Quantum Buzzwords*

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Abstract

Many scientists seeking to understand the quantum mechanics of measurement situations (Copenhagen quantum theory) agree on its overwhelmingly successful algorithms to predict the outcomes of laboratory measurements but disagree on what these algorithms mean and how they are to be interpreted. Some of these problems are briefly described and resolutions suggested from the decoherent (or consistent) histories quantum mechanics of closed systems like the Universe.

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I. INTRODUCTION

The Copenhagen quantum mechanics of measurement situations (CQM) found in standard textbooks\(^1\) is arguably the most successful theoretical framework in the history of physics. It is central to our understanding of a vast range of physical phenomena, including atoms, molecules, chemistry, the solid state, how stars are formed, shine, evolve, and die, nuclear energy, thermonuclear explosions, how transistors work, and many, many, many, more phenomena. It has been claimed that quantum mechanics is responsible for a significant fraction of the US GDP.

Work continues today to better understand Copenhagen quantum mechanics, to make its central notions of measurement and state vector reduction more precise, and to resolve ‘problems’ that it is alleged to have. Despite the lack of such precision early in its history, the author knows of no mistakes that were made as a consequence in correctly applying CQM in the century since it was first formulated.

A few ‘quantum buzzwords’ (or phrases) characterize some of the issues with CQM that challenge understanding. A short list would include ‘the definition of measurement’, ‘state vector collapse’, ‘many worlds’, ‘the locality of quantum theory’, ‘quantum states of subsystems’, ‘Schrödinger’s cat’, ‘living in a superposition’, ‘reality,’ the ‘quantum arrow of time’, consciousness, ‘the Heisenberg cut’, ‘observers’ ‘a role for consciousness’, ‘states for subsystems’, the principle of superposition, ... There are undoubtably others.\(^2\)

The Copenhagen quantum mechanics of measurement situations has to generalized for several reasons. The simplest reason is that quantum phenomena are not restricted just to laboratory measurements. Much of what we observe of our large scale universe is a consequence of quantum processes that started in the very early universe.\(^3\) A generalization

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\(^1\) By ‘Copenhagen quantum mechanics’, or ‘textbook quantum mechanics’ we mean the standard formulation that is found in many textbooks. We do not necessarily mean that it conforms exactly to what the founders of quantum mechanics meant by the ‘Copenhagen interpretation of quantum mechanics’ [1].

\(^2\) Some topics that require a discussion that would be too extensive for this paper have been left out. The ‘quantum measurement problem’ is one, but see e.g. [2]. Another is the many ways of deriving Born’s rule from the other postulates of quantum mechanics. See [24] for the author’s effort on this. There are a great many others.

\(^3\) A well known example is the growth of quantum density fluctuations in the early universe and their subsequent collapse due to gravitational attraction. We see the results in the fluctuations in the cosmic background radiation (CMB) a few hundred thousand years after the big bang and in the distribution of the galaxies in the present.
of CQM is thus needed for cosmology [3].

CQM must also be generalized to contribute to the current quest for ‘final theories’ that unify all interactions including gravity. CQM assumes a fixed, flat, classical spacetime. But in the very early universe, near the big-bang, spacetime will neither be flat nor fixed,. Rather it will be fluctuating quantum mechanically. A generalization of CQM is needed just to retrodict the probabilities of what went on then.

Generalizations of CQM can shed light on issues labeled by the quantum buzzwords. This paper is devoted to suggestions of how the consistent, or decoherent histories formulation of quantum theory (DHQM) [4, 5] could help understand and resolve some of these concerns.4

DHQM is a generalization of CQM that applies to closed systems like a spatially closed universe. It is an extension, and to some extent a completion, of the ideas pioneered by Everett [7]. Given theories of the closed system’s quantum state and dynamics, DHQM predicts probabilities for the individual members of sets of alternative coarse-grained time histories of what goes on in the closed system. These could be alternative histories of the expansion of the universe in cosmology for example. They could also be histories of how the universe began in the big bang. But they can also be alternative histories of the preparation and outcomes of an experiment in a laboratory along with the behavior of observers who are carrying out the experiment. CQM can thus be seen as an emergent approximation to the DHQM quantum mechanics of a closed system like the universe. That viewpoint gives a different and fruitful perspective on the quantum buzzwords.

Section II contains a bare bones exposition of the parts of DHQM that we will need for our discussion. Section III contains a discussion of these buzzwords. Section IV offers some brief conclusions and suggests directions for further research. An appendix contains an unpublished manuscript by Murray Gell-Mann and the author entitled ‘Copenhagen Quantum Mechanics and Decoherent Histories Quantum Mechanics’ [8]. It covers much the same ground as this paper but more briefly, with a different voice, and different emphases.

4 Robert Griffiths introduced consistent histories quantum mechanics in [4]. Independently, but later, the author and Murray Gell-Mann introduced a closely related framework which they called decoherent histories quantum theory [6]. Consistent histories quantum mechanics and decoherent histories quantum mechanics may be distinguished by their historical development, by different emphases, by terminology, and by application. But, in the author’s opinion, they both denote essentially the same framework for quantum prediction. In this paper we use the term ‘decoherent histories’ to be compatible with the author’s other writings.
that may be useful.

This paper is not an in depth review or an exposition of either CQM or DHQM and their applications. And it is certainly not of a history of the now century old discussion of these topics. The author aims only to provide a few brief suggestions for understanding these issues presented by the buzzwords and some references to follow these suggestions up. In one way or another most of the issues are discussed in the author’s papers and essays and therefore many of the references are to these. No models are developed in this paper and no calculations are presented. We aim rather at brief discussions of that might motivate models and calculation. Discussions at greater depth (and greater length) can be found in the author’s collection of essays\(^5\). For the most part the discussion is about the facts of these formulations and their connection. But occasionally author’s opinions on how to proceed are offered.

