various different approaches to ontology in quantum theory, with realist, anti-realist and pragmatic viewpoints on offer; I do not intend to discuss those issues explicitly here, although my tendency will be towards a realist viewpoint.

2.3  A basic standpoint

To ground this analysis in reality, I will adopt the following starting point for what follows:

**BASIC PREMISE:** Individual Events Happen.

Each word is important:

**Individual:** Statistics is not enough. An ensemble of events is made up of individual events. There is no ensemble if individual events don’t separately happen.

**Events:** Specific things occur. Universal laws describe multifold possibilities of what might happen, but we experience specific events in our own particular history.

**Happen:** They occur in time: they are about to occur, they occur, then they have occurred. Uncertainty about what might occur changes to the certainty of what has occurred.

**What is the evidence for this statement?** Apart from the overwhelming evidence from everyday life, every single physics experiment is proof it is true! - we plan experiments, carry them out, analyse the results, publish them. Each experiment is an individual event that occurs at a particular time and place in the history of the universe. Science would not be possible if this were not the case.

**This is true at every level of the hierarchy of structure and complexity,** summarized in Table 1 below.

At the **macrolevel:**
- the universe evolves, structures form,
- stars explode, planets move round the sun,
- objects fall to the surface of the earth, birds fly.

At the **micro level:**
- electrons in atoms change energy levels and emit photons, or absorb photons and change energy levels
- particles are emitted, go through slits, get scattered, impact on screens
- photons are emitted, go through polarizers, get scattered, are detected
- entanglement and decoherence take place.

This takes place irrespective of whether we know about it or not. Observers are not necessary for things to happen! Events (e.g. nucleosynthesis) took place in the early
universe long before any physical observers existed. In the absence of observation the wave function evolves unitarily, so in this case there is no clear meaning to before and after. Hence effective “observation” (i.e. collapse of the wave function) takes place all the time, because definite outcomes are occurring all the time, whether actually observed or not. Hence we do not need to involve consciousness in quantum theory foundations (ontology), although it is relevant to epistemology. Experimenters can make things happen, but they carry on happening whether observers exist or not.

The implication is that any complete theory of causation in the physical world, whether deterministic or not, must in some sense explain what is happening in specific instances both for inanimate matter and for life, otherwise it will be an incomplete explanation of the real world. It may not be able to explain why they are happening (it may assume there is some irreducible randomness that acts as as an effective cause, for example), but it must at least be able to describe that they are happening, as is shown by experiment, i.e. it must represent the fact that reduction to eigenstates takes place. Quantum theory predictions of energy levels, scattering angles, and statistics of interactions in general are of course sound testable physics, and it is a major success that they are correctly predicted. But they are not a complete theory of causation and events: they don’t even account for when specific events occur. They must be supplemented by some standpoint on when state vector reduction occurs in order to relate adequately to the macro world, even if they don’t uniquely predict the outcome. Simply to pragmatically ignore the problem is no resolution. The implications for the nature of time are considered in [45].

2.4 The context: the hierarchy of the structure and causation

The context in which this all occurs is the hierarchy of structure and causation. In simplified form, this is as set out in Table 1. This Table gives a simplified representation of this hierarchy of levels of reality as characterized by corresponding academic subjects, with the natural sciences on the left and the life sciences on the right. On both sides, each lower level underlies what happens at each higher level in terms of structure and causation. Note that there is no correlation between the left and the right hand columns above the level of chemistry, as emergence and causation is quite different in the two cases; but the first four levels are identical (life emerges out of physics!). On the left hand side higher level correspond to larger scales (each level is the encompassing domain or environment of the next lower level); on the right hand side goals and intentions are relevant, so that is what the higher levels refer to.

---

1What does it mean to say an event “has happened” if the system of interest is, say, a particle passing through a two-slit system in the absence of observation? Quantum mechanics forbids us from saying that (for example) the particle “really did” go through slit A, wave function collapse takes place — which can be much later. This can result in a delayed “passage of time” in an evolving block universe, see [49] for a discussion.

2The labels “higher” and “lower” are sometimes contested, but seem to provide a useful framework if they are defined in this way.
Implicit in this discussion is the view that the elements at each of the levels characterized by this table, except perhaps at the quantum level \[66, 90\], can be regarded as existing \[38, 41\]. A table exists, even though it is made of atoms, which also exist, even though they are made of electrons, protons, and neutrons; and of course the same applies to animals and people. This view too is needed in order that science makes sense. If an experimenter does not exist, then experiments are not possible.

Quantum Mechanics is applicable at the lower levels, but apparently not at the macrolevels except under very restricted circumstances - for example superconductivity, Bose-Einstein condensations, lasers, and the extraordinary recent quantum entanglement experiments over many kilometers. It is not apparent under ordinary every day circumstances at the macro level (which is why quantum dynamical principles are not obvious to us). Hence experimenters talk about the classical/quantum cut, or Heisenberg cut (\[151\]):15), necessary for them to analyze their experiments.

### 2.5 Inter–level relations

The higher and lower levels are related to each other because the higher levels are based in the lower levels. To characterize causation in this hierarchical context, it is useful to consider causation as proceeding in both a bottom-up and a top-down manner \[43\].

#### 2.5.1 Bottom-up Effects

A major theme of physics is that causation occurs from the lower to the higher levels of the hierarchy, leading to the emergence of structure and complexity. A feature that occurs here is the coarse-graining of lower level variables (e.g. particle states) to give higher level variables (e.g. density and pressure) \[4\], accompanied by a conversion of useful energy to non-usable energy when some energy is hidden in lower level variables, and hence not available to higher levels. This is the source of entropy growth and of effective non-conservation of energy at higher levels through friction and other dissipative effects.
But there are limits as to how far this bottom-up process of explanation can be carried out: physics per se cannot explain economics or psychology, for example. *More is different*, as famously stated by Anderson [5]; emergence of complexity takes place where quite different laws of behaviour hold at the higher levels than at the lower levels [84, 60]. Laughlin has elaborated how some higher level effects can only be understood in terms of variables expressed in terms of higher level concepts [91]. In particular, the linearity of lower level laws gets replaced by the complexity of non-linear interactions at higher levels, without which life could not come into existence.

### 2.5.2 Top-down effects

In addition to bottom-up causation, *contextual effects* occur whereby the upper levels exercise crucial influences on lower level events by setting the context and boundary conditions for the lower level actions. This is related to the emergence of effective laws of behaviour at higher levels that enable one to talk of existence of higher level entities in their own right. They then play an effective role not only at their own levels, but also influence the lower levels by setting the context for their action [43].

This idea of top down action in physics goes back at least to Ernst Mach in his work on Mach’s principle and the origin of inertia ([50, 40]; [137]:58-61), which strongly influenced Albert Einstein in developing general relativity theory and his static universe model. It is crucial in ideas about the origin of the arrow of time [147, 50, 29, 40, 115, 21]; nice popular discussions of how top-down effects may take place from the universe to local physics are given in [134, 24]. I will make the case that *top-down influences play a key role in relation to how quantum theory works*, particularly as regards both decoherence and state preparation. It is possible this line of thought can illuminate the way quantum measurement takes place.

### 3 Linearity, non-linearity, and quantum theory

The key issue I now focus on is how linearity and non-linearity in QM relate to each other. Section 3.1 considers the essential linearity of Quantum Mechanics (QM), and Section 3.2 its essential non-linearities. Section 3.3 looks at allowed non-linearities, and Section 3.4 at when we may expect QM to be valid, in the light of the above sections.

#### 3.1 The essential linearity of QM

Linearity is at the core of quantum theory. Ghirardi [62] states it thus:

“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 $|f\rangle$ is a state and $|g\rangle$ is a state, then (for $a$ and $b$ arbitrary complex numbers) also $|K\rangle = a|f\rangle + b|g\rangle$ is a state. Moreover, the state evolution is linear, i.e., it preserves superpositions: if $|f(t)\rangle$ and $|g(t)\rangle$ are the states obtained by
evolving the states $|f(0)\rangle$ and $|g(0)\rangle$, respectively, from the initial time $t = 0$ to the time $t$, then $a|f(t)\rangle + b|g(t)\rangle$ is the state obtained by the evolution of $a|f(0)\rangle + b|g(0)\rangle$. Finally, the completeness assumption is made, i.e., that the knowledge of its state vector represents, in principle, the most accurate information one can have about the state of an individual physical system.”

This linearity is central to

• the superposition principle for quantum states: (Dirac [31]:12-18, Isham [78]:4,11), see also [107, 121, 78, 67], leading to

• interference between quantum entities as in the 2-slit experiment ([52]:4-6),

• development of entanglement ([78]:148-149),

• linearity of the wave function ([78]:15-16), hence

• expansion of the wave function in terms of a basis ([31]:53-67, [52]:86-87),

• thus it is the reason that wave functions live in a vector space ([78]:19-20) and so is why a Hilbert space formalism is suitable for quantum theory ([31]:40, [78]:19-35, 71, [115]:530-538).

• It is based in the way the amplitude is linear sum over paths ([52]:6,19,29), and hence

• is embodied in the Schrodinger and Dirac equations, both of the form ([3], leading to

• unitary transformations ([31]:103-107; [78] 113-115).

• It occurs when scattering of identical particles takes place ([54]:4.1),(4.2)), and so

• underlies the unitarity of the S-matrix ([79], 166-167; [133], 307-319),

• as well as Bose-Einstein and Fermi-Dirac statistics ([54]:4-3 to 4-15) , because permutation of states ([31]:207-216) is a linear operation.

Consequently, it is crucial in applying quantum theory to physics and chemistry [123].

In more detail: quantum theory is applicable when the evolution of the state vector is linear. It takes the form (2):

$$|\Psi\rangle \rightarrow |\Psi'\rangle = \hat{U}|\Psi\rangle$$

(11)

where the operator $\hat{U}$ is linear:

$$\forall a, b, |\Psi\rangle, |\Phi\rangle : \hat{U} (a|\Psi\rangle + b|\Phi\rangle) = a\hat{U}|\Psi\rangle + b\hat{U}|\Phi\rangle.$$  

(12)

Because the norm of $|\Psi\rangle$ is preserved, $\hat{U}$ is a unitary matrix [5]. It is given by [4] in terms of the Hamiltonian; consequently energy is preserved

$$H|\Psi\rangle = E|\Psi\rangle \Rightarrow E = \text{const}$$

(13)
because anything that commutes with $H$ is a constant, and $H$ commutes with itself.

This relates to the Feynman path integral for particle motion in the following way ([52]:26-29): the probability $P(b,a)$ for a particle to go from a point $x_a$ at time $t_a$ to the point $x_b$ at time $t_b$ is the absolute square of an amplitude $K(b,a)$ to go from $a$ to $b$:

$$P(b,a) = |K(b,a)|^2. \quad (14)$$

The amplitude is a sum of contributions from each path between events $a$ and $b$:

$$K(b,a) = \sum_{\text{paths}} \phi[x(t)] \quad (15)$$

where the contribution of each path has a phase proportional to the action $S$:

$$\phi[x(t)] = Ae^{(i/h)S[x(t)]} \quad (16)$$

and the action is the path integral

$$S[x(t)] = \int_{t_a}^{t_b} L(\dot{x},x,t)dt \quad (17)$$

where $L(\dot{x},x,t)$ is the Lagrangian of the system ([52]:26). Linearity follows from this definition of $S$ and form of $L$, because by the way integrals are defined, for any time $t_c$ between $t_a$ and $t_b$, the action along any path between $a$ and $b$ can be written

$$S(b,a) = S(b,c) + S(c,a) \quad (18)$$

where $c$ is a point for which $t = t_c$ ([52]:36,76). This underlies the key property of path integrals:

$$K(b,a) = \int_{x_a}^{x_b} K(b,c)K(c,a)dx_c \quad (19)$$

which follows on integrating over all values $x_c$ ([52]:37), leading to the wave function integral equation

$$\psi(x_b,t_b) = \int K(x_b,t_b;x_c,t_c)\psi(x_c,t_c)dx_c \quad (20)$$

([52]:57), which is linear in $\psi$, even if the kernel $K$ is non-linear.

### 3.2 Essential non-linearities of QM

However there are also two essential non-linearities in quantum mechanics.

The first is the way probabilities are derived as squares of the wave function (eqn. [5]; [78]: eqn.(5.29)) or equivalently as squares of amplitudes (eqn.(14); [52]:29). It is this non-linearity that lies at the heart of the difference between classical and quantum statistics ([54]:1-1 to 1-10, [78]:11-14). This carries over to the way expectation values are derived for any operator ([31]:45-48; [78]:83-84):

$$\langle A \rangle_\psi = \langle \psi | A | \psi \rangle, \quad (21)$$
which is quadratic in the wave function (and hence non-linear). This non-linearity is compatible with the unitary evolution (3), indeed it is essential to its interpretation, and underlies the way a normed vector space representation of quantum probabilities makes sense ([78]:13-14).

The second essential non-linearity is state vector projection (9), which is not compatible with the unitary evolution (3), (11), see Section 2.2. It is essential because probabilities of outcomes depend on individual events happening; statistics of measurements can only emerge from specific individual measurements that have separately occurred. We return to the measurement issue in Section 6.

3.3 Allowed and non-allowed non-Linearity in QM

But additionally, non-linearities allow quantum theory to describe many non-linear effects, for example those expressed in Feynman diagrams. How can that happen in a way compatible with what has been said here about linearity (Section 3)?

Basically, both through linear systems being imbedded in non-linear environments in such a way that linearity is locally preserved for subsystems of the whole — the linearity of the subsystem is not interfered with by the environment — and through approximation methods involving higher and higher orders in a perturbation series.

Specifically, we can have arbitrarily complex behaviors in the Lagrangian, but the probability amplitudes and wave function must be affected in a linear way by the time evolution. Thus non-linearity in systems obeying the QM relations can arise in two ways:

**Firstly** via the Lagrangian \( L(\dot{x}, x, t) \) in the action (17). For example for a particle of mass \( m \) subject to a potential energy \( V(x, t) \)

\[
L = T - V(x, t), \quad T := \frac{1}{2} m \dot{x}^2
\]  

Apart from the non-linearity in the kinetic energy, the potential can be arbitrarily non-linear and non-linear behavior can result, but can sometimes be soluble. The Thirring model [139] for example is an exactly solvable quantum field theory which describes the self-interactions of a Dirac field in two dimensions. The matter Lagrangian is therefore of necessity non-linear; but the equation of motion for the wave function is a linear p.d.e.

**Secondly** through the expansion of the exponential in (15):

\[
\exp(iS) = \sum_n \frac{(iS)^n}{n!} = 1 + iS - \frac{1}{2!}S^2 - \frac{i}{3!}S^3 + \ldots
\]  

The complexities of Feynman diagrams arise from this series of nonlinear terms \( S^n \) ([52]:120-125), where additionally (by (17), (22)), they themselves are non-linear terms: \( S = S(V, T) \). Non-linearities result from the many different interactions represented by the terms in this expansion. But still in these cases the action of \( U \) must be linear in |\( \Psi \rangle \) as in (11), (12) (Dirac), hence also as in (20) (Feynman), in order to be compatible with...
the foundations of quantum physics.

However nonlinearities can also arise in ways that are incompatible with these linear foundations: there is no guarantee that higher level emergent behaviour will obey (11), (12), indeed generically it won’t do so. Equivalently, there are situations where a path integral formalism (14)-(17) is simply not applicable (at the chosen level of description). I will give examples below.

The implication is that in order that the unitary quantum mechanics formalism can be applicable, one must select a subsystem of the complex interacting whole where the unitary aspect (11) is true. This is what occurs when one focuses on the relations between elementary particles, for example, and when one constructs superconducting systems or lasers or Bose-Einstein condensates. But these are very special cases, as is shown by the care one has to take in constructing such systems. It is not possible to do this for generic complex systems - or even for some quite simple macro systems.

Before considering this in the next section, we need to consider three queries that might undermine this claim.

Firstly, why is the above argument not vitiated by the existence of nonlinear versions of the Schrödinger equation ('NLS')? The problem is that since the equations themselves are nonlinear, the solutions can’t be superposed in general. There are exceptions: plane wave solutions exist for the nonlinear Schrödinger equation [118], 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. 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 generic emergence of higher level systems I consider 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.

Secondly, what about linear solutions to other non-linear equations that might describe physical behaviour? There are linear families of solutions to some special non-linear equations such as the Sine-Gordon equation; could they not be used in a theory that satisfies the linearity requirements discussed above? Similar comments apply to those above: this is not possible for a theory that covers generic physical conditions, because in the case of these equations, this linearity only holds for special initial conditions; but a general physical theory must apply to very general initial conditions. The merit of linear solutions is that (as is shown by Fourier analysis) they can represent almost any initial conditions: so solutions to the linear equation (3) are not restricted to specific kinds of
Thirdly what about thinking of quantum theory as a theory of perturbations? Almost any system can be described in a perturbation series, where the linear terms will dominate the dynamics in many cases: it’s behaviour will be linear for all practical purposes (FAPP), even though the system as a whole may be highly non-linear. Many quantum phenomena can indeed be regarded in this way. So perhaps we can regard quantum theory as a theory of perturbations which can be applied locally to almost any situation, even if it cannot be applied globally.