II. DECOHERENT HISTORIES QUANTUM MECHANICS. (DHQM)

A BRIEF INTRODUCTION

A. Setup

To simplify the discussion we assume throughout a flat classical background spacetime with which to give time histories meaning. We are thus neglecting quantum gravity for the most part\(^6\). We consider a closed quantum system with a Hilbert space \(\mathcal{H}\). A spatially closed universe is a relevant example. The basic theoretical inputs to prediction are assumed to be a pure quantum state of the universe \(\ket{\Psi}\) and a Hamiltonian \(H\) specifying the system’s quantum dynamics. In the Heisenberg picture in which we work neither varies in time. We aim at predicting the probabilities of of the individual members of sets of alternative, coarse-grained time histories of this system. Theories of \(\ket{\Psi}\) and \(H\), together with the assumed classical background spacetime are the theoretical inputs to prediction in this paper. Sometimes we just denote the input theory by \((H, \Psi)\).

\(^5\) "The Quantum Universe", World Scientific, Singapore or arXiv1807.04126
\(^6\) For more on DHQM and quantum spacetime see e.g. \[\]
B. Histories

A time history (or just ‘history’ for short) is a sequence of alternatives at a series of times. Consider histories of the motion of the Earth’s center of mass. A coarse-grained history of this motion is specified by which of an exhaustive set of regions of space the center of mass occupies at a discrete series of times. The histories are *coarse-grained* because they only follow the center of mass of the Earth to an accuracy limited by the size of the regions and because they follow them, not at all times, but only at a discrete series of them. We next describe how such coarse-grained histories are represented in DHQM.

An exhaustive set of coarse-grained yes/no alternatives at *one time* $t$ is represented in the Heisenberg picture by a set of orthogonal projection operators $\{P_\alpha(t)\}, \alpha = 1, 2, 3, \ldots$. These satisfy

$$\sum_\alpha P_\alpha(t) = I, \quad \text{and} \quad P_\alpha(t) P_\beta(t) = \delta_{\alpha\beta} P_\alpha(t) ,$$

(2.1)

A one-dimensional $P_\alpha$ projects on a single pure state and is said to be *fine-grained*. Projections $P_\alpha$ that project on bigger subspaces of $\mathcal{H}$ are coarse-grained as in the discussion of the motion of the Earth’s center of mass above.

In the example of the Earth’s center of mass motion each of the projection operators in a set at time $t$ would project on a different spatial region at that time. For example the projection $P_\beta(t)$ represents the question “Is the Earth’s center of mass in region $\beta$ at time $t$ — yes or no?” How time sequences of such sets are turned into operators representing time histories of the Earth’s center of mass motion is described immediately below.

In the Heisenberg picture, the operators $P_\alpha(t)$ evolve with time according to

$$P_\alpha(t) = e^{+iHt/\hbar} P_\alpha(0) e^{-iHt/\hbar} .$$

(2.2)

The state $|\Psi\rangle$ and the Hamiltonian $H$ are unchanging in time in the Heisenberg picture.

An operator $P_\alpha$ projects on some subspace of the Hilbert space. We say that $P_\alpha$ *follows* the states in the subspace and *ignores* ones orthogonal to it.

The ignored variables are important because they can constitute an ‘environment’ whose interactions with followed variables carry away phases between followed histories and effect decoherence. For detailed examples of how this works see [10], and ([11], Section VI.)

Simple examples of sets of alternative histories can be specified by giving sets of single time alternatives $\{\{P^1_{\alpha_1}(t_1)\}, \{P^2_{\alpha_2}(t_2)\}, \ldots, \{P^n_{\alpha_n}(t_n)\}\}$ at a sequence of times $t_1 < t_2 < \cdots <
The sets at distinct times can differ and are distinguished by the superscript on the \( P \)’s. For instance, projections on ranges of position might be followed by projections on ranges of momentum, etc. An individual history \( \alpha \) in such a set is a particular sequence of alternatives \((\alpha_1, \alpha_2, \cdots, \alpha_n) \equiv \alpha \) and is represented by the corresponding chain of projections called a ‘class operator’, viz.

\[
C_\alpha \equiv P^n_{\alpha_n}(t_n) \cdots P^1_{\alpha_1}(t_1), \quad \sum_\alpha C_\alpha = 1.
\] (2.3)

A history with at least one coarse-grained projection is said to be a coarse-grained history. For any individual coarse-grained history \( \alpha \), there is a branch state vector defined by

\[
|\Psi_\alpha \rangle \equiv C_\alpha |\Psi \rangle, \quad \sum_\alpha |\Psi_\alpha \rangle = |\Psi \rangle.
\] (2.4)

When probabilities \( \{p(\alpha)\} \) can assigned to the individual histories in a set, they are given by

\[
p(\alpha) = \| |\Psi_\alpha \rangle \|^2 = \| C_\alpha |\Psi \rangle \|^2 = \| P^n_{\alpha_n}(t_n) \cdots P^1_{\alpha_1}(t_1) |\Psi \rangle \|^2.
\] (2.5)

Negligible interference between the branches of a set

\[
\langle \Psi_\alpha |\Psi_\beta \rangle \approx 0, \quad \text{for all} \quad \alpha \neq \beta \quad \text{(decoherence)}
\] (2.6)

is a necessary and sufficient condition for the probabilities (2.5) to be consistent with the rules of probability theory — whence the term ‘consistent histories’. The orthogonality of the branches is approximate in realistic situations. We mean by (2.6) equality to an accuracy that defines probabilities well beyond the standard to which the conditions can be checked or modeled. A set of alternative histories that satisfies the condition (2.6) is said to decohere or be decoherent.

To sum up: *Decoherence of a set of alternative histories is necessary for the probabilities of those histories to be consistent with the usual rules of probability theory. Coarse graining is necessary for decoherence.* It is a remarkable fact that in quantum mechanics some information has to be ignored in order to have any information at all.

*We call a decoherent set of alternative coarse-grained histories a realm.*

It is instructive to rewrite the expression (2.5) for the probabilities of a set of alternative histories in the Schrödinger picture. We denote the Schrödinger picture representative of a projection \( P_\alpha(t) \) by \( \hat{P}_\alpha \). Specifically,

\[
\hat{P}_\alpha \equiv e^{iHt/h} P_\alpha(t) e^{-iHt/h}.
\] (2.7)
Assume that the intervals $\Delta t$ between time steps are equal in (2.5). Defining $\tau \equiv \Delta t/\hbar$, we can write for (2.5).

$$p(\alpha) = \| \hat{P}_{\alpha_n} (e^{-iH\tau}) \hat{P}_{\alpha_{n-1}} \ldots \hat{P}_{\alpha_2} (e^{-iH\tau}) \hat{P}_{\alpha_1} (e^{-iH\tau}) \hat{\Psi} \|^2.$$  \hspace{1cm} (2.8)

The expression for the history on the right hand side of (2.8) could be described as unitary evolution represented by $e^{-iH\tau}$ interrupted by ‘reductions’ represented by the projections $\hat{P}_\alpha$’s. But these reductions have nothing to do with measurements in general. They are just the way alternatives at one moment of time are represented in the process of calculating probabilities for histories including histories of measurement situations e.g. ([12], and Sections II F and II G). The projections do not represent physical processes occurring in the measurement interaction between apparatus and measured subsystem. Rather, they are part of the description of the histories of measurement interactions whose probabilities are being calculated.

Thus we recover the first of von Neumann’s laws of evolution in a measurement situation but not the second — state vector reduction on measurement.

C. Prediction and Retrodiction.

In this subsection we make explicit how DHQM can be used to make predictions of the future and retrodictions of the past. To do that let’s fix a particular Lorentz frame in the assumed flat background spacetime. Suppose we are at rest at the present moment $t_p$ with a certain amount of data about what happened in the past. The past is towards the big bang and past moments are labeled by values of $t$ less than $t_p$. The future is the direction away from the big bang and moments there are denoted by values larger than $t_p$. (For more on what past, present, and future mean in a closed quantum system see [13]).

Suppose that alternatives $\alpha_1$ and $\alpha_2$ have happened at times $t_1$ and $t_2$ in the past. The probability that an alternative $\alpha_3$ will happen at a future time $t_3$ given that alternatives $\alpha_1, \alpha_2$ have happened in the past is

$$p(\alpha_3, t_3 | \alpha_2, t_2, \alpha_1, t_1) = \frac{p(\alpha_3, t_3, \alpha_2, t_2, \alpha_1, t_1)}{p(\alpha_2, t_2, \alpha_1, t_1)} \hspace{1cm} \text{(prediction)} \hspace{1cm} (2.9)$$

where all these probabilities are computed from $(H, |\Psi\rangle)$ via (2.5).

Retrodiction is through similar formulae for conditional probabilities for past alternatives given present alternatives. For example suppose we know just that $\alpha_3$ happened at a present
time \( t_p = t_3 \). The probability that \((\alpha_2, \alpha_1)\) happened at times \((t_2, t_1)\) in the past is

\[
p(\alpha_2, t_2, \alpha_1, t_1|\alpha_3, t_3) = \frac{p(\alpha_3 t_3 \alpha_2, t_2, \alpha_1, t_1)}{p(\alpha_3, t_3)} \quad \text{(retrodiction)} \tag{2.10}
\]

D. The Quantum State at a Moment of Time

Future predictions can all be obtained from an effective density matrix summarizing information about what has happened by the present time. For the example in (2.9) suppose \( t_2 \) is the present time and alternatives \( \alpha_1, \alpha_2 \) are known to have happened at past times \( t_1, t_2 \). We can define an effective density matrix \( \rho_{\text{eff}}(t_2) \) by

\[
\rho_{\text{eff}}(t_2) \equiv \frac{P^2_{\alpha_2}(t_2)P^1_{\alpha_1}(t_1)\rho P^1_{\alpha_1}(t_1)(P^2_{\alpha_2}(t_2))}{\text{Tr}[P^2_{\alpha_2}(t_2)P^1_{\alpha_1}(t_1)\rho P^1_{\alpha_1}(t_1)P^2_{\alpha_2}(t_2)]} \tag{2.11}
\]

where \( \rho \equiv |\Psi\rangle\langle\Psi| \). Then

\[
p(\alpha_3, t_3|\alpha_2, t_2, \alpha_1, t_1) = \text{Tr}[P^3_{\alpha_3}(t_3)\rho_{\text{eff}}(t_3)] \tag{2.12}
\]
in agreement with (2.9).

The density matrix \( \rho_{\text{eff}}(t_2) \) represents the usual notion of state of the system at time \( t_2 \). It is given here in the Heisenberg picture and is constant after \( t_2 \) until further information is acquired and a new \( \rho_{\text{eff}}(t_3) \) must be used for future prediction. See section III C.

In contrast to prediction, there is no effective density matrix representing present information from which probabilities for the past can be derived. Probabilities for past history require knowledge of both present data and the quantum state of the universe.

E. The Quasiclassical Realm

Perhaps the most striking feature of our quantum universe is its quasiclassical realm — the wide range of time, place and scale on which the deterministic laws of classical physics apply to an excellent approximation [14]. This includes the universe’s classical spacetime geometry extending from just after the big bang to the distant future. In DHQM the quasiclassical realm can be derived from suitable theories of the universe’s quantum state and dynamics \( (H, \Psi) \). To derive classical spacetime the theory \( (H, \Psi) \) must include quantum gravity in some approximation. [14, 15].
So manifest is the quasiclassical realm that parts of it are routinely simply assumed in constructing effective physical theories that apply in the late universe. Classical spacetime, for instance, is the starting assumption for the standard model of the elementary particle interactions. Classical spacetime obeying the Einstein equation is assumed in cosmology to reconstruct the past history of our universe. Classical spacetime is assumed in CQM just to define the time \( t \) in the Schrödinger equation, the times of measurement, the time of state vector collapse, etc. In Everett formulations classical spacetime is usually assumed to define the branching histories which are their characteristic feature.

F. Measurement Situations

Whenever there is an alternative correlated with an alternative of our Universe’s quasiclassical realm we say that we have a *measurement situation*. From the value of the alternative of the quasiclassical realm we can infer the value of the correlated alternative. In the Stern-Gerlach example the value of a spin (a quantum variable) becomes correlated with the spin’s position in space (a classical variable.)