This view has merit. However in some cases, there is no linear perturbation theory, in the sense demanded by QM, as a good approximation to higher level dynamics. I will give examples later on. In any case this formulation makes it clear this will only cover restricted physics situations: it will not apply when the non-linearities really matter.

3.4 When is quantum mechanics valid?

The conclusion is that QM centrally implies linearity; so attempts to extend quantum physics to macro objects requires selecting a linear subsystem from nonlinearity (hence it has in particular to be shielded from environmental noise). But there may be cases where this is not possible. Leggett states (93: 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 not applicable as an effective theory determining 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, inter alia we want to consider how causality works in the case of biological systems (the right hand column of Table 1). Such complex systems are based in networks of interactions (such as gene networks, protein networks, neural networks, brain circuits) that involve non-linear structural and causal relations between constituent elements [113, 83, 2], so superposition surely would not be expected to hold in them. Note that as discussed above, ordinary quantum theory allows a certain degree of non-linearity in that it allows non-linear potentials to occur in 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 introduces non-linearities such as network motifs into the dynamics [2].
3.4.1 The central proposal

Accordingly, we can make the central proposal of this paper as follows:

**Proposal: Nature of physical reality**

1. **Combinatorial structure**: Physical reality is made of linearly behaving components combined in non-linear ways.

2. **Emergence**: Higher level behaviour emerges from this lower level structure.

3. **Contextuality**: The way the lower level elements behaves depends on the context in which they are imbedded\(^3\)

4. **Quantum Foundations**: Quantum theory is the universal foundation of what happens, through applying locally to the lower level (very small scale) entities at all times and places.

5. **Quantum limitations**: The essential linearity of quantum theory cannot be assumed to necessarily hold at higher (larger scale) levels: it will be true only if it can be shown to emerge from the specific combination of lower level elements.

The last statement is an implication of the previous ones. It is something like a macrolevel superselection rule, which is not implied by the decoherence mechanism.

Thus there are limits on quantum theory, which won’t apply at higher levels when the context creates non-linearity at those levels in such a way that superposition is impossible; hence this is a route to creation of macro objects not subject to QM. This further suggests that quantum theory applications dealing with essentially non-linear phenomena do so by introducing classical elements into the experimental description (i.e. invoking a “quantum-classical cut” ([151]:15)). This is in accord with the Copenhagen interpretation of quantum theory ([148]; [78]:132) and the way classical apparatus is routinely invoked in quantum experimental setups (see e.g. [12]:93,327; [99]:108,110,122; [151]:77,84,93).

In the following, the concept of the combinatorial structure of matter will be present throughout. The theme of emergence is picked up in Sections 3.4.2 and 3.4.3 in general, in Section 4 as regards linear systems, and in Section 7 as regards classical systems. The theme of contextuality is followed up in Section 5 in general, and in relation to the measurement issue specifically in Section 6. The way quantum foundations underlie classical systems is discussed in Sections 7.2 and 8.

3.4.2 The emergence of higher level behavior

As a preliminary, we consider how higher level behavior relates to lower level behavior in two adjacent levels in the hierarchy of complexity (Diagram 1). As stated above, the fundamental viewpoint will be that the higher level behavior emerges from that at the lower levels.

\(^3\)As mentioned later, this use of the term “contextuality” here is not the same as the rather specific way it is sometimes used in discussions on the foundations of quantum theory (see [155, 87] and references therein). The use in this paper is carefully explained below (Section 5.1).
Diagram 1: The emergence of higher level behaviour from lower level theory. Coarse-graining the action of the lower-level theory results in an effective higher level theory.

The dynamics of the lower level theory maps an initial state $i$ to a final state $f$. Coarse-graining the lower level variables, state $i$ corresponds to the higher level state $I$ and state $f$ to the higher level state $F$; hence the lower level action $t: i \rightarrow f$ induces a higher level action $T : I \rightarrow F$. A coherent higher level dynamics $T$ emerges from the lower level action $t$ if the same higher level action $T$ results for all lower level states $i$ that correspond to the same higher level state $I$ [43], so defining an equivalence class of lower level states that give the same higher level action $T$ (if this is not the case, the lower level dynamics does not induce a coherent higher level dynamics, as for example in the case of a chaotic system). Then on coarse graining (i.e. integrating out fine scale degrees of freedom), the lower level action results in an emergent higher level dynamics: the effective theory at the higher level. Three key points follow.

**EM1: Non-Commutation:** coarse-graining and dynamical action do not commute in general, inter alia because a great deal of information is hidden in the higher level view, and also because

**EM2: Essential higher level variables:** not all effective higher level variables can be derived by coarse graining [43].

Consequently

**EM3: Emergent dynamics:** the effective higher level dynamics will in general not be the same as the lower level dynamics [5].

Here are some examples:

- **E1: Statistical physics** The underlying atomic theory leads to the macroscopic gas laws, thermodynamics, and thermal properties of gases ([4]:434-518). There is no similarity between the underlying theory and the emergent theory, except that concepts of mass, energy, and momentum conservation apply at both levels.

- **E2: Electrodynamics** The process of coarse graining leads to the polarization density of a polarized medium ([140]:343-349), where the electric field $E$ is a coarse-grained version of the microscopic electric field $e$, and the displacement vector $D = E + 4\pi P$ includes a polarization term $P$ representing coarse-grained dipole terms ([80]:103-108). The fields $D$ and $E$ are related by a polarization tensor $\epsilon_{ij}$ such that $D_i = \epsilon_{ij}E_j$. The tensor $\epsilon_{ij}$ depends on the micro structure of the medium; in an isotropic medium, $\epsilon_{ij} = \delta_{ij}$ (using Cartesian tensors); in an anisotropic medium this is not the case. The coarse grained version of Maxwell’s equations gives the divergence of $D$ and curl of $E$, so a modified version of the microscopic equations emerges. The emergent theory is largely similar to the underlying theory.
• E3: Gravitational theory Coarse graining leads to backreaction effects modifying the coarse grained Einstein equations [39], which can in principle significantly affect the macro dynamics. However in the context of current cosmology, these are very small effects [26]: the emergent theory is very similar to the underlying theory.

• E4: Physics to Chemistry The interactions of Fermions leads through the Fermi exclusion principle to the nature of the hydrogen atom (4:109-148) and the electronic structure of atoms (4:158-176) and so the periodic table [111,6]: the nature of the chemical bond emerges from physics [111,6]. There is no similarity between the underlying theory and the emergent laws.

• E5: Chemistry to Microbiology and Life The complex modular hierarchical structure of life emerges from the underlying physical and chemical laws [20]. There is no similarity between the underlying theory and the emergent behaviour, except that concepts of mass and energy balance apply at both levels.

In most cases, the underlying theory leads to a higher level theory characterizing quite different behaviour (after all, that is the essential content of Table 1).

3.4.3 The emergence of higher level quantum behavior

For quantum like behaviour to emerge at a higher level, one needs to select subsystems of the emergent whole where interference and entanglement are possible. When is this possible? Firstly,

**LSS: Linear state space:** the relevant variables must live in a linear space,

A vector space structure for a state space can be natural even mandatory, even with non-linear equations of evolution. Think of non-linear wave equations eg water!: the waves form a vector space under pointwise addition of functions[4]. But there are plenty of (one real-parameter groups of) non-linear maps on a vector space eg a Hilbert space. So one can have superposability of states, but the dynamics can fail to preserve a given superposition. One must avoid this (cf. the quote from Ghirardi in Section 3.1), so the second requirement is

**LE: Linear evolution:** the relevant dynamical evolution must be linear (a special case being unitarity), hence respects the linear state space structure.

Then the probability amplitude evolves linearly, so we need to find linearly behaving subsets of complex systems (possibly emerging as collective modes of lower level components). Inter alia this means we must

• **L1:** restrict them in phase space terms, so that they remain in a linearly behaving domain of phase space (which will always be limited in both position and momentum terms, as eventually non-linearities will occur for larger size and energy scales).

• **L2:** shield them from noise and interfering effects (so they must be isolated from the environment),

---

4I thank Jeremy Butterfield: for these comments.
• **L3:** restrict internal noise generation (so they must be cold),

It is very difficult to attain such a situation on a macroscale, or even a nano scale. Milburn ([104]:94-95) states this as follows, in regard to electrons in a crystal structure:

> “While we can carefully model the effect of the regular array of ions in the lattice, we have no knowledge at all of the details of the defects and impurities. Furthermore, at a finite temperature the ionic cores are wobbling around in a random way which we can only describe statistically. Were it not for these complications, we could use Schrödinger’s equation to assign probability amplitudes for an electron ....”

> “There are two things we can do to prevent phase-destroying collisions. We can try and make ultra pure samples in which the defects and impurities are carefully controlled. This is exactly what is done, and indeed the artificial crystals grown to form such devices are probably the most pure and perfect artificial constructions ever made. The only way to reduce the effect of random lattice vibrations is to cool the devices. Typically liquid helium temperatures are used, a few degrees above absolute zero .... Quantum nanodevices are very cold, extremely tiny, near-perfect electrical devices.”

This illustrates why we do not expect quantum behaviour to often emerge in a solid in a macro-context. It is easier to satisfy these conditions with photons, as in the case of quantum optics devices [99]. To investigate this further, it is useful to consider the variety of examples where linearity can emerge at higher levels. I will first give some examples where this is possible (Section 4.1), and then some where it is not (Section 4.3, which picks up on Point 5 in Section 3.4.1).

### 4 Emergence of linearity

Hence the issue is, under what conditions can an emergent higher level behaviour resulting from low level quantum theory still be described by the quantum theory laws of behaviour? (Diagram 2).

| Level $N + 1$: Higher level theory | Emergent Theory? |
|-----------------------------------|-----------------|
| $\uparrow$                         | $\uparrow$      |

| Level $N$: Underlying theory      | Quantum Theory   |

Diagram 2: *The emergence of higher level behaviour from the underlying quantum theory.*

Suppose higher levels have effective laws valid at that level that are emergent from the actions of lower level laws. Then behavior at a higher level $N + 1$ emerges from that at the lower level $N$. Suppose the laws of quantum physics hold at level $N$ with Hamiltonian $H_N$. Then three possibilities arise:

1. **Case 1:** Quantum theory remains valid at level $N + 1$ with the same Hamiltonian as at level $N$, i.e. $H_{N+1} = H_N$. Energy is conserved at level $N + 1$
2. **Case 2**: Quantum theory remains valid at level $N+1$ with a different Hamiltonian than at level $N$, i.e. $H_{N+1} \neq H_N$. Energy is conserved at level $N+1$.

3. **Case 3**: Quantum theory is not valid at level $N+1$: there is no Hamiltonian description applicable at that level; the evolution is not unitary. This must be the case if usable energy is not conserved at level $N+1$.

Section 4.1 considers when higher level linearity can emerge from lower level linear equations (Cases 1 and 2), while Section 4.2 makes the case that generically we may expect higher level behaviour to *not* be Hamiltonian (Case 3). Section 4.3 considers examples where this does not occur; this vindicates Point 5 in Section 3.4.1.

### 4.1 Cases where linearity can emerge

I now consider a series of cases where linear higher level behaviour emerges from linear lower level behaviour.

**Classical to classical example: Centre of Mass motion.** The classical example of emergence of higher level linear behaviour out of lower level linear behaviour is the case of centre of mass motion (see [63] for a clear description). Consider a system of $N$ point particles of mass $m_i$ at position $r_i$. Newton’s law of motion for the $i$th particle is

$$m_i \ddot{r}_i = F^*_i = F_i + \sum_j F_{ij}$$

(24)

Here $F^*_i$ is the total force on the $i$th particle, $F_i$ is the external force, and $F_{ij}$ is the internal force due to the $j$th particle (there is no self-force: $F_{ii} = 0$). Newton’s third law states action and reaction are equal and opposite:

$$F_{ij} = -F_{ji}.$$  

(25)

Consequently adding the equations (24) together for $i = 1$ to $N$,

$$\sum_i m_i \ddot{r}_i = \sum_i F^*_i = \sum_i F_i$$

(26)

Defining the total mass $m$, centre of mass position $\mathbf{r}$, and total external force $\mathbf{F}$ by

$$m := \sum_i m_i, \quad m \dot{\mathbf{r}} := \sum_i M_i \dot{r}_i, \quad \mathbf{F} := \sum_i F_i$$

(27)

we find

$$m \ddot{\mathbf{r}} = \mathbf{F}$$

(28)

so the linear law for the individual particles (first equality in (24)) is replicated by the coarse-grained variables (27) - irrespective of the nature of the internal forces.

This leads to the emergence of Hamiltonian dynamics for particle motion [56, 18], as for example applied in celestial dynamics (governing the dynamics of stars in galaxies [13]). This also applies to motion of objects on Earth in situations where friction may be
ignored: but they are very limited.

**Classical to classical example: Geometric optics.** In the high frequency limit, Maxwell’s equations for the electromagnetic field leads to geometric optics [80, 97, 75], with light propagating in a way described by Hamiltonian dynamics. The different wavelengths do not interfere with each other because the system is linear, hence spectral decomposition makes sense.

**Classical to classical example: Engineering and Natural systems.** As pointed out strongly by Bracewell [11], many manufactured and engineering systems have a linear dynamics that leads to periodic behaviour and the suitability of Fourier Analysis. This occurs particularly when the system is engineered to have linear modes, for example organ pipes, guitars, linear electrical and electronic circuits, and so on; however there may be such modes in other cases, for example wave modes in suspension bridges and torsional oscillations of buildings. There are also similar instances in the natural world, for example propagation of water waves and sound waves - indeed anywhere where Fourier Analysis applies, linearity of the relevant degrees of freedom leading to the splitting of the system into normal modes with different frequencies that don’t interfere with each other.

However these examples although ubiquitous are also limited: the engineering examples are carefully tailored to behave in this way, often at considerable expense, and they have frequency limits beyond which the linear behaviour ceases. Similarly the linear behaviour of natural systems is very limited in time and space. Non-linearities intrude when we examine behaviour beyond these limits.

**Quantum to classical example: Ehrenfest’s theorem.** As a consequence of the Schrödinger equation (3), the time derivative of the expectation value for a quantum mechanical operator is determined by the commutator of the operator with the Hamiltonian of the system:

\[
\frac{d}{dt} \langle A \rangle = \frac{1}{i\hbar} \langle [A, H] \rangle + \langle \frac{\partial A}{\partial t} \rangle
\]  

Applying this to the case of a particle of mass \( m \) and momentum \( p \) moving in a potential \( V \) (see (22)) so that \( H = p^2/2m + V \), and defining \( \langle F \rangle = -\langle \nabla V \rangle \), one finds

\[
\frac{d\langle p \rangle}{dt} = \langle F \rangle, \quad \frac{d^2\langle x \rangle}{dt^2} = \frac{1}{m} \langle F \rangle,
\]

in agreement with the classical equation (28). Hence the linearity of (3) results in the linearity of the relations (30), which are however not quantum relations (they have a classical form).

**Quantum to quantum: Renormalization group** In some cases one can prove that coarse-graining a Hamiltonian systems leads to another Hamiltonian system with the same Hamiltonian but different values of its constants. One example is the Wilson approach to renormalization theory, where the high momentum degrees of freedom in the generating functional \( Z[J] \) are integrated out, leading to the renormalization group relating

\[\text{For a conveniently accessible proof, see the Wikipedia entry on Ehrenfest’s theorem.}\]
parameters of the original Lagrangian to the new Lagrangian ([117]:394-409; [152]:341-345). However this is possible only in restricted circumstances ([117]:402-403).

Another example is the Kadanoff construction, explicitly coarse graining an Ising model, thus defining a coarse-grained lattice and block spin variables. The coarse-grained dynamics are governed by a Hamiltonian that is a function of the coarse grained variables on the coarse grained lattice ([22]:237-242); indeed the block spins interact via the same Hamiltonian as the original spins, leading to a scaling of free energy and applicability of the Wilson renormalization group ([150]), see ([22]:245-248).

**Quantum to quantum: Effective Theories** In some cases, coarse graining will result in a Hamiltonian theory at the higher level, but with a Hamiltonian that has a different form. This is the case of effective field theories that emerge at higher level from the underlying physics ([72], [152]:437-440): an effective Lagrangian or Hamiltonian governs the higher level dynamics, but it’s different from the one you started with. One cannot always derive this higher level effective action by explicit coarse graining, but can often determine the form the effective action should take by symmetry and conservation principles. The classic example ([152]:441) is Fermi’s β-decay theory ([49], now embodied in Fermi’s Golden Rule ([126]:332), which is of wide application (see e.g. [27]:84-86; [61]:20,165-166).

Other examples are effective field theories of a Hall fluid ([152]:302-303) and of proton decay ([152]:440-441). A more recent application relates to gravitational theory and the early universe. When one treats cosmological inflation in the early universe as being due to an effective theory, integrating out physics above some energy scale Λ induces non-renormalizable operators in the effective theory. This can also lead to corrections to the kinetic terms which contain higher powers of derivatives; the effects on the early universe are different than in the standard theory ([57, 58] and references therein).

**Quantum to quantum: Long range order** The electron system in superconductors can exhibit long range order, with strong correlations in the wave functions of pairs of particles over distances longer than the coherence length ([158]:402-403). Hence one can introduce a macroscopic wave function Ψ(r) (the Ginzburg-Landau order parameter) for the superfluid component of the electron density, leading to flux quantization ([158]:404-405) as a macroscopic manifestation of quantum mechanics. Ψ(r) obeys a time dependent Schrödinger equation ((11.87) in [158]) which underlies the Josephson effect ([158]: 405-410).

This is possible only in the context of metals with a periodic lattice structure, or other materials that allow superconductivity ([158]:396,410-414). The restricted nature of the contexts that allow this emergence of higher level effective quantum equations is shown in the great difficulty of the search for superconductors other than metals. In the case of metals, it is only possible when the temperature is exceedingly low, so that the non-linear interactions that would occur at higher temperatures are suppressed.
4.2 Hamiltonian environment?

The focus in this section is to make the case that generically the environment of a quantum system may be expected to not behave in a Hamiltonian way.

4.2.1 Example of Non-Hamiltonian emergence

An example of the latter type is as follows: Two systems $A$ and $B$ with respective states $|\psi_A\rangle$ and $|\psi_B\rangle$ in Hilbert spaces $\mathcal{H}_A$ and $\mathcal{H}_B$ have a joint wave function

$$|\psi_{AB}\rangle = |\psi_A\rangle \otimes |\psi_B\rangle$$  \hspace{1cm} (31)

A general state is

$$|\psi_{AB}\rangle = \sum_{i,j} c_{nm} |u_n(x)\rangle_A \otimes |u_m(x)\rangle_B$$  \hspace{1cm} (32)

Two states are entangled when their wavefunctions cannot be written as a simple product state (31). If their evolution is given by

$$|\psi_2\rangle_A = U(t_2,t_1)_A |\psi_1\rangle_A, \quad |\psi_2\rangle_B = U(t_2,t_1)_B |\psi_1\rangle_B,$$  \hspace{1cm} (33)

then

$$|\psi_{2AB}\rangle = U(t_2,t_1)_A |\psi_{1AB}\rangle, \quad U(t_2,t_1)_{AB} := U(t_2,t_1)_A \otimes U(t_2,t_1)_B$$  \hspace{1cm} (34)

so the joint evolution is unitary. However if a wave function projection (9) takes place for either component then it’s evolution is not unitary and neither is that of the composite state: it cannot be represented as (34). Thus non-unitary evolution emerges at the higher level from the non-unitary evolution at the lower level (which is reflected in the way the density matrix evolves through a Markovian master equation in Lindblad form ([61]:54-58; [12]:297-299; [151]:119-121), with consequent entropy generation [154].

This example is perhaps controversial because it involves the disputed nature of the quantum measurement process. I will give other examples of non-linear emergence in the next section and Section 4.3 and then pick the theme up in Section 7.

4.2.2 Open systems and their environment

Effect of the environment on the system: Following Breuer and Petruccione, consider an open quantum system $S$ (‘the system’) coupled to another quantum system $B$ (‘the environment’), with respective Hilbert spaces $\mathcal{H}_S$ and $\mathcal{H}_B$ ([12]:110-120). The Hilbert space $\mathcal{H}$ of the combined system $T = S + B$ is $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_B$. The total Hamiltonian $H_T$ is taken to be of the form

$$H_T = H_S \otimes I_B + I_S \otimes H_B + \hat{H}_I(t)$$  \hspace{1cm} (35)

where $H_S$ is the self Hamiltonian of the open system, $H_B$ the free Hamiltonian of the environment, and $\hat{H}_I(t)$ the Hamiltonian describing the interaction between the system and the environment. Now an ensemble $\mathcal{E}$ of pure ensembles $\mathcal{E}_\alpha$ for the total system $S$ with weights $w_\alpha$ has a density matrix

$$\rho = \sum_{\alpha} w_\alpha |\psi_\alpha\rangle \langle \psi_\alpha|.$$  \hspace{1cm} (36)
The reduced density matrix for the system $S$, given by tracing out the environment, is

$$\rho_S = \text{tr}_S \rho$$

(37)

It follows from the unitary evolution of the total density matrix $\rho$ that the reduced density matrix evolves according to the Lindblad master equation

$$\frac{d}{dt} \rho_S(t) = -i [H, \rho_S(t)] + \mathcal{D}(\rho_S(t))$$

(38)

where the unitary part of the dynamics is generated by the new Hamiltonian $H$ and the dissipator $\mathcal{D}(\rho_S)$ is determined by the spectral decomposition of the density matrix $\rho_B$ of the environment ([12]:103-119). The viewpoint here is that shown in Diagram 3.

The two key points then are that (i) in general $H \neq H_S$ – this is what opens the way to the renormalization group and higher level effective Hamiltonian theories – and (ii) generically $\mathcal{D}(\rho_S) \neq 0$: the higher level system is not Hamiltonian, and hence (38) is associated with the generation of entropy ([12]:123-125; [154]). This carries through to all the other versions of the master equation, for example the interaction picture master equation ([12]:130) and the quantum optical master equation ([12]:140-149).

\begin{tabular}{|c|c|}
\hline
(Hamiltonian) & System plus environment $\mathcal{T}$ \\
\hline
& $\downarrow \downarrow$ (Coarse grained) \\
\hline
System $S$ & $\iff$ components $\iff$ Environment $B$ \\
\hline
(Non-Hamiltonian) & \\
\hline
\end{tabular}

Diagram 3: The system plus environment evolve in a Hamiltonian way, and interact with each other. When the environment is traced over, the system evolves in a non-Hamiltonian way.

Another example is the Hawking effect [73], in which tracing over modes (of a pure state quantum field) that are lost behind a black hole horizon results in a thermal state in the external region.

Effect of the system on the environment: Now change viewpoint: coarse grain the system not the environment. But the same equations apply! Just swap the labelling ($B \leftrightarrow S$) in the above equations and the result will be

$$\frac{d}{dt} \rho_B(t) = -i [\bar{H}, \rho_B(t)] + \bar{\mathcal{D}}(\rho_B(t))$$

(39)

(where now the Hamiltonian $\bar{H}$ and dissipator $\bar{\mathcal{D}}$ are different than in the previous case). This shows the system can cause non-Hamiltonian behavior in the environment. Realizing that in terms of the hierarchy in Table 1, the environment is at a higher level than the system, we can represent the situation as in Diagram 4.

---

6I thank the referee for this suggestion.
But this raises the key issue: *why are we entitled to assume the combined system \( T \) behaves in a Hamiltonian way*? We could start with \( B \) as the total system and then separate out a subsystem of \( B \) to be designated as the subsystem \( S_1 \) of interest. We are surely entitled to query why we should assume that the top level (\( T \) in Diagram 3, \( B \) in Diagram 4) behaves in a Hamiltonian way?

| (Coarse grained) | Environment \( B \) (Non-Hamiltonian) | ↑ |
|-----------------|--------------------------------------|---|
|                  | System \( S \) (Hamiltonian)         |   |

**Diagram 4:** When coarse-grained, the Hamiltonian system \( S \) induces non-Hamiltonian behaviour in the environment \( B \).

### 4.2.3 Emergence of non-linearity

Now this contradicts what is usually understood as the standard hypothesis of quantum physics: as stated by the referee of this paper, this is as follows:

**Standard Hypothesis:** *In a closed system obeying quantum mechanics at the lower level, nonlinearity cannot emerge at a higher level from quantum mechanics plus interactions alone. Only if the system is open can nonlinearity feed into the system. A full quantum description of an isolated macroscopic system may be practically impossible, but either it is possible in principle, or quantum mechanics breaks down at some level of size or complexity. In an isolated system one cannot appeal to openness to inject the crucial nonlinearity. Where do the the nonlinearities come from, if they are not present in the constituent particles and their interactions alone?*

But a main point of this paper is that the assumption of linearity at all scales is an *a priori* untested assumption that extrapolates what happens at micro scales to arbitrarily large scales, and may or may not be true. It is an assumption involving extrapolation of extraordinary scope when applied to the universe as a whole. The standard view is that things are linear on the largest scales, and non-linearity sometimes emerges by top-down action from these large scales to smaller scales. The view in this paper is the converse:

**Alternative view:** *Linearity holds on the smallest scales, and higher level behaviour emerges from the local applicability of such linear behaviour everywhere; this higher level behaviour may or may not be linear. The non-linearity arises from specific configurations of particles that lead to complex networks of interactions; these configurations are higher level properties of the system. It is initially an experimental question whether higher level behaviours are linear or not. Theory must then accommodate to whatever experiments determine; and they appear to show that quantum mechanics does indeed break down at higher levels of size or complexity.*

An example is the non-linear explosive behaviour of a mixture of trinitrotoluene (TNT) and oxygen in a closed container, which is not due to the mixture being an open system
(it is not), it is due to the molecular structure of the TNT. In section 3.4.2 and in the next section I give examples where the usual assumption is indeed wrong. The situation shown in Diagram 3, where the higher level is Hamiltonian, is not generic; it will only hold under special circumstances. The suggestion is that this vindicates the claim made in Point 4, Section 3.4.1. One view would be that the examples in the next Section are merely phenomenological practical procedures leading to effective theories for dealing with large systems, as opposed to fundamental. The idea here is that they may indeed be fundamental: each level should be regarded as having an existence in its own right, rather than merely derivative from the level below; emergence is real emergence, rather than an illusion [5, 91, 41]. The TNT has real causal power not implied by the constituent particles and their interactions alone: it is in the organization of those particles that the crucial causal power resides (the same constituent particles are still there after the explosion, subject to the same interactions; it is their organization that is different). This possibility of real emergent higher level causal powers occurs because top-down causation takes place in the hierarchy of complexity [48], as discussed below (Section 5).

What then determines how nonlinearity emerges from linearity? It resides in the details of the physics of emergence [135], which leads to new levels of complexity with their own logic of behaviour and associated causal powers. The details are very different in different cases, as the examples that follow show.

### 4.3 Cases where unitary behaviour does not emerge

Here I consider some examples where the coarse grained behaviour arising from the underlying theory is not Hamiltonian and so does not exhibit quantum characteristics. There will be four levels at which this happens.

- The Anderson idea of novel notions at higher levels [5] (e.g. Section 3.4.2);
- The non-interference of states at higher levels (e.g. Section 4.3.1);
- Non-unitary evolution at higher levels (e.g. Section 4.3.2);
- The general idea of classical emergence at higher levels (Section 7).

Much of this is perhaps rather obvious; it is worth pursuing for two reasons. First, as I will consider later (Section 7), any situation where unitary behaviour does not emerge is a possible channel for creating classical systems out of quantum components. Second, some of the present day literature (e.g. [143, 71]) assumes that quantum behavior will be always be present at higher levels. The present view contradicts that assumption (see Section 7.3).

#### 4.3.1 Stochastic situations: equilibrium

**Boson Gas:** In the case of a boson gas, the wave function at the quantum level is symmetric, ([31]:205-211), resulting in the Bose-Einstein distribution law ([4]:528-530) on coarse-graining. Non-linear macroscopic laws of behaviour emerge, describable in purely classical terms. For example, in the case of photons one obtains the black body spectrum for radiation ([4]:7-11;531-532), and the consequent formula for energy density and
pressure of a photon gas:

\[ \rho(T) = \frac{8\pi h}{c^3} \int_0^\infty \frac{\nu^3 d\nu}{e^{\hbar \nu / kT} - 1}, \quad p(T) = \frac{\rho(T)}{3c^2} \]  

(40)

The key point is that these are relations for classical variables: there is nothing in the behaviour at this higher level corresponding to superposition of states or entanglement. The pressure \( p(T) \) and density \( \rho(T) \) given by (40) are not in any sense fictitious variables. Rather they are the essential causally effective variables at their level of description in the hierarchy (Table 1), for example playing a key role in astrophysics and cosmology [34, 47]. The situation is shown in Diagram 5:

| Classical Level | Gas laws | Temperature \( T \), Density \( \rho \), Pressure \( p \) |
|-----------------|----------|-----------------------------------------------|
| **Coarse Grain** | ↑        | ↑ Bose Einstein statistics                     |
| Quantum Level   | Photon gas | symmetric wave function                        |

Diagram 5: The emergence of higher level effective classical variables from the underlying quantum theory.

Similarly one attains macro formula for the pressure and density of a gas of molecules with zero integral spin ([4]:Eqn.(13.32)). In a metal, a phonon gas leads to formula for the heat capacity \( C_V \) of a solid ([4]:Eqn.(13.28)). These are all emergent classical properties, as in the case of the energy density and pressure in (40).

**Fermi Dirac gas:** In the case of an electron gas, the wave function at the quantum level is anti-symmetric ([31]:205-211), resulting in Fermi-Dirac statistics ([4]:519-522). This again results in higher level non-linear behaviour describable in purely classical terms, e.g. the thermo-electric current density coming from a metal surface in terms of the temperature of the metal ([4]:Eqn.(13.11)).

Overall, the emergence of these classical levels from the underlying quantum theory is in accord with the view put in Section 2.4:

*Each of the higher levels of the hierarchy of complexity is real in its own right, described by relevant variables for that level, and laws of behaviour that are effective at that level. These variables and interactions emerge from the underlying quantum variables, and in the case of equilibrium states are classical variables.*

But the word “effective” sounds perjorative: they are the laws of behaviour applicable at that level. When equilibrium occurs, classical higher level thermodynamic behaviour emerges from the underlying quantum structure. The way this happens is presented by Gemmer, Michel and Mahler [61]. The essential point is that the statistical interactions between the components that lead to equilibrium destroy any coherence among the higher level variables. An example is that the transition to equilibrium in a crystal relies on the Umklapp process ([61]:223), which does not preserve momentum, and so is not a unitary process. Presumably this corresponds to frequent collapse of the wave function.
at the micro-level: for if that does not take place, the necessary interactions between the components for thermalization will not have occurred, and they can be expected to occur very frequently.

4.3.2 Dissipative effects: non-equilibrium

Dissipative effects, and consequent entropy increase enshrined in the second law of thermodynamics ([29]:139-144, [6]:119-124) are a fundamental part of what goes on at the macroscale [38]. This is associated with coarse graining of microphysics [115]: 688-699; [61]:45-48), whereby energy stored in microscopic states are inaccessible via macro variables, and so lead to unusable energy and hence effective energy loss experienced at the macro scale (even though no energy is actually lost if one takes into account also the inaccessible internal energy degrees of freedom). These states thus act like the environment in Section 4.2.2. The process whereby this emerges from the underlying unitary theory is coarse graining by integrating out micro variables.

Clearly this is a non-Hamiltonian macrolevel behaviour, emerging from Hamiltonian microlevel behaviour. It derives from the underlying unitary quantum systems, and a large literature on dissipative quantum systems discusses how this happens (see [12]:166-194,465-480); but as in the previous case (Section 4.3.1 and Diagram 5), it results in effective classical behaviour at the higher level (this has to be so, as that behaviour is dissipative and hence non-unitary; clearly superposition, interference, and entanglement cannot be expected to occur in terms of the interaction dynamics of these macro variables). It results for example in the existence of dissipative systems in biology ([113]:40-56,62-72), which are essential for life to exist ([113],[20]).

4.3.3 Chaotic systems

Quantum systems do not exhibit chaotic behaviour (subject to exponential sensitivity to initial conditions), but non-linear classical systems can do so. Quantum chaos theory examines the problem of how this can be possible, in view of the correspondence principle relating classical to quantum mechanics [68].

4.3.4 Elements or circuits with a threshold

Whenever an element or circuit has a threshold, the behaviour is non-linear when one crosses the threshold. Examples are rectifiers and digital elements such as inverters, logic gates, and more complex digital circuits ([103]:34-57). Important examples are photodiodes and photovoltaic cells ([103]:200), based in the photoelectric effect ([3]:11-14). Other examples are chemical and nuclear systems with an activation threshold.

4.3.5 Feedback control loops

A key example is feedback control systems with fixed goals, such as a thermostat. Such systems are classically described, and hence non-unitary; they will also usually be dissipative, so there will be no question of a Hamiltonian description. They are ubiquitous in engineering [70] and in biology [105, 19, 77], and are an important form of top-down
action [43]. Their functioning is indicated in Diagram 6.

| Controller | ⇐ Correction signal |
|------------|---------------------|
| **Action** | ⇑ Feedback ↑ |
| **State**  | ⇔ Comparator ⇔ Goal |

**Diagram 6:** *The basic features of a feedback control system. 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.*

At each cycle of the system, a measurement of the system state is compared with a desired state, and an error signal sent to a controller to correct the error and make the system state approach the desired state [10] [33]. Hence the feedback control process demands a determination of the current state of the system, to give the information contained in the feedback control signal to the controller. This specific information utilized to determine the further dynamics can only be obtained by a measurement process entailing collapse of the wave function at the underlying quantum level. Non-unitary collapse interposes at each time step. Furthermore the macro dynamics clearly will not support superposition or constructive interference: whatever the input state, the output state is the same (the desired temperature, in the case of a thermostat). This outcome is due to the choice of goals - a high level property of the system that is not reducible to lower level entities, or even describable in lower level language [43]. An example is the choice of setting of the desired temperature in a thermostat, which can be chosen at will; this sets the goal (the chosen temperature), which the system then implements (many electrons flow to make this happen).