Consider the example of a fission track in a slab of mica left by the decay of a radioactive nucleus embedded in the slab at its formation long ago. The track is produced by a quantum mechanical decay but described in quasiclassical variables. There was ‘preparation’ a long time ago, but not by human IGUSes. There has been irreversible amplification. The track is a record of what happened. The decay and track is a measurement situation.

Correlation between two alternatives of the quasiclassical realm is a classical measurement situation. Correlation between an alternative of the quasiclassical realm and a ‘quantum variable’ like a spin is a measurement situation whose results probe quantum theory.

Note that there is no requirement that anything as sophisticated as a human observer read the record. The track might have existed for millions of years before having been noticed by a human being. Measurement situations do not necessarily require anything as sophisticated as human observers to be one element of the correlation.
G. Predicting Measurement Outcomes in DHQM

DHQM is a comprehensive quantum theory that predicts probabilities for suitably coarse-grained time histories of what goes on in a closed system — most generally the Universe. Measurement situations play no preferred role in the formulation of DHQM. But the probabilities of outcomes of measurement situations inside the closed system can be predicted in DHQM with decoherent sets of alternative histories that describe the interactions between the subsystem being measured (‘the system’) and the subsystem doing the measuring (‘the apparatus’) so as to produce a record of the outcome accessible to relevant IGUSes including human observers.\textsuperscript{7} Sequences of repeated measurements are described in DHQM by decoherent sets of histories that describe a series of such interactions and the creation of a record record for each instance. Standard measurement models e.g. \cite{16,17} show how this all works.

H. Who Ordered DHQM?

After working through this brief exposition of DHQM a reader may well ask where DHQM came from. “Who ordered that?” The answer is that it is an inescapable inference from both the experimental and theoretical physics of the last century together with our large scale cosmological observations that we live in quantum mechanical Universe. We therefore need a formulation of quantum mechanics that is adequate for cosmology. That cannot just be a quantum mechanics of measurement situations. Specifically, we need a generalization of CQM with the following attributes:

* A quantum mechanics of a closed system in which measurements and observers can be described but are not central to the formulation of the theory.

* A formulation of quantum mechanics general enough to deal with quantum spacetime geometry in particular that near the big bang, and what emerged from it.

* A formulation of quantum mechanics general enough to retrodict histories of the past of the Universe back to the big bang to simplify the prediction of the future \cite{18}.

* A formulation of quantum mechanics that can describe the emergence of classical spacetime in the early early Universe and, along with it its quasiclassical realm. cf. \cite{19}, and with

\textsuperscript{7} A more detailed example of this can be found in \cite{9} Sections II.9 and II.10.
those both predict the future and retrodict the past.

* A formulation of quantum mechanics to which the Copenhagen quantum mechanics is an approximation appropriate for measurement situations.

DHQM is such a formulation. DHQM is logically consistent, consistent with experiment as far as is known, applicable to cosmology, consistent with the rest of modern physics including special relativity, quantum field theory, general relativity, and is generalizable to include quantum gravity (at least semiclassically) so that its capable of predicting the emergence of classical spacetime, and with that both predict the future and retrodict the past. It is unlikely to be the only formulation with these properties cf. [20]), but it is perhaps the most developed.

I. CQM from DHQM

Within DHQM of framework an approximate quantum mechanics of measurement situations, aka CQM, can be derived. A measurement situation is a correlation between one alternative and an alternative of the quasiclassical realm described in Section II E. If one is known the other is also. Measurement models show how this works. An example can be found [9] Sections II.9 and II.10, and [17].

In models where a record of the outcome of the measurement is produced the probability of a history of the value of the record is all that is needed to recover a part of CQM.

But there is also a part of CQM that does not follow from DHQM, namely the second law of evolution — state vector reduction on completion of an ‘ideal’ measurement. As far as the author knows this is not inconsistent with theory or experiment.

CQM and DHQM are not separate independent theories. CQM is best understood as an approximation to DHQM for measurement situations. Therein lies the utility of DHQM to issues that arise in CQM that are the subject of this paper.

J. A Note on Classical Spacetime

As mentioned above the classical spacetime of our quantum Universe is an essential component of the quasiclassical realm. Many of laws of classical physics follow from its local and global symmetries. The Navier-Stokes equations are an important example [8, 10].
Another is the emergence of suitably coarse-grained classical space time obeying the Einstein equation.

Classical behavior of anything is not a given in quantum mechanics. In a quantum universe classical behavior is a matter of the quantum probabilities of appropriately defined histories supplied by the theories of the quantum state and dynamics ($\Psi, H$). A quantum system behaves classically when these probabilities are high for suitably coarse-grained histories of its evolution that exhibit correlations in time governed by deterministic classical laws. The classical behavior of the flight of a tennis ball, the orbit of the Earth, the collapse of a star to a black hole, and the emergence and of classical spacetime in the early universe and its subsequent evolution obeying the Einstein equation are all examples e.g. [21, 22].

K. Final Theories

Many, if not most, of today’s proposals for ‘final theories’ aim at a unification of all the forces of nature including gravity. To enable such a theory to predict our quasiclassical realm, including emergent classical spacetime, and also to retrodict what went on in the very early universe where classical spacetime breaks down, requires a general enough formulation of quantum mechanics such as DHQM.

Such a generalization of quantum mechanics is likely to be important for the experimental tests of such theories. The characteristic energy scale for unification is the Planck scale, $\approx 10^{19}$Gev. It seems unlikely that accelerators that reach this scale will be constructed on Earth in the near future. But these energies were reached in the big-bang. We can treat the big-bang as an experiment done once to test the predictions of these final theories with resulting data scattered over visible universe.

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III. BUZZWORDS

This section treats the quantum buzzwords one by one in no very systematic order.

A. States at Moments of Time and The State of the Universe

It is important to distinguish between a “state at a moment of time” represented by $\rho_{\text{eff}}(t)$ defined in (2.11) and the quantum state of the closed system (like the universe) represented by the Heisenberg $\rho = |\Psi\rangle \langle \Psi|$ for appropriate $|\Psi\rangle$. A theory of the quantum state $|\Psi\rangle$ is an essential input to any quantum mechanical theory describing a closed system. A notion of “state at a moment of time” is not a necessary part of that theory. DHQM may be organized fully four-dimensionally in terms of histories without a notion of state at a moment of time. Indeed, in quantum theories of spacetime, where spacetime geometry is fluctuating and without definite value near the big-bang there will be no “state at a moment of time” not least because there will not be a classical notion of ‘moment of time near the big-bang. Without classical spacetime there will be no CQM. Rather, we expect CQM to emerge along with a classical spacetime in the evolution of the Universe to give meaning to CQM’s notions of time, and state at a moment of time [21, 23].