What then about the burgeoning literature on quantum feedback control (see [151]:216-340)? Does this not contradict what has just been said? No, it does not. Inspection will show that all such schemes use classical detectors to feed back a control signal to the quantum system (e.g. [128]; [151]: Fig 5.1, Fig 5.2, Fig 6.1; [127]). This has to be the case, as a purely quantum system could not provide the needed classical control signal. It can’t do this unless specific individual measurements take place to provide the classical signal! And one should note the following point: suppose one linearizes to the case of small disturbances about the equilibrium state. It will still be true that a measurement is needed to complete the circuit, so quantum theory won’t be able to handle it; and it will still be true that, because the dynamics drives all input values to zero, there will be no superposition of solutions. Hence even the linearized version of the equations will not be of the unitary form [2].

### 4.3.6 Complex networks

A feedback control loop is just one of the network motifs identified by Alon as occurring in biological networks [2]. Real biological networks are immensely complex [30], and will contain many complex interactions and network motifs, including feedback control loops. Hence they too will be non-Hamiltonian systems. This will apply in particular to the
connections between neurons in a brain [83], which are made up out of microcircuits that are themselves very complex [136].

4.3.7 Adaptive Selection

| System state | ⇐ Selection agent: selects state | Meta-goals: |
|--------------|----------------------------------|-------------|
| Variation    | ⇑                               | Selection criteria |
| Ensemble of System States | ⇒ Preferred state in ensemble ⇐ |             |
| Environment  | ⇑                               |             |

Diagram 7: The basic features of adaptive selection. Selection takes place from an ensemble of states, the selection being based on the action of some selection criteria in the context of the specific current environment.

A further key example is the process of adaptive selection [84, 60], ubiquitous in biology [20], but also occurring in digital computers, for example in artificial neural networks and genetic algorithms [43]. Selection takes place from an ensemble of initial states to produce a restricted set of final states that satisfy some selection criterion. The process is summarized in Diagram 7. Note that it can take place in a once-off form: in biology it gains its enormous strength because it is repeated so many times, but that repetition is not essential to the concept of selection. In a selection event, in effect the selection agent compares the entities available in the initial ensemble to determine the best candidates on the basis of the preset selection criteria, evaluated in the current environmental context. The best candidate is selected and retained as the outcome of the event; the rest are discarded. The meta-goals embodied in the selection criteria do not necessarily lead to a specific final state (although they may do in some restricted circumstances): 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 initial data; 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 selection criteria and the environment [76].

One could call it simply selection, but I prefer adaptive selection to emphasize that it always take place as a consequence of the existence of selection criteria, which are higher level entities in the hierarchy of causation; hence this is another form of top-down action [43]. An example is the case of state vector preparation by a polarizer, which I will show below (Section 5.2.6) can be regarded as a case of adaptive selection, because it selects the desired specific polarization state from a jumble of incoming random polarization states. The experimenter chooses the axes of the polarizer; this determines which polarization state gets selected from those arriving. This is a simple model of the general way in which adaptive selection is guided by the meta-goals; in most cases they are not as specific (in biology for example, it is simply survival). Note the difference from feedback control, where no ensemble of incoming states is involved.

Like the case of feedback control, this also demands an effective collapse of the wave function, firstly as the selection process results in specific determinate outcomes, and sec-
ondly because the process in effect makes a decision on the basis of the specific outcomes of the individual variations that underlie such selection processes. Superposition of outcome states is hardly possible: it is not a Hamiltonian process. As in the case of feedback control loops, even if one linearizes there will be no Hamiltonian description possible; inter alia this is because a selection process involves thresholds, which are non-Hamiltonian (as discussed above in Section 4.3.4).

The importance of this process is that it is the way meaningful information enters the physical world in a way that is unpredictable on the basis of the underlying physics, thereby enabling the emergence and functioning of true complexity \[20, 43\]. This takes place by selection of a subset of states from an ensemble, \textit{which is the basic process whereby information that is relevant in a specific context} \[124\] \textit{is selected from a jumble of irrelevant information}. Some information is selected, some discarded. This is what enables an apparent local violation of the second law of thermodynamics, as in the case of Maxwell’s Demon (\[53\]:46-5; \[92\], \[1\]:4-6; \[21\]:186-189, 196-199) – who is indeed an example of an adaptive selection agent, acting against the local stream of entropy growth by selecting high-energy molecules from those with random velocities approaching a trap-door between two compartments. The selection criterion is the threshold velocity \(v_c\) deciding if a molecule will be admitted into the other partition or not. It is significant that Maxwell’s demon type devices can be created in the lab \[125, 119, 120, 131\], explicitly demonstrating that adaptive selection can arise in a quantum physics context. It occurs also in microbiology, where active transport systems are enabled by voltage gated ion channels (\[95\]:191-206).

\textbf{Darwinian selection} is just the process of repeated adaptive selection in biology, with reproduction and variation between each stage of selection \[20\]; it certainly takes place in the real world as an emergent feature from the underlying quantum Hamiltonian dynamics, and is the core feature leading to the existence of life. It is obviously not a Hamiltonian process.

5 Contextual effects in quantum physics

Now I turn to the converse of emergence, namely the way that contextual effects change the nature of interactions at the lower levels. Section 5.1 considers the broad nature of top-down causation in general, and Section 5.2 specific cases where it occurs in quantum physics. This relates to some of the examples given in the previous section.

5.1 Top-down causation

The higher levels of the hierarchy of complexity and causation (Table 1) provide the context within which the lower level actions take place. By setting the context in terms of initial conditions, boundary conditions, and structural relations, the higher levels determine the way the lower level actions occur.

A simple example is a digital computer \[138\]: the lower level transistors and integral circuits function in exactly the same way whatever higher level program is loaded; but the
higher level program determines the outcomes - music, pictures, graphs, or whatever. A physics example is the way that cosmological-level coarse grained variables control nuclear reaction rates in the early universe by determining how the temperature $T$ varies with time, thereby determining the way cosmological nucleosynthesis pans out [34, 47].

The general picture is that in Diagram 8:

*The lower levels do the work, but the higher levels decide what is to be done.*

| Level N+1: Higher level theory | **Effective Theory** |
|-------------------------------|----------------------|
| **Top-down effects**          | ↓                    |
| Level N: Quantum Theory       | **Contextual effects**|

**Diagram 8:** *The effective higher level theory exerts contextual effects on the operation of the underlying quantum theory.*

This can be regarded as top-down causation in the hierarchy of complexity. 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 [43, 46]). The fundamental importance of top-down causation is that it changes the causal relation between upper and lower levels in the hierarchy, in particular enabling inter-level feedback loops. It is a common view that “only if the system is open can nonlinearity feed into the system.” [7] but then the fundamental point is that things are interconnected:

**Interacting systems:** *there are no closed systems in the real universe, apart from the universe itself.*

All finite systems are open because their environment influences them both in historical terms, setting the initial condition for the system to exist, and in functional terms, affecting them on an ongoing basis, as acknowledged for example in the discussions of environmental decoherence [159, 160, 67]. This is a top-down influence from the environment to the system. Furthermore the whole point of causal networks, such as feedback control loops [33] and other network motifs [2], is that they ensure that the individual components are not closed systems: they feed information to each other.

**Proving top-down causation** How do we prove top-down effects are occurring? One has to show that changing some higher level condition changes lower level dynamics or behaviour. For example, changing the length of an organ pipe changes the wavelengths of possible standing waves, so the sound it emits depends on its size; similarly changing the shape of a drum changes the sounds it emits. By contrast, the black body spectrum [40] is independent of the size and shape of an oven that emits blackbody radiation; it is determined by purely local effects.

**Equivalence classes** Technically, the way this works is that equivalence classes of lower level states correspond to a single higher level state [7]; for example in the case of a gas in a cylinder, a myriad of lower level molecular states $s_i$ will correspond to a

---

[7] This comment comes from the referee.
specific higher level state $S$ characterized by a temperature $T$, volume $V$, and pressure $p$, which are the effective macroscopic variables. The number of such lower level states that correspond to the higher level state determines the entropy of that state. One can only access the equivalence class by manipulating higher level variables rather than the detailed lower level variables, hence cannot by higher level action determine which specific lower level state $s_i$ realizes the higher level state $S$ (a proviso: one can design the kind of apparatus that occurs in a quantum optics laboratory so that some higher level variables access specific lower level states; but these are exceptional situations). Philosophers characterise this existence of equivalence classes through the phrase “multiple realization”.

**Changing the basic elements** One further point of importance is that it is not necessarily the case that one always has unchanging lower level elements being combined in different ways to form higher level complex structures. It may occur that the higher level context actually changes the very nature of the lower level entities that are combined to make the whole. An example from physics is that a free neutron has completely different behaviour than one bound in a nucleus: the former decays with a half life of 11 minutes, the latter last billions of years, hence it’s essential nature is changed by context. A chemistry example is that a free hydrogen is quite different than a hydrogen atom incorporated in a water molecule. It is an essentially different entity. In biology, this effect is of crucial importance: for example initially identical cells are adapted to be different cell types according to their position in the human body [20].

## 5.2 Quantum mechanics examples

I now give a series of examples where contextuality in the sense outlined above plays a role in quantum theory. I call this **top-down causation**, to distinguish it from the way the term “contextuality” is currently being used in many papers on quantum theory (see [155, 87] and references therein). They are undoubtedly related, but I wish to specifically refer to the kinds of effect referred to in Section 5.1 and in [43].

### 5.2.1 Particle-Wave duality

Whether an entity acts as a particle or a wave is context dependent: this is the heart of particle-wave duality, where one can determine whether particles going through a slit should behave as particles or waves by the way one carries out the experiment ([54]:1-1 to 1-7). This has now been realised experimentally in the case of a version of Wheeler’s delayed choice experiment [146] where the which-way choice is made after the particle has passed the slits [81]: a case of top down causation from the apparatus to the very nature of the particle/wave at the time it passed through the slits.

### 5.2.2 Potentials emerging from forces

One way top-down causation takes place is via the representation of the interactions between many atoms in terms of an effective potential, treated as a classical entity. Gemmer *et al* give an illuminating example ([61]:74-77) in discussing the example of an ideal gas in a container.
The container provides the environment for the gas, and is made up of an interacting set of particles (Fig. 7.2 in [61]). Starting with a standard interaction Hamiltonian, coarse graining leads to an effective “box” potential $\hat{V}^g$ for each gas particle, comprising the mean effect of all the container walls. This mean potential is then the higher level context within which the gas particle moves; it can be represented (Fig. 7.3 in [61]) by a smooth set of equipotential lines, the transition from Fig. 7.2 to Fig. 7.3 being a classic illustration of the coarse graining process. One can regard the result as top-down action by the potential (regarded as an entity in its own right) on the gas particles. The underlying equivalence classes are all the different configurations of particles that lead to the same effective potential; it is these equivalence classes that are the significant causal entity, rather than any detailed particle configuration that leads to the potential.

Similar examples are the potential wells used in nuclear shell models ([35]:140-144), and the Slater treatment of complex atoms, explained by Pauling and Wilson thus ([112]:230):

“All of the methods we shall consider are based on the approximation in which the interaction of the electrons with each other has either been omitted or been replaced by a centrally symmetric force field approximately representing the average effect of all the other electrons on the one under consideration”.

A similar method in astronomy is the way a coarse-grained potential energy is derived for a galaxy, and then used to find the motions of stars ([13]:67-90,103-186; [130]:3-6).

These are examples of the method of mean field theory ([22]:198-208), which can be applied in many other contexts. It can for example represent the way that electrical wiring channels currents in electric circuits, through an extremely complicated effective potential: an emergent higher level entity. Indeed it enables one to represent arbitrary higher level structures emerging from the underlying physical levels, and then acting down on the lower level components by channelling the way they interact with each other. One does not need to include a representation of each individual interacting molecule. Examples range from integrated circuits to split-gate devices used in nanotechnology ([104]:96,104,112) to telephone systems, chemical plants, and neuronal connections via dendrites and axons in a brain.

Another example is the Caldeira-Leggett model, a system plus heat reservoir model for the description of dissipation phenomena in solid state physics ([12]:166-172, [17]). Here the Lagrangian of the composite system $T$ consisting of the system $S$ of interest and a heat reservoir $B$ takes the form

$$L_T = L_S + L_B + L_I + L_{CT},$$  \hspace{1cm} (41)

where $L_S$ is the Lagrangian for the system of interest, $L_B$ that for the reservoir (a set of non-interacting harmonic oscillators), and $L_I$ that for the interaction between them. The last term $L_{CT}$ is a counter term, introduced to cancel an extra harmonic contribution that would come from the coupling to the environmental oscillators. This term represents a top-down effect from the environment to the system, because $L_I$ completely represents the lower-level interactions between the system and the environment. $L_{CT}$ would not be there if there was no heat bath; the effect of the heat bath is more than the sum of its
parts when $L_{CT} \neq 0$, because the summed effect of the parts is given by $L_I$. Thus $L_{CT}$ should be called the \textit{contextual term} rather than the counter term.

\subsection*{5.2.3 Binding energies}

When there are such extra terms in the interaction, this will result in changes in energies. A crucial example is \textit{nuclear binding energies}, the cost of putting emergent nuclear structures together, which can be reclaimed on dismantling the structure. These energies would not be there if the structure (a nucleus) was not there, so it is a direct result of the existence of the higher level structure, nucleons on their own have no such energy term.

Molecular binding energies are another example, of crucial importance in chemistry.

\subsection*{5.2.4 Lattice waves and quasiparticles}

The periodic crystal structure in a metal leads (via Bloch’s theorem, \cite{158}:16-20) to lattice waves \cite{158}:27-75, and an electronic band structure depending on the particular solid involved \cite{158}:93-94,119-128, resulting in all the associated phenomena resulting from the band structure. The entire machinery for describing the lattice periodicity refers to a scale much larger than that of the electron, and hence is not describable in terms appropriate to that scale. Thus these effects all exist because of the macro properties of the solid - the crystal structure - and hence represent top-down causation from that structure to the electron states.

For example, this can lead to existence of quasiparticles such as \textit{phonons} \cite{158}:59-62 that result from vibrations of the lattice structure, and hence associated phenomena such as the \textit{U-process} whereby momentum in electron scattering processes is transferred to the system as a whole. It also leads to \textit{Cooper pairs} produced by the exchange of phonons between electrons \cite{158}:382-386 and hence to superconductivity \cite{158}:386-394 and associated phenomena such as superfluidity in metals \cite{158}:394-396. Because these are all based in top-down action, they are \textit{emergent phenomena} in the sense that they simply would not exist if the macro-structure did not exist, and hence cannot be understood by a purely bottom-up analysis, as emphasized strongly by Laughlin \cite{91}.

Other examples are \textit{holes}, conduction electrons with negative effective mass as determined by the energy surface $\mathcal{E}(k)$ \cite{158}:182-186, which are central to the physics of semiconductors \cite{158}:59-62, and \textit{plasmons} (particles derived from plasma oscillations). The quantum Hall effect is a result of the existence of composite Fermions, realised in the interface between two semiconductors \cite{82}. In all cases, it is the higher level context that leads to their existence, because it determines the form of $\mathcal{E}(k)$. This represents the effective result of the existence of the macro structure, similarly to the way effective potentials do (Section 5.2.2).

\subsection*{5.2.5 Decoherence}

Decoherence is the process whereby the environment (a macro context) decoheres the wave function and selects preferred pointer states, thus crucially determining the nature
of micro outcomes ([78] 155; [12], 212-270; [151], 121-141).

Zurek argues this can be seen as a Darwinian like process he calls environmental selection (Einselection) [159, 160]. This can therefore be seen as a case of top-down causation by adaptive selection (Section 4.3.7): the lower level dynamics does not by itself determine the outcome, which is shaped by the higher level context of the environment.

5.2.6 State Preparation

State preparation in QM is a non-unitary process, because it can produce particles in a specific eigenstate. Indeed it acts just like state vector reduction (9), being a non-unitary transition that maps a mixed state to a pure state. How can this happen in a way compatible with quantum theory dynamics?

The crucial feature of quantum state preparation is pointed out by Isham ([78]:74,134) as follows: selected states are drawn from some collection $E_i$ of initial states by some suitable apparatus, for example to have some specific spin state, as in the Stern-Gerlach experiment; the other states are discarded. This is another case of adaptive selection, (see Section 4.3.7): selection takes place from a (statistical) variety of initial states according to some higher level selection criterion. As explained in Section 4.3.7 this is the characteristic way one can generate order out of a disordered set of states by a process of selection from an ensemble of systems, and so generate useful information [124], just as in the case of Maxwell’s demon. This happens in two basic ways: separation and selection, which is unitary up to the moment of selection, and selective absorption, which absorbs energy and so is non-unitary all the time.

Collimation, Deflection, and Selection

This is a very general basis for state selection. In the case of the Stern-Gerlach experiment ([54]:5-1 to 5-9), collimation of an incoming stream of atoms by some slits is followed by deflection in a non-uniform magnetic field, which separates the initial beam into final beams according to their spin; each final beam is then a polarized beam in a prepared spin state. Thus when we choose to examine a particular spin by selecting one of these beams, one set of incoming states is selected and the other sets discarded. A mass spectrometer works on the same principle, separating out masses, as does a spectrograph, where a prism or diffraction grating sorts out light by wavelength (so you can select a specific pure colour by using a slit to collimate the light after it has passed through the prism).

Another example is a Nicol prism, used to generate a beam of polarized light ([97]:132). A crystal of Iceland spar is cut diagonally, the two parts being joined by Canada balsam. When unpolarized light enters the crystal, it is split into two polarized rays by birefringence ([97]:131,[75]:111-118), the decomposition of a light ray into two rays by an anisotropic crystal. The crystal is shaped so that one beam is totally internally reflected and lost; the other emerges parallel to the incidence direction. Birefringence is caused by electromagnetic polarization in an anisotropic medium with dielectric tensor $\epsilon_{ij}$ resulting from the coarse-graining of the dipole contributions to the electric field (Section 3.4.2 and [80]: 116-122)).
Polarization is also caused by reflection of light at less than the critical angle at a surface separating two transparent media. Then partial reflection and partial transmission takes place ([97]:109-110;[75]:40-41,108-109), again separating the initial beam into two polarized beams; so this can also be used to prepare polarized states. The anisotropy in this case is caused by the layer separating the two media; the reflected light is polarized normal to the incidence plane.

Selective absorption Dichroism is the selective absorption of one polarization state due to a linear structure in a polarizer, which therefore selects a specific spin state from a beam of incoming photons, thereby rejecting the other states. This may be realised by a wire grid polarizer ([75]:105-106): a set of closely spaced fine conducting wires. If a wave interacts with these wires, the electric field component parallel to the wires drives electrons along the wire, generating an alternating current which encounters resistance; this absorbs energy from this component of the incoming field, heating the material; the electrons re-radiate a wave which further tends to cancel this component of the incident wave, while the transverse component is not so affected. Hence the transmitted wave is linearly polarized. The same effect occurs in a polaroid polarizer, consisting of many parallely aligned microscopic crystals embedded in a transparent polymer film ([97]:132-133;[75]:105). Similarly a spin-polarized current in a metal can be generated by passing the current through a ferromagnetic material.

A different example is a filter that absorbs some wavelengths of light and transmits others, because of the molecular structure of the glass, hence selecting a particular frequency range by adaptive absorption.

| Classical Apparatus | Non-linear system | Non-unitary |
|---------------------|-------------------|-------------|
| Emergence ↑         | Contextual effects ↓ | Adaptive selection |
| Quantum systems     | State vector selection | Non-unitary |

Diagram 9: The postulated contextual view of state vector preparation.

Emergence and top-down action: In each case, the underlying unitary quantum electrodynamics leads to emergence of higher level classical structures (wires, crystals, and so on) that can then act down to the particle level to cause non-unitary transformations which can change a mixed incoming beam to a pure state (Diagram 9). As in the case of the band structures of metals, this top-down action depends on the physical structure of the polarizing material or device as indicated in the above examples, and so is a case of top-down causation by adaptive selection in the context of the structure of the material. In the case of separation and selection, the lower level evolution is unitary until selection takes place. In the case of selective absorption, the ongoing non-unitary nature of the resulting higher level effective action is reflected in an energy loss and heating associated with the process.
5.2.7 Measurement

Measurement is a process with significant parallels to the process of state preparation, as just pointed out. The experimental viewpoint is that the macro observer and apparatus have an existence as macro entities that can be taken for granted, and that can influence states both in terms of state preparation, and in terms of determining the outcomes of a measurement, for example by choosing the axes along which spin will be measured. These are of course both cases of top-down causation.

Does it go further than this: is the measurement process itself in some sense also a case of top-down causation? In section 6 I will show that this is indeed so in that the non-unitary measurement process is enabled by top-down action from the structure of the detector to the particle interactions. Here, I want to make just one other point: some of the more advanced measurement techniques seem to directly involve adaptive selection. For example this occurs in weak measurements, which are based in post-selection ([1]:225-227,230-235). This kind of selection of some outcomes and discarding others is also central to the generalized theory of quantum measurement characterized by Breuer and Petruccione ([12]:83-85). It may well be worth pursuing the idea that adaptive selection is the heart of the measurement process (see Section 8).

5.2.8 The arrow of time

A further very significant case of top-down causation is the determination of the arrow of time. It is a major topic, dealt with in a companion paper [45]. The picture that emerges from the discussion there is shown in Diagram 10.

| The Arrow of Time |
|------------------|
| Cosmology        | Brain, Society |
| Top-down effects | † Bottom-up effects |
| Non-equilibrium environment ⇒ Molecular processes |
| Top-down effects | † Bottom-up effects |
| Quantum Theory   ⇒ Quantum Theory |

In summary: this view proposes that

- Spacetime is an evolving block universe, which grows as time evolves [42]. This fundamental arrow of time was set at the start of the universe.
- The observable part of the universe started off in a special state which allowed structure formation to take place and entropy to grow.
- The arrow of time cascades down from cosmology to the quantum level (top down effects) and then cascades up in biological systems (emergence effects).
• There are an array of technological and biological mechanisms that can detect the direction of time, measure time at various levels of precision, and record the passage of time in physically embodied memories.

• These are irreversible processes that occur at the classical level, even when they have a quantum origin such as a tunneling process, and at a foundational level must based either in a time-irreversible quantum measurement process or are a consequence of the special initial state and the coupling of the atom to an infinite number of electromagnetic degrees of freedom.

• In conceptual terms they are the way the arrow of time parameter $t$ in the basic equations of physics (the Dirac and Schrödinger equations (3), Maxwell’s equations and Einstein’s equations on the 1+3 covariant formulation [17]) is realised and determines the rate of physical processes and hence the way time emerges in relation to physical objects.

• Each of these processes is enabled by top-down action taking place in suitable emergent local structural contexts, provided by molecular or solid-state structures. These effects could not occur in a purely bottom-up way.

The detailed argument is in [45].

6 The Measurement issue and contextuality

Underlying the flow of time is the quantum measurement process. The point to be made now is that a measuring apparatus such as a Charge Coupled Device (CCD) is a classical object. That is why it is able to produce a specific measurement result — it is not a quantum system. How is this possible? The resolution I propose is that a classical system emerges from the underlying quantum components (see Section 7.3.1 below), for example through the arbitrary allowed potential terms $V(x)$ (Sections 3.3 and 5.2.2), and then acts top-down on the quantum elements of the system to make a measurement take place. Hence it is a contextual effect. The way this works is set out in Diagram 11, with obvious similarities to Diagram 9. Philosophically, the difference between state preparation and measurement is that the outcome is largely determined by the experimenter in the former case, but to a lesser degree in the latter case.

| Non-linear system | Classical Apparatus |
|-------------------|---------------------|
| Emergence ↑       | ↓ Contextual effects|
| Linear components | Quantum systems      |

Diagram 11: The contextual view of quantum measurement. Linearly acting quantum systems are assembled in a non-linear way to create a classical apparatus with non-linear state space, and non-Hamiltonian (non-unitary) evolution emergent from the underlying physics (as discussed above). This macro apparatus acts down on the micro quantum system being monitored by the experimenter, resulting in both non-unitary state preparation, and a set of specific measurement events where non-unitary state vector projection takes
Section 6.1 considers the way state vector reduction is related to context in general, and Section 6.2 fleshes this out in the case of photon detection.

### 6.1 Contextuality and state vector reduction

Real experiments, such as the Haroche single photon measurement ([151]:45), involve classical apparatus such as ionization detectors. These provide the context within which measurements take place. Wiseman and Milburn ask ([151]:98)

“Should we include these as quantum systems in our description? No, for two reasons. First, it is too hard. Quantum systems with many degrees of freedom are generally intractable. ... Second, it is unnecessary. Detectors are not arbitrary many body systems. They are designed for a particular purpose: to be a detector. This means that despite being coupled to a large environment, there are certain properties of the detector that, if initially well defined, remain well defined over time. These classical like properties are those that are robust in the face of decoherence... one of those properties is precisely the one that becomes correlated with the quantum system and so constitutes the measurement result.”

This emphasizes that the detection is a result of the detector structure. Considering it as a classical system, the way the measurement takes place depends on the physical details of this detector, which is the local context for the measurement, for example determining which spin component is measured. Thus this is what one should concentrate on, to flesh out the abstract concept of measurement embodied in the rule (9).

In what follows I will concentrate on photon detection, in order to be definite. In this case, we have the following proposal:

**Thesis: The measurement process depends on the local context.**

*Measurement (collapse to an eigenstate of some variables of the system) occurs whenever the local context of the detector structure causes such a projection to reliably take place in the case that a photon impinges on an electron located in the detector.*

I explore this view, in accord with Landsman’s review of the Bohr-Einstein debate [89], in some detail below. A similar discussion could be given for particle detection, magnetic field detection, and so on.

### 6.2 Photon detection

**What characterizes a measurement** (at the micro level)? When does the interaction between a photon and an electron amount to a measurement? When is it just scattering, and when is it absorption of energy by the electron leading to the photoelectric effect as

---

8Examples such as the quantum eraser and delayed choice experiments show that the issue of “when” the detection takes is a subtle issue; c.f. [19].
part of a measurement process? It may be either an active measurement process or a passive measurement process depending on the context.

6.2.1 Contexts

A range of contexts is as follows:

- **Plasma**: Electron in plasma: free electrons are not bound to nuclei, so interaction involves only an electron and a photon; Rayleigh scattering takes place ([32]:656-660), [4]:14-20, [79]:224-230,286); [117]:158-167). This heats up the plasma.

- **Gas**: Electron in free atom: (i) a photon does not change the state of the atom (Rayleigh and Compton scattering: [32]:656-659), (ii) changes the orbital level of the electron ([31]:175-178,239-248; [27]:86-93), or (iii) frees it and so ionizes the atom ([4]:30-31, [27]:105-107) and thus ionizes the gas ([96]:151-153). This leads to heating of the gas and reradiation of energy ([27]:94-98).

- **Passive surface**: Electron in a physical structure where the photon is absorbed on interacting with the electron, but this does not free the electron. The surface heats up, which effect can be used to create a bolometer ([96]:180-182, [25]:269-272), and re-radiates light, which makes it visible; this enables indirect measurement ([12]:93).

- **Active surface**: Electron in a physical structure that absorbs a photon and is thereby freed from that structure (the photoelectric effect), and then is used in a structure (a detector of some kind) to generate specific classical effects. This is the context in which photon detection occurs, rather than just an interaction.

Note that the kinds of calculation to determine the effect are quite different in the different cases listed here. It is the latter the constitutes an actual detection; only this case constitutes an active measurement. One can contrast this with the way measurement is expressed in quantum theory texts in terms of operators and eigenvalues (cf. Section 2.1). That is the basis for what happens; this is where it becomes real.

6.2.2 The Photoelectric effect

The basis of detection devices is the photoelectric effect ([4]:11-14), which occurs if an electron in a surface absorbs the energy of a photon and thus has more energy than the work function (the electron binding energy) of the material. It is then ejected and produces a freely moving electron; if the photon energy is too low, the electron is unable to escape the material ([4]:526; [158]:336-343; [25]:227-229; [96]:148-151).

Detection is when a photon impacts a structure and causes an electron to be released which then causes a specific physical effect on the structure. It is non-linear because there is a detection threshold below which no signal is detected.

All of this is a statement that what happens depends on the local context: the work function is a macro property, depending on the nature of the material ([158]:196-199). In
the case of a metal, the periodic crystal structure leads (via Bloch’s theorem, (158):16-20) to the electronic band structure depending on the particular solid involved (158):93-94,119-128). That is the origin of the work function associated with the particular metallic structure and associated optical properties (158):255-291). The specific outcome is a result of the layered atomic structure in which the electron is imbedded, which creates the electronic band structure and work functions. Unlike the case of free electrons, because these conduction electrons are in the context of a crystalline structure, energy and momentum are not conserved for the electron-photon pair; this is because the crystal absorbs energy and momentum (158):60-61). This is at the heart of why these processes are not unitary. As in Section 4.3.2 an open system can evolve non-unitarily and with loss of energy since energy goes into environmental degrees of freedom.

Increasing the intensity of the light beam increases the number of photons in the light beam, and thus increases the number of electrons excited, but does not increase the energy that each electron possesses. The output does not depend linearly on the input: it has discrete steps in it because nothing is emitted up to threshold intensity. Hence there is no superposition or entanglement (Section 4.3.4). The equivalence classes characterizing this as top-down action are a consequence of Bloch’s theorem (see the remark on equivalence following (1.41) in 158).

There are many calculations of how photo-ionization arises from QED, e.g. (133):420-422; 101]:179-184; 126]:339-341), but very few looking at the photoelectric effect when the electron is in the band structure in a solid (e.g. 157). And these are statistical calculations- they do not show how the wave function collapses in a specific interaction event.

6.2.3 Types of Detectors

The different types of photon detector include the following; as indicated, each arises out of well understood quantum processes.

1. Photographic emulsions Photographic plates (96]:175-177) record images via chemical reactions induced in the photographic emulsion by the photochemical effect (96]:150-151). Grains of silver bromide (Ag+Br) are imbedded in a transparent gelatin matrix; photons interact with the grains to turn them into silver. When radiation of the right wavelength impacts a silver bromide crystal, a series of reactions produce a small amount of free silver in the grain [108].

Initially, a free bromine atom is produced when the bromide ion absorbs a photon:

\[ Ag^+Br + h\nu \rightarrow Ag^+ + Br + e^- \]  \hspace{1cm} (42)

The silver ion can then combine with the electron to produce a silver atom.

\[ Ag^+ + e^- \rightarrow Ag^0 \]  \hspace{1cm} (43)

The detection event is the splitting up of the bromide ion, so releasing a free electron.
2. **Photon counters and Photomultipliers** A photon counter contains a fine wire in a positively charged cylinder ([32]:555). A photon ejects an electron from the wire by the photoelectric effect, which generates a small pulse of current. A photomultiplier tube (PMT) is a vacuum device where a photocathode is held at a large negative voltage ([96]:161-162; [25]:260-262). When a photon hits the photocathode and ejects an electron into the vacuum due to the photoelectric effect, the electron is accelerated to a more positively charged electrode called a dynode, coated with a material such as CsK₂Sb or BeO that easily releases several electrons to the vacuum when hit by a single energetic electron (this is the electronic variant of the photoelectric effect). A greatly multiplying cascade of electrons proceeds down a chain of eight such dynodes and leads to an electric pulse at the anode of the PMT.

3. **Charge-Coupled Devices (CCDs)** A Metal-Oxide-Semiconductor (MOS) capacitor ([25]:219-221) is a sandwich of a grounded block of p-type semiconductor, a thin insulator layer of SiO₂, and a thin layer of metal held at a positive voltage. It has an electronic band structure such that when an electron-hole pair is created by a photon in the depletion region in the semiconductor adjacent to the insulator, photoelectrons are stored in a potential well. A CCD ([96]:171-173, [28]:351-355; [25]:243-260,317-321) contains a two-dimensional array of MOS capacitors (one capacitor per pixel) so that when an image is projected onto it, each capacitor accumulates an electric charge proportional to the light intensity at that location. After such an exposure, electronic control circuits read out each pixel successively to produce a sequence of bits in the output line.

A newer development is CMOS imagers ([158]:355-357) where charge to voltage conversion takes place in each pixel.

4. **Photodiodes** ([96]:150,154-156; [158]:336-343; [99]:107; [25]:223-227) A photodiode is a p – n junction with a potential across it. When a photon of sufficient energy strikes an electron in the diode, via the photoelectric effect it creates a free electron and a positively charged hole in the region between the p-doped and n-doped layers. This generates a photocurrent which is the sum of the dark current (without light) and the light current ([141]:Ch4.6)

5. **Super-conducting tunnel junctions (STJ)** These tunnel effect junctions ([96]:156) are the most sensitive light detecting diodes. An STJ is a Josephson junction (two pieces of superconducting material separated by a very thin insulating layer) with a bias voltage applied to the superconductors and a magnetic field applied parallel to the junction ([25]:229-232). The current caused by quasiparticles tunnelling across the barrier is suppressed for voltages less than twice the superconducting energy gap. A single photon can break apart multiple Cooper pairs, promoting electrons into excited states. These tunnel across the insulator and produce a current pulse.

6. **Plant Leafs** Photosynthesis ([14]:29-30) occurs when a photon causes a transition of a chlorophyll molecule, situated in a light harvesting complex in a leaf, from its ground state to an excited state ([20]:182-195). After a chain of energy transfers, an electron is transferred from a special α-chlorophyll molecule to a primary electron receptor where it causes a redox reaction, which then sets up an electron transfer
chain that releases NADPH and ATP to a Calvin cycle. Immediate loss of energy by fluorescence of the excited molecules is prevented because of their context: “each photosystem - a reaction centre surrounded by light harvesting complexes - functions in the chloroplast as a unit” (20:189). An isolated chlorophyll molecule simply re-radiates the energy as the photo-excited electrons drop back to their ground state.

7. Animal eyes Photoreceptors in the eye harvest energy by phototransduction enabled by rhodopsin ([22]:269-274, [83]:508-522). The primary step in the process is photon absorption followed by isomerization in a π to π* or n to π* orbital transition occurring in the light absorbing portion of rhodopsin ([8]:597), changing 11-cis retinal to All-trans retinal. This is enabled by an 11-cis C=C conjugate double bond, and proceeds by causing a conformational change in the opsin portion of rhodopsin, which triggers the further steps in the process ([83]:511): the rhodopsin molecule activates further molecules that open sodium channels in a rod cell and so producing hyperpolarization of the cell, eventually transduced into action potentials that travel to the optic nerve.