B. IGUSES (Observers)

In this paper, instead of the term ‘observer’, we will use the more general term ‘IGUS’ (Information Gathering and Utilizing System). This emphasizes that whatever role such systems play in quantum mechanics they do not have to be human beings. Humans, both individually and in various collections, are examples of IGUSes. There are many other examples — self driving cars., certain computers, etc. A thermostat is a trivial example. The collection of humans working in science we call the ‘human scientific ‘IGUS’ or HSI for short. All IGUSes are physical systems within the Universe not outside it some sense.

As physical systems within the universe, IGUSes are subject to the laws of quantum theory. But IGUSes are not a necessary part of formulating quantum theory. In DHQM for example, probabilities are predicted alternative positions of the Moon whether or nor there is an IGUS looking at it or measuring it. Quantum probabilities from the theory $(H, \Psi)$ predict probabilities for alternative values of density fluctuations in the very early universe
whether or not they were participants in a measurement situation and certainly whether or not there was an observer registering their values.

C. State Reduction

As an IGUS acquires new information the probabilities for prediction of the future like (2.9) and the effective density matrix representing current information have to be updated. Consider the example of prediction represented by the density matrix (2.11). Suppose by measurement or otherwise we find out that alternative $\alpha_3$ has happened at time $t_3$ and want to predict the probabilities of further events at later times. The density matrix $\rho_{\text{eff}}(t_2)$ at time $t_2$ would be updated to time $t_3$ as follows:

$$\rho_{\text{eff}}(t_3) \equiv \frac{1}{N} P_{\alpha_3}(t_3) P_{\alpha_2}(t_2) P_{\alpha_1}(t_1) \rho P_{\alpha_1}(t_1) P_{\alpha_2}(t_2) P_{\alpha_3}(t_3)$$  \hspace{1cm} (3.13)

where $\rho \equiv |\Psi\rangle \langle \Psi|$ and $N$ is the normalizing factor:

$$N \equiv Tr[P_{\alpha_3}(t_3) P_{\alpha_2}(t_2) P_{\alpha_1}(t_1) \rho P_{\alpha_1}(t_1) P_{\alpha_2}(t_2) P_{\alpha_3}(t_3)].$$  \hspace{1cm} (3.14)

This updating has been described in various other ways. We could say that the sequence of projections in (3.13) has ‘reduced’ the state $\rho$ or that $\rho$ has ‘collapsed’ under their action, or that the state is following the second law of evolution. It’s the same meaning for all of these.

Much has been made of this updating of the probabilities for prediction. We could say that the state $\rho = |\Psi\rangle \langle \Psi|$ has been “reduced”, or “collapsed” by action of these projections on $\rho$. However, there is nothing specifically quantum mechanical about it. It occurs in any statistical theory. In a sequence of horse races the joint probabilities for a sequence of eight races is naturally converted, after the winners of the first three are known, into conditional probabilities for the outcomes of the remaining five races by exactly this process.

In the quantum mechanics of a closed system, this second law of evolution” or collapse of the state $\rho_{\text{eff}}(t)$ has no special status in DHQM and no particular association with a measurement situation or any physical process. It is simply a convenient way of organizing the time sequence of probabilities that are of interest to a particular IGUS. Indeed, DHQM can be formulated without ever mentioning “measurement”, “an effective density matrix”, its “reduction” or its “evolution”. Further, as in quantum theories of spacetime (quantum
gravity), there can be situations where it is not possible to introduce an effective density matrix at all, much less discuss its “evolution” or “reduction”.

### D. Consciousness

Does consciousness play a role in formulating a quantum mechanics of measurement situations? Some distinguished theorists have said something like this. CQM is a theory of a single subsystem whose state evolves by von Neumann’s two laws of evolution. — unitary evolution when it is isolated and state vector reduction when it is (ideally) measured. These processes can alternate in a history of successive measurements situations. But at least some of the founders of the subject thought that the series ended in a final “reduction in consciousness” e.g. [12, 26]. This is problematical since, as far as the author knows, ‘consciousness’ is a complex phenomenon that is imperfectly understood e.g. [27]. Consciousness plays no role in formulating DHQM. But nothing excludes DHQM from helping to understand consciousness.

In DHQM realistic measurement situations can be described in terms of histories of an apparatus that interacts with the measured subsystem and creates a classical record of the outcome of the measurement that is accessible to an IGUS. A measurement model illustrating this in the context of DHQM is described in Sections II.9 and II.10 of [9]. Consciousness is not involved.

### E. Does ‘Measurement’ Need a Mathematically Precise Definition?

Measurement plays a fundamental role in the formulation of CQM. It is therefore natural to ask that ‘measurement’ be precisely and mathematically defined. Essential features of measurement have been seen to be: irreversible amplification beyond a certain level, association with a macroscopic variable, a further association with a long chain of such variables, and the formation of enduring records. Efforts have been made to attach some degree of

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8 E. Wigner, J.A. Wheeler, D. Page, H. Stapp, and R. Penrose and even the author early on in [24] come to mind.

9 In his book unitary evolution was the second of the two laws [25] and reduction the first, but modern practice has turned these around.
precision to words like “irreversible”, “macroscopic”, and “record”, and to discuss what level of “amplification” needs to be achieved and how much the entropy has to go up. for irreversibility. The author’s impression is that no precise definition has been universally accepted. But the author also knows of no mistake that has been made by this absence of a mathematically precise definition over the more than a century since CQM was first formulated.