In the latter two cases it is molecules imbedded in biological structures that act as detectors. These are obviously highly non-linear structures, physically of a scale much larger than that of the electron. They form the classical context for the electron that turns the electron-photon interaction into a detection. Note that major further issues arise as to how detectors are configured (in photomultipliers, bolometers, spectrographs, interferometers for example) to obtain specific information [96, 25], and how the data obtained is then processed. This all happens on the classical side of the classical-quantum cut, and so is not the concern here.

6.2.4 The non-linear nature of physical measurement processes

What is clear is that none of the detection processes considered here obey the linearity conditions essential for quantum theory superposition to apply (see Section 3), even though they are enabled through well understood underlying quantum interactions. As in the case of state preparation (Section 5.2.6), superposition does not take place in the state space (that is after all the nature of the measurement process) due to the dynamics induced by top-down effects caused by the local environment provided by the structure of the detector. Hence the reason these processes can be regarded as classical processes is that, because of the way the context shapes the outcomes, they don’t satisfy the requirements of being unitary.

At a certain level, that is a resolution of the measurement paradox (see Section 2.2): there simply is no reason to believe that quantum theory will apply to any realistically represented measurement apparatus. The measurement problem arises when the abstraction of the measurement process (Section 2.1) is separated from the reality of detection events as outlined here. When discussions of measurement do become more realistic (e.g. [51]:42-49), they usually do so by implicitly invoking the Heisenberg cut: macro apparatus such as detectors are present (e.g. [96]:Fig 1.3) as sites where the actual measurement takes place, via the kind of processes outlined here. Detection processes like those discussed above take place because the structure of the detector is designed to behave in a
non-linear way. That is what enables the non-unitary measurement.

This does not of course solve the issue of what if anything determines the specific outcome of that process: it is agnostic re the source of quantum uncertainty. But the discussion here, in conjunction with the examples in Section 4.3, does indicate how non-linear detection events can arise from the underlying linear quantum processes.

7 Emergence of classical systems

One of the puzzling issues in quantum theory is how to make a classical apparatus emerge out of quantum foundations. How large a system can be described by quantum theory? Where does the micro-macro cut take place? This is the inverse to the issue of making as large as possible a system behave quantum mechanically: an answer to the one implies the answer to the other.

Section 7.1 considers basic criteria for when we may expect a classical system to emerge, and Section 7.2 how this may relate to the classical-quantum cut. Section 7.3 gives some applications of criteria developed there to some contentious examples.

7.1 The basic criterion

We have seen that to create a higher level quantum system, we don’t only have to protect it from decoherence - we also have to isolate a linear system from all the messy non-linear entities in the world around. This ensures a context where linearity holds for this part of the whole, so that the quantum nature of the components comprising the system results in a quantum nature of the system itself when we coarse grain from smaller to system scales (Section 4). To get the possibility of a quantum system, we need to create conditions where the linearity conditions L1-L3 of Section 3.4.3 hold at the system level, allowing both a linear state space and linear dynamics.

Conversely, if we want classical systems to emerge, we must create conditions where these conditions are not fulfilled. Ways of doing so were indicated in Section 4.3, with specific examples given in Section 6.2.3. In particular, we can note the following:

Quantum Limits: Purely quantum behaviour will generically not be possible at any level of description of an isolated system where there are equilibrium states, dissipative effects, threshold effects, feedback loops occur, or where adaptive selection takes place.\(^9\)

We can therefore arrange for classical behavior to emerge by setting a context where one or other of these elements occurs. Generically this will happen as we consider larger and larger systems, which is one reason why it is so difficult to make macroscopic quantum systems. Considering the above examples gives guidance as to when this will occur.

\(^9\)An experimenter can ‘reach down’ and elicit quantum behaviour, using cleverly designed apparatus: but this is a highly exceptional situation.
7.2 The classical to quantum cut

7.2.1 Quantum effects

On the basis of the above examples, one may suggest the following:

Quantum dynamical effects will mostly occur at the molecular level; however it can with great care be extended to much larger systems (maybe 100 km) by creating appropriately linear systems, but this will not occur naturally.

That the molecular level can be reached is shown both by investigations showing that quantum effects can occur in fullerenes and biomolecules \[14, 69\] and occur in radical-ion pair reactions \[88\]. This is of course compatible with the usual understandings of QM as being a theory normally applicable on small scales as indicated by the de Broglie wavelength \(\lambda = \frac{h}{p} = \frac{h}{(m_0v)}\), which for thermalized electrons in a non-metal at room temperature is about \(8 \times 10^{-9} m\), while the smallest molecules have a length of about \(10^{-10} m\). But note the important distinction:

Applicability of quantum theory versus significance of entanglement effects: There are separate issues as to whether entanglement effects (i) can exist, and (ii) are significant. The latter depends on how large physical objects are relative to scales set by the Planck constant \(\hbar\). The former is a qualitative issue related to the possibility of describing causality at a particular level in the hierarchy (Table 1) by Hamiltonian dynamics. There is no chance of entanglement effects being significant if they can't exist due to one or other of the situations mentioned above.

Thus relating scales to the Planck constant is important as far as significance of quantum effects is concerned, but is not the whole story.

7.2.2 Exceptional cases?

There are a series of exceptions where quantum effects are significant on larger scales than the molecular scales.

Entangled photons From the viewpoint put here, an essential part of the wonderful experimental work establishing entanglement over distances of many kilometers (e.g. \[142, 132\]) is the careful construction of linearly interacting systems over these macroscopic scales: this is the endeavor to extend the linear aspects of physics emphasized in Section 3 to these distances (for otherwise entanglement on such distances would be impossible). This is possible in these cases because photons are able to travel macroscopic distances in transparent media with virtually no interaction. These are truly macroscopic versions of essentially quantum phenomena.

Interferometric quantum non-demolition experiments Each LIGO gravitational wave observatory is based in a L-shaped ultra high vacuum system, measuring 4 kilometers on each side, forming a power-recycled Michelson interferometer with Fabry–Pérot arms. Squeezed optical states are fed in and read out by quantum non-demolition
technology [15, 16, 86]. Hence this corresponds to setting up quantum states on a scale of 4 km. This is possible under similar conditions to the previous case: it is a quantum photon state, enabled by ultra-high vacuum and rigorous filtering of background noise. This kind of detector centres on a remarkable creation of macro-scale quantum states under very artificial conditions that enable linearity to hold on these scales [85].

**Superconductors** Similar comments regarding linearity apply, at much smaller scales, regarding the drive to quantum computing and the search for high temperature superconductivity: these also depend on isolating linearly interacting degrees of freedom in a suitable system. One might note here that ordinary (low temperature) superconductivity cannot occur spontaneously in nature, because the universe is permeated with black body photons whose present temperature is 2.75K, which sets a lower limit to the temperatures of naturally occurring bodies; hence the low temperatures needed for superconductivity cannot occur without human intervention.

However the issue now is, should we regard large superconducting magnets such as at those at the Large Hadron Collider as single multi-particle quantum systems, hence with one macro-scale wave function describing their entire state, or rather as local small scale quantum systems, acting together to give quantum-based macroscopic behaviour? According to ([35]:105), superconducting magnets on scales of meters are enabled by cooling to a few degrees K and manufacturing imperfection free wires (in accord with Section 3.4.3). The bound Cooper pairs resulting from individual electrons interacting with the crystal lattice and the lattice interacting with the other electrons are not localized at one place in space, but are represented by wavefunctions within the metal that spread out over a range of as much as 1µm. which is more than 1000 times the distance between the individual electrons in the superconductor. But this is not a macroscopic scale interaction; hence superconducting macro behaviour is obtained by a collection of many local entangled wave functions rather than a macro-scale wave function. The quantum classical cut in this case is at about the 1µm level.

**Degeneracy pressure: White Dwarfs and Neutron stars** White Dwarfs are stars with masses about 1.2M☉, radii between 3000 and 2000 km, and so densities of about 10⁶ gr/cc ≃ 1 ton/cm³. They have stopped burning their nuclear fuels and are supported almost entirely by the pressure of a degenerate electron gas ([23]:412-451, [156]:271-279, [106]:619,627). Neutron stars have also stopped burning their nuclear fuels, and are also of mass about 1M☉, but with radii of about 10 km, so their densities are about 10¹⁴ gm/cc. Their cores are almost pure neutrons, rather like one nucleus of 10⁵⁷ neutrons in a superfluid state , but with enough protons to prevent decay and enough electrons to create charge neutrality [109]. They are supported against gravity by pressure of degenerate neutrons ([109], [156]:279-285, [106]:619).

These stars are prevented from collapsing by electron and neutron degeneracy pressure respectively, hence they are held apart by pressure generated by Pauli exclusion principle. In broad terms, possible quantum states, limited by exclusion principle because the wave function is antisymmetric, fill up from the bottom to the Fermi level due to exclusion principle. The Fermi-Dirac equation of state results and degeneracy pressure acts to
stabilize the star ([23]:357-402). So the system is demonstrating quantum state effects on scales of 10km to thousands of km.

The same issue arises as for the superconducting magnets: is there one antisymmetric wave function for the states of the star as a whole, with its energy levels filling up to generate the needed pressure, or are there effective local boxes where degeneracy pressure is generated, the star as a whole being held up by the combined degeneracy pressures generated in all the little boxes? In this case there is no global wavefunction for the star: the antisymmetric wave function is only locally applicable. Discussions of these stars [23, 109, 156, 106] are ambiguous on this issue. Of course the real physics of degenerate gases is very complex ([51]: 21-31,120-170) with nuclear matter ([51]:341-388,503-577) a model for the effects one might expect in neutron star cores.

The issue is what is the relevant antisymmetric quantum state to which the Pauli exclusion principle can be applied ([23]:382-384). It seems reasonable to assume one only needs this antisymmetry of states for nearby electrons in a white dwarf: swapping it with one far distant will be irrelevant to real physical behaviour. That is, the asymmetry

\[ \Psi(q_1, q_2, q_3, \ldots, q_N) = -\Psi(q_2, q_1, q_3, \ldots, q_N) \] (44)

need only apply when the particles \( q_1, q_2 \) are neighbouring particles (it is true that if (44) holds for all neighboring particles, it will also hold for arbitrarily distant ones; but that will be a physically irrelevant byproduct of the significance of physical crucial interchange asymmetry of neighbouring particles). This suggests that local skew quantum state functions will suffice to derive local classical gas properties ([23]:360-362) that then get combined to determine the overall star structure; there need be no global wave function for the star as whole, even thought the degeneracy pressure can be thought of as being based in filling available electron states for the star as a whole.

This conclusion is supported by the fact that the local gas properties vary across the star, so can hardly all be described as in the same state, and by the use of a modified form of the Bethe-Goldstone picture for two interacting nucleons in a Fermi sea, providing a qualitative basis for the independent particle model of nuclear matter ([51]:358-366) developing out of the Hartree-Fock approximation ([51]:121-127). Eddington has emphasized beautifully [37] the hurly-burly nature of what goes on in a stellar interior: hardly a benign place to maintain quantum entanglement. Accordingly I suggest the

**Local Degeneracy Hypothesis:** the physics of macroscopic objects held apart by degeneracy pressure is determined by local skew-symmetric state functions in boxes of sufficient scale to determine a hydrodynamic approximation, rather than a global wave function for the degenerate core as a whole.

How large an averaging box is needed? Andre Peshier points out that in heavy ion collisions, a hydrodynamic or thermodynamic approximation is used when one has as few as 100 interacting entities. This might be a reasonable estimate also for the cases of what is required for the averaging volumes in white dwarfs and neutron stars.
Black Holes and Inflation: The same issue arises also as to whether quantum mechanics can be applied to black holes of arbitrary size (following Hawking [74]) or the early universe (as in inflation [34]). My suggestion will be the same: local quantum mechanical effects everywhere will give the desired consequences, without requiring a global wave function that applies everywhere (although this might happen: such a global wave function might be an emergent property of the system as a whole). This is a proposal that needs testing.

Overall Andrew Briggs comments (private communication), “we have very little experience of large entangled systems, indeed it is an open question whether there is an upper limit of ‘macroscopicness’ (whatever that might mean) for a system to exhibit quantum superposition (and hence entanglement). We are a very long way from this in the laboratory, priding ourselves (I speak of the community as a whole) in creating entanglement between, say, eight trapped ions.” I suggest that the examination of possible exceptions in this section supports the view in the previous section:

The classical quantum cut: With a few rare carefully engineered exceptions (which cannot occur naturally), the classical quantum cut is at the molecular level or below. The exceptional cases can extend quantum states up to the order of $10 - 10^2$ Km.

7.3 Applications

Immediate corollaries of this discussion and the examples in Section 4.3 are,

- **Corollary 1**: generically, systems in thermodynamic equilibrium will not exhibit quantum behaviour at a macroscopic scale (because the effective laws describing their macroscopic behaviour are classical laws);

- **Corollary 2**: generically, systems with threshold effects will not exhibit quantum behaviour at a macroscopic scale (because superposition does not apply across the threshold);

- **Corollary 3**: generically, living cells will not exhibit quantum behaviour (because there are thousands of feedback loops in a living cell);

- **Corollary 4**: generically, animal brains will not exhibit quantum behaviour (because they are complex networks involving both feedback loops and adaptive selection).

All these (complex) systems will “typically” not exhibit quantum phenomena. Given a clever experimental design by a quantum physicist, on some appropriately short time-scale and some appropriately chosen subsystem, perhaps quantum effects should become visible – even in a living cell. But this is a highly exceptional situation. There are literally thousands of processes going on in living cell. Quantum processes underlie them, and for example tunnelling may take place. Genuinely quantum phenomena such as entanglement are exceptional cases [30] almost without exception these processes are described in purely classical terms [20]. This has implications for well known controversies.

---

10I am taking for granted the stability of matter and the periodic table, as classical outcomes.
7.3.1 Classical Measuring apparatus

A long standing question is how it can be that one can construct a classically behaving laboratory apparatus out of elementary particles whose behaviour is quantum-based. The arguments presented here suggest an answer:

A measuring apparatus is made of metals and other materials that are in equilibrium states, hence Corollary 1 protects them from quantum effects. Photon detectors rely on the photoelectric or related photon effects, which rely on thresholds and so Corollary 2 protects them.

It is a moot question as to whether the experimenter should be regarded as part of the apparatus or not; in any case Corollaries 3 and 4 will help here, ensuring that the observer too is a classically behaving system. Once detectors exist as classical objects, they can exert a top-down influence on the detection processes (Section 6).

**Conclusion:** The conditions highlighted in the Corollaries above, based in the linearity requirements for the validity of quantum theory (Section 3), are sufficient to explain why a classical observing apparatus can emerge from its underlying quantum components.

Actually it goes much further than that: the conditions highlighted in Section 7.1 are sufficient to establish the existence of the classical world in general as a generic macrophenomenon, except under very unusual circumstances (like an experimental setup that can generate entangled particle pairs over Km distances). Thus they underlie the feature (emphasized in section 2.4) that

**Classical reality** We can regard each of the higher levels of the hierarchy of complexity as a classical domain, emergent from the underlying quantum theory but existing in its own right, with occasional quantum intrusions.

7.3.2 Schrödinger’s cat

In their discussion ([1]:121-124) of the Schrödinger’s cat paradox, Aharonov and Rohrlich include the following representation of a final entangled state of the cat and its environment ([1]:eqn.(9.8)):

\[
|\Psi(T)\rangle = \frac{1}{\sqrt{2}} |\text{undecayed}\rangle \otimes |\text{untriggered}\rangle \otimes |\text{unactivated}\rangle \otimes |\text{unbroken}\rangle \otimes |\text{live}\rangle \\
+ \frac{1}{\sqrt{2}} |\text{decayed}\rangle \otimes |\text{triggered}\rangle \otimes |\text{activated}\rangle \otimes |\text{broken}\rangle \otimes |\text{dead}\rangle
\]

One can certainly challenge the last term in each product, if not the earlier ones, by considering the examples in Section 4.3 and the Corollaries above. The cat will not exhibit quantum behaviour both because it is made of living cells, and has a brain.

**Conclusion:** Schrödinger’s cat can’t be in a superposition because a Hamiltonian description allowing the necessary unitary evolution does not apply to complex objects such as a cat.

Schrödinger’s cat states can however be constructed in quantum optics contexts ([99]:77,105).
8 A View of the Classical World

8.1 A viewpoint

In the *New York Review of Books*, Freeman Dyson wrote [36]

*Toward the end of Feynman’s life, his conservative view of quantum science became unfashionable. The fashionable theorists reject his dualistic picture of nature, with the classical world and the quantum world existing side by side. They believe that only the quantum world is real, and the classical world must be explained as some kind of illusion arising out of quantum processes. They disagree about the way in which quantum laws should be interpreted. Their basic problem is to explain how a world of quantum probabilities can generate the illusions of classical certainty that we experience in our daily lives. Their various interpretations of quantum theory lead to competing philosophical speculations about the role of the observer in the description of nature. Feynman had no patience for such speculations. He said that nature tells us that both the quantum world and the classical world exist and are real. We do not understand precisely how they fit together. According to Feynman, the road to understanding is not to argue about philosophy but to continue exploring the facts of nature."