F. CQM As an Approximation to DHQM

Measurement is not a fundamental notion in the formulation DHQM so a precise mathematical definition is neither required nor possible. The probabilities of the outcomes of specific measurement situations can be predicted in DHQM as described in Section II.G. A more detailed example can be found in Sections II.9 and II.10. Sequences of repeated measurements are described in DHQM by sets of histories that describe a series of such interactions. Standard measurement models e.g. [16, 17] suggest how this all works. Measurements and the CQM that describes them are approximations to DHQM valid in particular circumstances. Once measurement is seen as an approximate notion there is less of an imperative for its precise mathematical characterization. What is not recovered from DHQM is the second law of evolution — state vector reduction. As far as the author knows this is not in conflict with experiment or observation.

G. Many Worlds

DHQM predicts probabilities for the individual members of decoherent sets of coarse-grained alternative histories of the universe. Within a given set one cannot assign “reality” simultaneously to different alternatives because they are contradictory. Everett [7], DeWitt [28], and others have described this situation, not incorrectly, but in a way that has confused some, by saying that all the alternative histories are “equally real”. What is meant is that quantum mechanics prefers no alternative history over another except through its probability [2].

Probabilities may be assigned to alternative positions of the Moon and to alternative values of density fluctuations whether or not they were participants in a measurement situation
and certainly whether or not there was an observer registering their values.

**H. CQM vs Everett?**

CQM is not in any sense opposed to Everett’s idea of applying quantum mechanics to closed systems like the Universe. It is an approximation to the more general framework of DHQM which is consistent with Everett’s ideas. It is an approximation that is appropriate in the special cases of measurement situations in which the observer is treated as a physical system within the Universe. From this point of view the many successes CQM should be seen as supporting DHQM, and along with it, the Everett viewpoint.

**I. The Origin of the Quasiclassical Realm**

Suppose our Universe is understood fundamentally by a unified quantum theory of dynamics in $H$ and a quantum theory of its state $|\Psi\rangle$ both characterized by the Planck scale. What is the origin of our universe’s quasiclassical realm? Some key steps in its emergence are the following. [10, 14, 29]:

- Classical spacetime emerges from the quantum fog at the beginning.
- Local Lorentz invariance of the classical spacetime implies conservation laws for energy, momentum, number, etc for fields moving in the spacetime.
- Sets of alternative histories of averages of densities of conserved quantities over suitably small volumes (quasiclassical variables) decohere.
- Approximate conservation implies that quasiclassical variables are predictable despite the noise from mechanisms of decoherence.
- Local equilibrium implies closed sets of classical equations of motion [8, 30, 31].

**J. When Does CQM Emerge in the History of the Universe?**

CQM is most naturally applicable to laboratory measurement situations. It relies on a number of features of our Universe notably its quasiclassical realm described in Section [II-E].
that includes the classical spacetime in which IGUSes evolve, operate, build laboratories, carry out experiments, and otherwise act like observers. These prerequisites are not available in all epochs of the Universe’s history. They emerge over time as described in Section III. We can therefore pose the question when in the history of our Universe did CQM emerge as an approximation to DHQM [32].

To answer crudely divide cosmological time roughly up into four epochs:

- **The Epoch of Quantum Gravity**: A short era $t \sim 10^{-43}\,\text{s}$ in which the geometry of spacetime and matter fields exhibited large quantum fluctuations. The histories constituting a quasiclassical realm including classical spacetime start only after this period.

- **The Early Universe**: The early universe contained a hot plasma of nucleons, electrons, neutrinos, and photons. As revealed by the observations of the cosmic background radiation (CMB) in this epoch the universe was homogeneous, isotropic and featureless to an excellent approximation (deviations from exact isotropy of 1 part in $10^5$).

- **The Middle Universe**: As the universe expands the temperature drops. When it has dropped sufficiently, electrons, protons and nucleons recombine and nuclei are synthesized. The initial fluctuations from the quantum gravity era grow under the action of gravitational attraction. Eventually they collapse under the forces of gravitational attraction to produce the universe of galaxies, stars, planets, biota and IGUSes that we find today.

- **The Late Universe**: The cosmological constant causes the universe to expand and cool exponentially quickly. Stars exhaust their thermonuclear fuel and die out. Black holes have evaporate. The density of matter and the temperature approach zero. The universe is cold, dark and inhospitable.

When in this history would one expect to find IGUSes, a quasiclassical realm, laboratories, experiments and CQM? Not in the quantum gravity epoch where there isn’t even classical spacetime to define a notion of localized subsystem. Not in the early universe. That period has regularity in its homogeneity and isotropy, but it lacks the complexity that would give an evolutionary advantage to being an IGUS [32]. Not in the late universe for the same reason (and also because of the failure environmental mechanisms of decoherence in the far
future [59]). Only in the middle universe do we have both regularities for an IGUSes to exploit and enough complexity to make exploiting those regularities fruitful. That is where we do find them (for more on this see [32]). Thus only in the middle Universe would we expect CQM to be implementable as an approximation to DHQM.

K. The Principle of Superposition

The principle of superposition is a fundamental part of any quantum mechanical framework. It is incorporated into DHQM and its approximation CQM.

Suppose, as in the two-slit example, there are two histories A and B with branch state vectors $|\psi_A \rangle$ and $|\psi_B \rangle$ leading to the same outcome, cf Section II B. The probability of the outcome is the absolute square of sum of the branch state vectors. It is not the sum of the absolute squares of the branch state vectors unless the two vectors are orthogonal so the set of two decoheres. The interference between the two branches results in characteristic interference patterns as in the two-slit case.\(^{10}\).

L. Is CQM Non-Local?

Situations such as that in the Einstein-Podolsky-Rosen thought experiment have suggested to some to that CQM is non-local. However, it is straightforward to show very generally using techniques of the present formulation that it involves no non-locality in the sense of quantum field theory and no signaling outside the light cone. (For alternative demonstrations cf. e.g. [34, 35]) and Section 5 of the Appendix ‘Buzzwords’ of [9]).

Bohmian mechanics is an alternative formulation of quantum theory that is explicitly non-local but is said to be consistent with relativistic causality [36]. In at least one of its formulations it makes predictions which are different from DHQM e.g. [37].

M. When Does a Subsystem Have a Pure Quantum State?

By ‘subsystem’ we usually mean very roughly an approximately localized collection of matter interacting weakly with the rest of the Universe over a period of time. Stars, planets,\(^{10}\) For much more detail by the author on the two-slit example see [3].
trees, animals, bacteria are familiar examples. In classical physics a subsystem is described by classical variables which we can take to be averages of densities of energy, momentum, and number over the individual members of a partition of space into suitably small volumes. These are called the ‘quasiclassical variables’ or sometimes ‘hydrodynamic variables’ like those that occur in the Navier-Stokes equation for instance.

The question naturally arises as to whether such a subsystem is described by a quantum state in the Hilbert space of the whole. In very carefully prepared situations such as a spin moving through a Stern-Gerlach apparatus the answer is ‘yes’. But generally the answer is ‘no’. Subsystems generally are interacting with their environment and entangled with it. After an electron in the two-slit experiment is detected by making a mark on photographic plate it is entangled with other atoms in the screen where it is detected.

Indeed, if the interaction with an environment is the typical mechanism for decohering sets of histories of the subsystem (for example coarse-grained histories of its position) it will always be entangled with the environment and not pure.

When does a subsystem have a quantum state? Only in carefully designed laboratory situations. Almost never in generic realistic situations.

N. The Quantum Arrow of Time

In the introduction to DHQM in Section II the expressions for the probabilities of histories like (2.5) and (2.7) are not time neutral. The state $|\Psi\rangle$ on one end of the chain of projections and nothing on the other end. That asymmetry is called the quantum mechanical arrow of time. It is built in to the the version of DHQM described in Section II.

However, as noted by several authors e.g. [37–41], DHQM can be formulated time neutrally and more generally be employing both initial and final density matrices that enter by symmetrically into the expressions like (2.5) for the probabilities of histories. Then all of the arrows of time exhibited by the universe emerge from differences between these initial and final conditions even with time neutral dynamics $H$. These include the thermodynamic arrow (increasing entropy), electromagnetic arrow (retarded radiation), the psychological arrow (we remember the past, experience the present and predict the future), the expansion of the universe arrow, the growth of cosmological fluctuations arrow, and the quantum arrow under discussion.
Following von Neumann \[25\], CQM is usually formulated in terms of two laws. First, the law for the unitary evolution of the state vector described by the Schrödinger equation. Second, the law for the reduction of the state vector after a measurement that disturbs the measured subsystem as little as possible. The Schrödinger equation can be run both forward and backward in time. However, state vector reduction can be run in only one direction in time — usually assumed to be towards the future or in the direction of increasing entropy. The second law of evolution thus singles out a direction in time defining the quantum arrow of time. See, e.g. \[38–40\].

DHQM of the universe can be formulated time neutrally with initial and final conditions playing symmetric roles in the formulation \[39, 40\] and no built in arrows of time. Rather all arrows of time, including the quantum mechanical one, are emergent features of the differences between the initial and final conditions of our particular Universe e.g. \[40\].

O. Is Schrödinger’s Cat Paradoxical?

In the Schrödinger’s cat thought experiment \[42\], the cat is a subsystem of the ‘universe’ defined by the containing box and its contents. But the cat is not an isolated subsystem inside that box. The cat is interacting with particles of the walls of the box, with the electromagnetic radiation in the box, and with the cyanide gas that is released when geiger counter clicks. The cat is entangled with all those other things. We can think of an initial state where the box is full of air, where the geiger counter is turned on, and the cat is standing, alive, and another state where geiger counter has clicked and the cat is dead on the floor of the box. These are exclusive alternatives represented by a set of two orthogonal projection operators as in (2.8) referring to the whole box plus cat which we can compactly label \((P_{\text{alive}}; P_{\text{dead}})\) adding to unity. There is no sense in which the cat is simultaneously both alive and dead. That would be represented by the product of the two projections but that is zero. The state of the box is in a superposition of the histories in which the cat is dead and the cat remains alive. It’s either or — One of these happens and the other does not. There is no paradox.

In quantum cosmology a state of the universe like the no boundary wave function \[43\], is a superposition of different histories of what happens. We (the HSI) are living in this superposition. We are all Schrödinger cats in the no-boundary quantum state of the universe.
P. Living in a Superposition

A generic wave function of the universe will not predict a single history with unit probability. Rather it predicts decoherent sets of alternative histories together with the probabilities of which history occurs. The wave function of the universe $\Psi$ is a superposition of these $[2, 3]$. Physical systems within the universe like us can occur in one or possibly more of these histories. We have no way of detecting or feeling the other histories — they are exclusive. We don’t see the other things ‘smeared out’ because everything we look at is in the histories of the ensemble along with us. cf. [15].

Occasionally even distinguished scientists ask: “If I am in a superposition of states why don’t I feel that I am in a superposition?” An interference pattern is an experimental signature of a superposition as in the two-slit experiment. But we can’t naturally come equipped with an interferometer that would enable either us or Schrödinger’s cat to ‘feel’ a superposition. for example. There isn’t ny physical mechanism by which us or Schrödinger’s cat could feel a superposition. Indeed, from the perspective of quantum cosmology we are all Schrödinger cats superposed in the wave function of the universe e.g. [43]. A thought experiment where a human IGUS is a participant in a huge two-slit experiment is described in [44]. Such an IGUS could detect whether its state was a superposition by observing quantum interference. We could say with the late Bryce DeWitt: “People who say that they don’t feel themselves to be in a superposition are like the people who said that they didn’t feel the Earth move in its orbit around the Sun”.

Q. Human IGUSes and the Quasiclassical Realm

In DHQM the quasiclassical realm described in Section [IIH] is a decoherent set of alternative histories coarse-grained by values of quasiclassical variables such as the ‘hydrodynamic variables’ briefly defined in Section [II M]. The quasiclassical realm includes classical spacetime$^{11}$.

$^{11}$ A quantitative measure of a realm’s classicality was defined in [43]. Roughly the. measure is the augmented entropy e.g. [46] — the sum of the entropy of the set and the algorithmic information content of its...
The quasiclassical realm of our universe exhibits a high level of predictability because of its deterministic regularities. It exhibits a high level of simplicity because its histories are defined by a small set of ‘classical’ variables operating on scales that are very small compared to those of the large scales characterizing our Universe. Both individually and collectively human IGUSes, and the HSI in particular, are described in terms of quasiclassical variables. We are therefore not separate from our Universe’s quasiclassical realm but rather part of it.