This paper supports such a view. The basic theme is that 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 and adaptive selection. This prevents superposition of states, and hence quantum phenomena will not be expected to occur on macroscopic scales. Macro-scale entities will exist as entities with causal powers in their own right, thus enabling top-down causation to take place as well as bottom up. Hence all the levels of emergent reality should be treated on an equal ontological basis: none is a privileged level of existence, all are equally real (see Denis Nobel’s article in [46]):

**HYPOTHESIS 1**: Macrophysics exists on an equal basis to the micro. It is just as real and just as causally effective.

This view is implicit in all quantum mechanics studies where macro-concepts like a ‘photon detector’ are used, often without comment. They are part of the experimental machinery that must be taken for granted in order that experimental physics can proceed.

As a consequence, emergence and contextuality should be seen as a key feature of science. On the one hand, we need to take the bottom up emergence of higher level properties seriously, as we consider the degree to which quantum theory may be applicable to higher levels of the hierarchy of complexity. Some approaches at use in present in effect don’t do so: they implicitly assume this process will lead to quantum behaviour at higher levels, when that assumption may not be true.
On the other hand, top-down influences crucially affect quantum level outcomes, as for example in the process of decoherence. Because top down action takes place, a concept of non-quantum macro systems is essential in formulating quantum theory. This is essentially the Copenhagen interpretation of QM.

**HYPOTHESIS 2:** Contextuality is crucial: one should see quantum behaviour as the result of an interaction of bottom up and top down effects.

In other words, complexity is the key criterion in the classicalisation of the universe. Leggett states,

“QM is a very ‘totalitarian’ theory, and if it applies to individual atoms and electrons, then it should prima facie equally apply to the macroscopic objects made up by them, including any devices which we have set up as a measuring apparatus” [94].

By contrast, this paper proposes that the appropriate dynamics at higher levels is determined by coarse graining of the dynamics at lower levels (see Diagrams 1 and 2). In that case, QM will only apply to higher levels in the hierarchy under very restricted circumstances.

### 8.2 Questions

In summary, This paper has provided a broad framework to look at some issues in the relation of quantum theory to the macro world, based on the proposals given in Section 3.4, and summarized in diagrams 1, 2, and 8. This view respects the reality check provided in Section 2.3, but obviously leaves many questions unanswered. Particular issues to explore include,

- **Almost linearity:** Section 3 has emphasized the need for linearity in order that quantum physics is applicable, but has not considered how linear a system has to be: when is ‘almost linearity’ adequate? This is a key question, relating to such issues as spatial and temporal coherence. It relates to considering quantum theory as a theory of perturbations: many systems can be regarded as linear if one restricts the space, time, and energy scales enough, so the issue will be for how long and over what scales almost-linearity will be at acceptable levels. This is where the uncertainty principle will enter, and relates to issues such as to what degree genuinely quantum properties occur in biology [98, 8]. Put another way, if complexity is the key criterion in the classicalisation of the universe how is complexity to be quantified for this job? Can it be done in a way that avoids introducing additional dimensional constants into physics?

- **Detection Processes:** It will be useful to develop detailed QED models of the kinds of detection processes discussed in Section 6.2.3, keeping careful track of precisely where the projection process (9) occurs and what contextual features constrain how it happens. This might possibly provide a framework for explicit context dependent collapse models as an alternative to those by Ghirardi et al [62] and Penrose [114, 115], based in a top-down process of adaptive selection (Section 4.3.7) because adaptive selection underlies the dual process of state vector preparation (Section
This might possibly induce an extra term in the Schrödinger equation, in a way similar to the way effective potentials arise (Section [5.2.2]). This raises a further issue: if a time scale for collapse is introduced into the theory, representing a new fundamental parameter in physics, how is this constant related to the measure of complexity of the higher level?

- **State Vector Preparation:** Investigating that proposal will be assisted by developing detailed QED models of the process of state vector preparation, which as just remarked is based in a top-down process of adaptive selection (Section [5.2.6]). This will clarify how it provides a well-founded route, based in established quantum physics, that can lead from mixed to pure states and is able to produce an effective collapse of the wave function, because it can produce eigenstates. A key issue here is clarity on precisely how the idea of state vector reduction relates to particle creation and annihilation as represented in QED.

- **Coarse graining and detection** Related to this is the fact that any coarse-graining implicitly involves both a temporal and spatial scale, and it will often also involve an energy scale. Thus for example a density measurement for a gas will correspond to a specific averaging length scale; an image obtained by a detector will correspond to specific angular, exposure time, and energy scales. Hence measuring coarse grained entities involves convolution with a detection function or window function. The effect of such coarse graining on detected entities will affect what we can actually measure, and it selects the information we gather from all the other incoming stuff we don’t want (another form of adaptive selection). Such filtering of what we detect is essentially the start of pattern recognition, indeed sophisticated filters can implement genuine pattern recognition, thereby collecting useful information. Exploring these effects in relation to issues of emergence and information may be useful.

- **Quantum theory and the arrow of time** As part of this project, it should be that the time-asymmetry of the quantum measurement process emerges in a contextual way. There seem to be two parts to this. (a) The first is that a detection process depends on setting the detector into a ground state before detection takes place (analogously to the way computer memories have to be notionally cleared before a calculation can begin). This is an asymmetric adaptive selection process, whereby any possible initial state of the detector is reduced to a starting state, thereby decreasing entropy. It will be implemented as part of the detector design. (b) The asymmetry of the collapse process may rely on the fact that the future does not yet exist in a EBU [42], hence we cannot have advanced Green functions contributing to a Feynman propagator. There does not seem to be any other plausible way to relate the global cosmological arrow of time to the local arrow of time involved in collapse of the wave function. This needs to be elucidated; a start is made in [45].

- **Test of non-linearities** This implied coarse graining in any detection relates to a precision test of quantum mechanics proposed by Weinberg [145], based on searching for the detuning of resonant transitions in $^9Be^+$ ions. Such an experiment in effect involves a window function of scale the size of the $^9Be^+$ ion, which has a radius of 1.12Å. Extending such tests to larger scales is obviously extremely difficult; but still one might have that as a goal.
• **Inequalities:** Like many other studies, Leggett’s “macroscopic realism” condition \(^9\) is based on the view that quantum theory applies at all levels (as in Diagram 3). The present paper suggests this cannot be taken for granted; higher level quantum behaviour will not generally emerge from the combination of lower level quantum systems. Hence the Leggett-Garg inequalities and their generalizations \(^9\) may be a way to test the relative viability of these two approaches. Developing such tests would clearly be useful.

Perhaps the most unexpected feature emerging from this analysis is the conclusion that *adaptive selection may play a key role in quantum physics, as well as in biology.* This conclusion is foreshadowed by the way it may be seen as playing a key role in environmental decoherence \(^15, 16\), which is central to the emergence of classical states.

Does this view regard unitary quantum physics as an essentially fundamental theory (no exceptions are allowed)? \(^11\) No, it subscribes to the “Leggett program”, according to which one should expect inherent (fundamental) limits to quantum behavior of higher level (more complex) systems. Unitary quantum physics is fundamental in that it applies to everything at a foundational level in the hierarchy of complexity, except when state vector reduction takes place in consequence of a process that is yet to be determined. This does not mean it necessarily applies at arbitrary higher levels. That depends on the emergence of higher level behaviour, which may or may not obey unitary quantum precepts; indeed it is clear it often does not do so (as illustrated above by many examples). That emergence is due to the state vector collapse process at the lower levels (as emphasized by Leggett).

How can one distinguish a fundamental collapse event from a “standard” environment-induced one? On this view, they are all environmentally induced. How can one ever distinguish a fundamental non-Hamiltonian behavior from an effective non-Hamiltonian behavior resulting from a reduced description of an underlying Hamiltonian system? Such effective descriptions abound. On this view, those reduced descriptions that result in a non-Hamiltonian behaviour do so by implicitly assuming a lower level state reduction mechanism (underlying events such as an Umklapp-process). All “phenomena” are contextual, in the sense that what we see depends on our resources. Now take the resources to specify the observer; this observer cannot be “exorcised”, he is needed to condition and select the appropriate physical description.

The standard view is that any isolated system can in principle be described by a single wave function, no matter how large they are. Often the wave function can be written as a product state of wavefunctions of individual systems. If that cannot be done then the individual systems are entangled; but decoherence will rapidly remove such entanglement in realworld situations. If it can, then these are the local wave functions that underlie local physics. This paper proposes that this view must be treated with caution: one should check if such a wave function emerges from the micro level.

**The ultimate take home message** is three fold:

---

\(^{11}\)I am indebted to Guenter Mahler for these questions and the following comment.
• Considering issues such as state preparation and the process of state vector reduction should be done taking realistic contexts into account: on the one hand, the cosmic environment in which we live (cf. [45]); on the other, the complexities of life as we experience it in the everyday world. When we tackle such issues, the abstractions of our scientific models must be rich enough to take this complexity seriously.

• It is not OK to just assume that a Hamiltonian formulation will apply to any old system, no matter how large. You can assume it will apply to the component parts at the quantum level; but when these parts are assembled into a complex system, a Hamiltonian description may or may not be valid as a description of the higher level dynamics. You have to investigate whether this is so or not. In many cases the answer will be that it is not applicable.

• The complexity we see arises from a combination of bottom-up emergence of higher levels of behaviour, combined with top-down influences that determine the actual outcomes in specific contexts. How do you tell when it is bottom up causation alone? – when lower level action by itself leads to well-determined higher level behaviour, as in the perfect gas laws and the black-body radiation formula. How do you tell when top-down causation makes a significant difference to outcomes? When higher level effects such as the band structure of metals is the main determinant of the specific lower level outcomes, as in the case of superconductivity and semiconductors: you cannot determine the outcome on the basis of the lower level properties alone [91].

One of the most important examples of top-down causation is the existence and direction of the arrow of time. This is a crucial feature of the daily world, without which we would not be here. The accompanying paper [45] makes the case that this key issue is best studied by looking in detail at how physical systems, arising out of the underlying unitary physics, detect the one-way flow of time.

Acknowledgement:

I thank Anton Zeilinger, Andrew Briggs, Jeff Murugan, David Aschman, Raoul Viollier, Andre Peshier, and particularly Paul Davies for useful discussions, Guenter Mahler for helpful comments, Per Sundin for a correction to a previous version, and particularly Jeremy Butterfield for detailed comments on a previous version of the paper. I thank an anonymous referee for detailed comments that have improved parts of this paper.

I thank Anton Zeilinger for hospitality at meetings at the International Academy, Traunkirchen, that were very helpful in developing these ideas. I thank the National Research Foundation (South Africa) and the University of Cape Town for support.
References

[1] Y Aharaonov and D Rohrlich (2005) *Quantum paradoxes* (Weinheim: Wiley-VCH).

[2] U Alon (2007) *An Introduction to Systems Biology: Design principles of biological circuits* (London: Chapman and Hall).

[3] A E Allahverdyan, R Balian, and T M Nieuwenhuizen (2011) “Understanding quantum measurement from the solution of dynamical models” [arXiv:1107.2138v1].

[4] M Alonso and E J Finn (1971) *Fundamental University Physics III: Quantum and Statistical Physics* (Reading, Mass: Addison Wesley).

[5] P W Anderson (1972) “More is Different” *Science* **177**, 377. Reprinted in *P W Anderson: A Career in Theoretical Physics*. (World Scientific, Singapore. 1994).

[6] P W Atkins (1994) *Physical Chemistry* (Oxford: Oxford University Press).

[7] G Auletta, G Ellis, and L Jaeger (2008) “Top-Down Causation: From a Philosophical Problem to a Scientific Research Program” *J R Soc Interface* **5**: 1159-1172 [http://arXiv.org/abs/0710.4235].

[8] P Ball (2011) “The dawn of quantum biology” *Nature* **474**:272-274.

[9] A Bassi G-C and Ghirardi (2003) “Dynamical Reduction Models” *Phys.Rept.* **379**: 257 [quant-ph/0302164v2].

[10] R Bellman and R Kalaba (1964) *Selected papers on Mathematical trends in Control Theory* (New York: Dover).

[11] R N Bracewell (1986) *The Fourier Transform and its Applications* (New York: McGraw Hill)

[12] H.-P Breuer and F Petruccione (2006) *The Theory of open quantum systems* (Oxford: Clarendon Press).

[13] J Binney and S Tremaine (1987) *Galactic Dynamics* (Princeton: Princeton University Press).

[14] B. Brezger, L. Hackermuller, S. Uttenthaler, J. Petschinka, M. Arndt, and A. Zeilinger (2002) “Matter-wave interferometer for large molecules” *Phys. Rev. Lett* **88**: 100404 [arXiv:quant-ph/0202158v1].

[15] A Buonanno and Y Chen (2001) “Optical noise correlations and beating the standard quantum limit in advanced gravitational-wave detectors” *Class.Quant.Grav.* **18**:L95-L101 [arXiv:gr-qc/0010011].

[16] A Buonanno and Y Chen (2001) “Quantum noise in second generation, signal-recycled laser interferometric gravitational-wave detectors” *Phys.Rev.* **D64**: 042006 [arXiv:gr-qc/0102012v2].
REFERENCES

[17] A O Caldeira (2010) “Caldeira-Leggett model”: Scholarpedia article.

[18] M G Calkin (1996) Lagrangian and Hamiltonian Mechanics (Singapore: World Scientific).

[19] P Calow (1976) Biological Machines: A Cybernetic Approach to Life (London: Edward Arnold)

[20] N A Campbell and J B Reece (2005) Biology (Benjamin Cummings).

[21] S Carroll (2010) From Eternity to here: the quest for the ultimate arrow of time (New York: Dutton).

[22] P M Chaikin and T C Lubensky (2000) Principles of condensed matter physics (Cambridge: Cambridge University Press).

[23] S Chandrasekhar (1957) An Introduction to the Study of Stellar Structure (Minealo, New York: Dover)

[24] M Chown (2010) We need to talk about Kelvin (London: Faber and Faber).

[25] F R Chromey (2010) To Measure the sky: An introduction to observational astronomy (Cambridge: Cambridge University Press).

[26] C Clarkson, G F R Ellis, J Larena, and O Umeh (2011) “Averaging and backreaction in cosmology: Is it important?” Rep. Prog. Phys. 74: 112901.

[27] D P Craig and T Thirunamachandran (1984) Molecular Quantum Electrodynamics: an introduction to Radiation Molecule Interactions (Mineola, New York: Dover).

[28] J D Cressler (2009) Silicon Earth: Introduction to the Microelectronics and Nanotechnology Revolution (Cambridge: Cambridge University Press).

[29] P C W Davies (1974) The Physics of Time Asymmetry (Surrey University Press).

[30] E H Davidson (2006) The regulatory genome: Gene regulatory networks in development and evolution (New York: Academic Press).

[31] P A M Dirac (1958) The Principles of Quantum Mechanics (Oxford: Oxford University Press).

[32] R W Ditchburn (1958) Light (London: Blackie).

[33] J J Distefano, A R Stubberud and I J Wliams (1990) Feedback control systems (New York: McGraw Hill).

[34] S Dodelson (2003) Modern Cosmology (New York: Academic Press).

[35] A Durrant (2000) Quantum Physiscs of Matter (Bristol: Institute of Physics and The Open University).

[36] F Dyson (2011) “The ‘Dramatic Picture’ of Richard Feynman” New York Review of Books (July 14).
REFERENCES

[37] A S Eddington (1926). 1926. *The Internal Constitution of Stars*. (Cambridge: Cambridge University Press.)

[38] A S Eddington (1928). *The Nature of the Physical World*. (London: MacMillan)

[39] G F R Ellis (1984) “Relativistic cosmology: its nature, aims and problems”. In *General Relativity and Gravitation*, Ed B Bertotti et al (Reidel), 215-288.

[40] G F R Ellis (2002) “Cosmology and Local Physics”. *New Astronomy Reviews* 46: 645-658 [http://arxiv.org/abs/gr-qc/0102017].

[41] G F R Ellis (2004): “True Complexity and its Associated Ontology”. In *Science and Ultimate Reality*. Ed. J D Barrow, P C W Davies, and C L Harper (Cambridge: Cambridge University Press), 607-636.

[42] G F R Ellis (2006) “Physics in the Real Universe: Time and Spacetime”. *GRG* 38: 1797-1824 [http://arxiv.org/abs/gr-qc/0605049].

[43] G F R Ellis (2008) “On the nature of causation in complex systems” *Trans Roy Soc South Africa* 63: 69-84.

[web: \protect\vrule width0pt\protect\href{http://www.mth.uct.ac.za/~ellis/Top-downcausation.html}{\topdowncausation.html}]

[44] G F R Ellis (2012) “Top down causation and emergence: some comments on mechanisms” *Journ Roy Soc Interface* (London) 2: 126-140

[web: \protect\vrule width0pt\protect\href{http://www.mth.uct.ac.za/~ellis/Interface2_1_2012.html}{Interface2_1_2012.html}]

[45] G F R Ellis (2011) “The arrow of time, the nature of spacetime, and quantum measurement”: Preprint.

[web: \protect\vrule width0pt\protect\href{http://www.mth.uct.ac.za/~ellis/QuantumMeasure.html}{QuantumMeasure.html}]

[46] G F R Ellis, D Noble, and T O’Connor (2011) (Eds) Special issue *Journ Roy Soc Interface Focus* (London) on top down causation, to appear.

[47] G F R Ellis, R Maartens and M A H MacCallum (2011) *Relativistic Cosmology* (Cambridge: Cambridge University Press).

[48] GF R Ellis, D Noble, and T O’Connor (2012) (Eds) Special issue of the *Journ Roy Soc Interface Focus* (London) on top down causation: *Interface Focus* 2, Issue 1: February 6, 2012.

[49] G F R Ellis and T Rothman (2010): ”Crystallizing block universes”. *International Journal of Theoretical Physics* 49: 988. [arXiv:0912.0808]

[50] G F R Ellis and D W Sciama (1972) “Global and non-global problems in cosmology”. In *General Relativity (A Synge Festschrift)*, ed. L. O’Raifeartaigh (Oxford: Oxford University Press), 35-59.
[51] A L Fetter and J D Walecka (2003) *Quantum Theory of Many Body Systems* (Mineola, New York: Dover).

[52] R P Feynman and A R Hibbs (1965) *Quantum Mechanics and Path Integrals*, Ed D F Styer (Dover: Mineola, New York).

[53] R P Feynman, R B Leighton and M Sands (1963) *The Feynman Lectures on Physics: Mainly Mechanics, Radiation, and Heat* (Reading, Mass: Addison-Wesley).

[54] R P Feynman, R B Leighton and M Sands (1965) *The Feynman Lectures on Physics: Quantum Mechanics* (Reading, Mass: Addison-Wesley).

[55] S Fishman, Y Krivolapov, and A Soffer (2011) “The Nonlinear Schroedinger Equation with a random potential: Results and Puzzles” [arXiv:1108.2956v1].

[56] G R Fowles (2004), *Analytical Mechanics*. (Brooks Cole).

[57] P Franche, R Gwyn, B Underwood, and A Wissanji (2009) “Attractive Lagrangians for Noncanonical Inflation” *Phys Rev D* 81: 123526 [arXiv:0912.1857v3].

[58] P Franche, R Gwyn, B Underwood, and A Wissanji (2010) “Initial Conditions for Non-Canonical Inflation” *Phys Rev D* 82: 063528 [arXiv:1002.2639v1].

[59] H U Fuchs (1996) *The dynamics of Heat* (New York: Springer).

[60] M Gell-Mann (1994) *The Quark and the Jaguar: Adventures in the Simple and the Complex* (London: Abacus).

[61] J Gemmer, M Michel and G Mahler (2004) *Quantum Thermodynamics: Emergence of Thermodynamic Behaviour Within Composite Quantum Systems* (Heidelberg: Springer).

[62] G-C Ghirardi (2007) “Collapse theories” In *Stanford Encyclopaedia of Philosophy*: [http://plato.stanford.edu/entries/qm-collapse/](http://plato.stanford.edu/entries/qm-collapse/)

[63] M B Glauert (1960) *Principles of Dynamics* (London: Routledge and Kegan Paul).

[64] . P Goettig1, M Groll, J-S Kim, R Huber and H Brandstetter (2002) “Structures of the tricorn-interacting aminopeptidase F1 with different ligands explain its catalytic mechanism” *EMBO Journal* 21, 5343 - 5352.

[65] Gray, P (2011) *Psychology* (New York: Worth).

[66] D M Greenberger, M A Horne, and A Zeilinger (1989) “Going Beyond Bell’s Theorem” In: *Bell’s Theorem, Quantum Theory, and Conceptions of the Universe*, M. Kafatos (Ed.), (Dordrecht:Kluwer), 69-72 [arXiv:0712.0921v1].

[67] G Greenstein and A G Zajonc (2006) *The Quantum Challenge: Modern Research on the Foundations of Quantum Mechanics* (Sudbury, Mass: Jones and Bartlett).

[68] F Haake (2001) *Quantum Signatures of Chaos* (Heidelberg: Springer).
REFERENCES

[69] L Hackermueller, S Uttenhalter, K Hornberger, E Reiger, B Brezger, A Zeilinger, and M Arndt (2003) “The wave nature of biomolecules and fluorofullerenes” Phys. Rev. Lett. 91:090408 [arXiv:quant-ph/0309016v1].

[70] H L Harrison, J G Bollinger (1969) Introduction to automatic controls (Scranton, PA: International Textbook Company).

[71] J Hartle (2011) “The quasiclassical realms of this quantum universe” Found. Phys. 41:982-1006 [arXiv:00806.377].

[72] S Hartmann (2001). “Effective Field Theories, Reductionism, and Scientific Explanation”. Stud Hist Phil Mod Phys 32: 267.

[73] S W Hawking (1975) “Particle creation by black holes” Comm Math Phys 43:199-220.

[74] S W Hawking (1984) “The quantum state of the universe” Nucl. Phys. B239:2447.

[75] E Hecht (1975) Optics (McGraw Hill: Schaum).

[76] J H Holland (1992) Adaptation in natural and artificial systems (Cambridge, Mass: MIT Press).

[77] P A Iglesias and B P Iglesias (2010) Control Theory and Systems Biology (Harvard, Mass: MIT Press).

[78] C J Isham (1995) Lectures on Quantum Theory: Mathematical and Structural Foundations (London: Imperial College Press).

[79] C Itzykson and J-B Zuber (1980) Quantum Field Theory (McGraw Hill).

[80] J C Jackson (1967) Classical Electrodynamics (New York: Wiley).

[81] V Jacques, E Wu, F Grosshans, F Treussart, P Grangier, A Aspect, and J-F Roch (2007) “Experimental realization of Wheeler’s delayed-choice GedankenExperiment” Science 315:5814 [arXiv:quant-ph/0610241v1].

[82] J K Jain (2000) “The composite fermion: a quantum particle and its quantumfluids” Physics Today April 2000: 39-45.

[83] E R Kandel, J H Schwartz, and T M Jessell (2000) Principles of Neuroscience (New York: McGraw Hill).

[84] S A Kauffman (1993) The Origins of Order: Self-Organisation and Selection in Evolution (New York: Oxford).

[85] F Y Khalili, H Miao, Y Chen (2009) “Increasing the sensitivity of future gravitational-wave detectors with double squeezed-input” Phys.Rev.D80: 042006 [arXiv:0905.1291].
REFERENCES

[86] H J Kimble, Y Levin, A B Matsko, K S Thorne, S P Vyatchanin (2002) “Conversion of conventional gravitational-wave interferometers into QND interferometers by modifying their input and/or output optics” Phys.Rev. D65: 022002 [arXiv:gr-qc/0008026v2].

[87] G. Kirchmair, F Zähringer, R Gerritsma, M Kleinmann, O Gühne, A Cabello, R Blatt, and C F Roos (2009) “State-independent experimental test of quantum contextuality” Nature 460: 494-497 [arXiv:0904.1655].

[88] I K Kominis (2011) “Nature’s biochemical double slit: how many molecules react?” IEEE Trans. Plasma Science 39:644 [arXiv:1009.2897v1].

[89] N P Landsman (2005) “When champs meet: rethinkng the Bohr-Einstein debate” Studies in History and Philosophy of Modern Physics 37:212-242

[90] R Lapkiewicz, P Li, C Schaeff, N K Langford, S Ramelow, M Wiesniak, and A Zeilinger (2011) “Experimental non-classicality of an indivisible quantum system” Nature 474: 490 [arXiv:1106.4481v1].

[91] R B Laughlin (2000) “Fractional Quantisation”. Reviews of Modern Physics 71: 863.

[92] H S Leff and A F Rex (eds) (1990) Maxwell’s Demon: Entropy, Information, Computing (Bristol: Adam Hilger).

[93] A J Leggett (1991) “Reflections on the Quantum Measurement Paradox”. In Quantum Implications: Essays in Honour of David Bohm, Ed. B J Hiley and F D Peat (London: Routledge), 85-104.

[94] A J Leggett (2008) “Realism and the physical world” Rep Prog Phys 71:022001 (6pp).

[95] A L Lehninger (1973) Bioenergetics (Menlo Park: W A Benjamin).

[96] P Léna (1986) Observational astrophysics (Heidelberg: Springer).

[97] S G Lipson and H Lipson (1969) Optical Physics (Cambridge: Cambridge University Press).

[98] S Lloyd (2011) “A bit of quantum hanky-panky” Physics World January 2011: 26-29.

[99] U Leonhardt (2010) Essential quantum optics (Cambridge: Cambridge University Press).

[100] F London and E Bauer (1983) “The theory of observation in quantum mechanics”. In Quantum Theory and Measurement, J A Wheeler and W H Zurek (Eds), (Princeton: Princeton University Press), 217-259.

[101] R Loudon (1983) The quantum theory of light (Oxford: Oxford University Press)

[102] R D Mattuck (1992) A guide to Feynman diagrams in the many-body problem (Dover Publications).
REFERENCES

[103] A C Melissinos(1990) Principles of Modern Technology (Cambridge: Cambridge University Press).

[104] G J Milburn (1997) Schrödinger’s Machines: The quantum technology reshaping everyday life (New York: W H Freeman).

[105] J H Milsum (1966) Biological control systems analysis (McGraw Hill).

[106] C W Misner, K S Thorne and J A Wheeler (1973) Gravitation (Freeman: San Francisco).

[107] M A Morrison (1990) Understanding Quantum Physics: a user’s manual (Englewood Ciffs: Prentice Hall International).

[108] D Myers (2010) “Chemistry of Photography”, http://www.cheresources.com/content/articles/other-topics/chemistry-of-photography.

[109] J R Oppenheimer and G M Volkoff (1939) “On Massive Neuron Cores” Phys Rev 55:374—381.

[110] J D Palmer (2002) The Living Clock: The Orchestrator Of Biological Rhythms (New York: Oxford University Press)

[111] L Pauling (1960) The nature of the chemical bond and the structure of molecules and crystals: an introduction to modern structural chemistry (Ithaca: Cornell University Press).

[112] L Pauling and E B Wilson (1963) Introduction to Quantum Mechanics with applications to Chemistry (Mineola, NY: Dover)

[113] A R Peacocke (1989) An introduction to the physical chemistry of biological organization (Oxford: Oxford University Press).

[114] R Penrose (1989) The Emperor’s New Mind: Concerning Computers, Minds and the Laws of Physics (Oxford: Oxford University Press).

[115] R Penrose (2004) The Road to Reality: A complete guide to the Laws of the Universe (London: Jonathan Cape).

[116] I Percival (1991) “Schrödinger’s quantum cat”. Nature 351: 357.

[117] M E Peskin and D V Schroeder (1995), An Introduction to Quantum Field Theory (Reading, Mass: Perseus books).

[118] A D Polyanin (2004) “Non-linear Schröedinger equation of general form” Equation World, http://eqworld.ipmnet.ru/en/solutions/npde/npde1403.pdf

[119] G N Price, S T Bannerman, E Narevicius, and M G Raizen (2007), “Single-Photon Atomic Cooling” Laser Physics 17:14.

[120] G N Price, S T Bannerman, K Viering, E Narevicius, and M G Raizen (2008) “Single-Photon Atomic Cooling” Phys Rev Lett 100:093004.
[121] A Rae (1994) *Quantum Physics: Illusion or Reality?* (Cambridge: Cambridge University Press).

[122] R Rhoades and R Pflanzer (1996) *Human Physiology* (Fort Worth: Saunders College Publishing).

[123] F Rioux (2005) “Illustrating the superposition principle with single particle interference.” *The Chemical Educator* **10**:424-426.

[124] J G Roederer (2005) *Information and its role in Nature* (Heidelberg: Springer).

[125] A Ruschhaupt, J G Muga and M G Raizen (2006) “One-photon atomic cooling with an optical Maxwell Demon valve” *J. Phys. B: At. Mol. Opt. Phys.* **39**:3833—3838.

[126] J J Sakurai (1994) *Modern Quantum Mechanics* (Reading, Mass: Addison Wesley Longman).

[127] C Sayrin, I Dotsenko, X Zhou, B Peaudecterf, T Rybarczyk, S Gleyzes, P Rouchon, M Mirrahimi, M Bruen, J-M Raimond, and S Haroche (2011) “Real-time quantum feedback prepares and stabilizes photon number states” *Nature* **477**:73-77.

[128] M Sarovar and G J Milburn (2004) “Continuous quantum error correction” In *Quantum Communication, Measurement and Computing (QCMC04)*, ed. S. M. Barnett, E. Andersson, J. Jeffers, P. Ohberg, O. Hirota (AIP Conference Proceedings), p. 121 [arXiv:quant-ph/0501049].

[129] S Saunders, Barrett, A Kent, D Wallace (2011) *Many Worlds: Everett, Quantum Theory and Reality* (Oxford: Oxford University Press)

[130] W C Saslaw (1987) *Gravitational Physics of stellar and galactic systems* (Cambridge: Cambridge University Press).

[131] G Schaller, C Emary, G Kiesslich, and T Brandes (2011) “Probing the power of an electronic Maxwell Demon” [arXiv:1106.4670v2].

[132] T Scheidl, R Ursin, A Fedrizzi, S Ramelow, X-S Ma, T Herbst, R Prevedel, L Ratschbacher, J Kofler, T Jennewein, A Zeilinger (2009) “Feasibility of 300 km Quantum Key Distribution with Entangled States” *New J. Phys.* **11**: 085002 [arXiv:1007.4645v1].

[133] L I Schiff (1968) *Quantum Mechanics* (McGraw Hill).

[134] D W Sciama (1959) *The Unity of the Universe* (London: Faber andf Faber).

[135] A C Scott (2007) *The non-linear universe: chaos, emergence, and life* (Heidelberg: Springer).

[136] G M Shepherd and S Grillner (2010) *Handbook of brain microcircuits* (Oxford: Oxford University Press).

[137] J Silk (2001) *The Big Bang* (New York: Freeman).
[138] A S Tanenbaum (1990) *Structured Computer Organisation* (Englewood Cliffs: Prentice Hall).

[139] W Thirring W (1958). ”A Soluble Relativistic Field Theory?” *Annals of Physics* 3: 91112.

[140] K Umashankar (1989) *Introduction to engineering electromagnetic fields* (Singapore: World Scientific).

[141] B Van Zeghbroeck, (2007) *Principles of Semiconductor Devices* [http://ecee.colorado.edu/~bart/book/book/contents.htm](http://ecee.colorado.edu/~bart/book/book/contents.htm).

[142] P Villoresi, T Jennewein, F Tamburini, M Aspelmeyer, C Bonato R Ursin, C Pernechele, Luceri, G Bianco, A Zeilinger, and C Barbieri (2008) “Experimental verification of the feasibility of a quantum channel between Space and Earth” *New Journal of Physics* 10: 033038 [arXiv:0803.1871v1](http://arxiv.org/abs/0803.1871v1).

[143] D Wallace (2002) “Worlds in the Everett Interpretation” *Studies in the History and Philosophy of Modern Physics* 33:637–661.

[144] D Wallace (2008) “The Quantum Measurement Problem: State of Play”, chapter 1 of D. Rickles (ed), *The Ashgate Companion to the New Philosophy of Physics* (Ashgate).

[145] S W Weinberg (1989) “Precision test of quantum mechanics” *Phys Rev Lett* 62:485-488.

[146] J A Wheeler (1978), “The ‘Past’ and the ‘Delayed-Choice Double-Slit Experiment’,,” in A.R. Marlow, editor, *Mathematical Foundations of Quantum Theory* (New York: Academic Press), 948.

[147] J A Wheeler and R P Feynman (1945), “Interaction with the Absorber as the Mechanism of Radiation”. *Rev. Mod. Phys.* 17: 157-181.

[148] J A Wheeler and W H Zurek (1983), *Quantum Theory and Measurement* (Princeton University Press: Princeton).

[149] F L Wilson (1968) “Fermi’s Theory of β-decay” *Am Jour Phys* 36: 1150-1160.

[150] K G Wilson (1975) “The renormalization group: Critical phenomena and the Kondo problem” *Rev. Mod. Phys.* 47: 773840.

[151] H M Wiseman and G J Milburn (2010) *Quantum Measurement and Control* (Cambridge: Cambridge University Press).

[152] A Zee (2003) *Quantum Field Theory in a nutshell* (Princeton: Princeton University Press).

[153] H-D Zeh (2007) *The Physical Basis of the Direction of Time* (Berlin: Springer Verlag).
[154] H D Zeh (1990) “Quantum measurement and entropy” In Complexity, Entropy and the Physics of Information, Ed W H Zurek (Redwood City: Addison Wesley), 405-421.

[155] A Zeilinger (1999) “Experiment and the foundations of quantum physics” Rev. Mod. Phys. 71: S288S297.

[156] Ya B Zeldovich and I D Novikov (1971) Relativistic Astrophysics: Volume 1. Stars and Relativity (Chicago: University of Chicago Press).

[157] H Zink (2008) “Ionisation by quantised electromagnetic fields: The photoelectric effect” Rev.Math.Phys. 20:367-406 [http://lanl.arxiv.org/abs/math-ph/0610023].

[158] J M Ziman (1979) Principles of the theory of solids (Cambridge: Cambridge University Press).

[159] W H Zurek (2003) “Decoherence, Einselection, and the Quantum Origins of the Classical.” Rev. Mod. Phys. 75, 715 [http://lanl.arxiv.org/abs/quant-ph/0105127]

[160] W H Zurek (2004) “Quantum Darwinism and Envariance”. In Science and ultimate reality: Quantum theory, Cosmology, and Complexity, J Barrow, P C W Davies and C Harper (Eds), (Cambridge University Press: Cambridge), 121-134.