As human IGUSes we utilize almost exclusively the variables that define the quasiclassical realm, operate by its quasiclassical laws, and focus on features and subsystems of the Universe that can be described in quasiclassical terms [14]. Essentially all the data that we have about the universe are recorded in the variables of the quasiclassical realm. A theory is more successful when it predicts correlations in our data. For more discussion of how the correlations are predicted and the distinction between ‘top-down’ and ‘bottom up’ approaches to prediction see [47].

Plausibly, both individually and collectively, we and other living things evolved to exploit the regularities that characterize the quasiclassical realm in order to satisfy the age-old imperatives: get food — yes, be food — no, make more — yes. That evolution is in principle described by sets histories that follow biological evolution. These are characterized by frozen accidents such as mutations, recombination, and genetic drift — chance events with long term, widespread consequences. The probabilities of most of these histories are well beyond our power to compute or measure today but see e.g [48, 49] and the remarks in [14, 32, 37].

R. Other Quasiclassical Realms, Other IGUSes?

A fascinating question is whether the Universe exhibits realms coarse-grained by variables different from the usual quasiclassical ones that also have high levels of predictivity and simplicity as judged by a quantitative measure like that for classicality as discussed in [45]. Would such a realm have evolved IGUSes that are different from the ones we find in the usual quasiclassical realm, and if so could we communicate with them?

course-grained description.
S. Separate Quantum and Classical Worlds? The Heisenberg Cut?

Older formulations of CQM sometimes assumed a classical world and a separate quantum world, with a movable boundary between the two called the Heisenberg cut e.g. [55]. Observers and their measuring apparatus make use of the classical world, so that the results of a “measurement” are ultimately expressed in one or more “c-numbers”.

In DHQM there is no such division and no such boundary. All things are quantum but some things behave classically. A subsystem behaves classically when, as consequence of \((H,\Psi)\), it is described by a suitably coarse-grained decoherent set of alternative histories of the universe whose probabilities favor correlations in time following classical deterministic laws.

There is no Heisenberg cut. Classical behavior in our Universe is not something to be posited. It is something to be calculated from \((H,\Psi)\). A separate classical world is neither needed nor correct — it is all quantum mechanical. Classical behavior emerges from quantum mechanics and \((H,\Psi)\)— it’s all quantum mechanical.

T. Beyond Measurement Situations – Quantum Cosmology

It’s an inescapable inference from the physics of the last century that we live in a quantum mechanical universe. If so, there is no escaping generalizing CQM to provide a formulation general enough to be applicable to cosmology. Too much our understanding of the universe depends on such a generalization — the quantum nature of the big bang, the origin of coarse-grained classical spacetime, the origin of the large scale structure seen in the CMB and the distribution of galaxies in early quantum the existence of localized systems including IGUSes, etc. and, indeed, the origin of, IGUSES, and CQM itself.

DHQM is such a generalization [9, 56]. DHQM is logically consistent, consistent with experiment as far as is known, consistent with the rest of modern physics such as special relativity, and quantum field theory, general enough or cosmology, and generalizable to apply to semiclassical quantum spacetime [56]. It can both predict the future and retrodict the past of our Universe. It is not the only quantum framework for cosmology (e.g [57]) but it is one of the the most developed of the ones we have at present.

CQM, deals with measurement situations. Predictions of CQM are therefore predictions
of DHQM. But beyond measurement situations DHQM is the basis for predictions in cos-

mology of our large scale observations of the universe from quantum theories of that follow
from the theory \((H, \Psi)\) e.g. quantum field theory.) These predict for example, the universe’s
classical spacetime, its approximate homogeneity and isotropy on scales above several hun-
dred Mpc today, and deviations from these symmetries that we see today in the fluctuations
of the cosmic background radiation and in the large scale distribution of the galaxies. See

\[22\].

U. Final Theories

Many, if not most, of today’s candidates for final theories aim at a unification of all
the forces of nature including gravity. The Planck energy is their characteristic energy
scale. Such a theory must predict our observable quasiclassical realm including its classical
spacetime and also to retrodict what goes on in the very early universe where classical
spacetime breaks down. The early universe may be the only place where Planck scale
energies that are characteristic of these theories to occur in our Universe. One can therefore
think of the big bang as an experiment in which Planck scale energies are reached with
data on the outcome spread over a large part of universe now that can be used to test such
theories. Quantum cosmology seems destined to play an important role in in the physics of
the elementary particles.

IV. CONCLUSION

A. No Escape from Generalizing CQM

for Cosmology, Final Theories, and Unification

As discussed in the Introduction and in \[3\] there is is no escaping generalizing CQM to a
quantum framework applicable to cosmology and to quantum spacetime. Too much of our
understanding of the Universe depends on it — the quantum nature of the big-bang, the
quantum origin of classical spacetime, the origin of large scale structure in the gravitational
collapse of early quantum fluctuations, the emergence of localized systems, and the origin
of IGUses through the frozen accidents of biological evolution. More succinctly, we need
a generalization of CQM to explain the emergence of the quasiclassical realm of everyday experience including emergent classical spacetime and, indeed, to explain the emergence of the CQM approximation itself.

Further, a generalization of CQM is needed to calculate and test the predictions of final theories that unify the quantum theories of fundamental interactions with quantum gravity. In short we need a generalization of CQM to unify the physics of the very large with the physics of the very small. DHQM is one such generalization but probably not the only one.

This paper briefly explored the idea that many of the difficulties with understanding the CQM of measurement situations can be clarified by examining its generalization — DHQM. The aim has been has been to show by many short expositions a certain unity in the explanations and to briefly suggest starting points for further research.

The utility of generalizations for improving understanding is not surprising. Similar clarifications have been instructive elsewhere in physics. We understand thermodynamics better with the help of statistical mechanics. The solar system regularities of Ptolemaic astronomy were better understood from Newtonian mechanics and the gravitational force law. The nature of gravity and of the spacetime in which we live are best understood from Einstein’s theory of gravity — general relativity — and the distribution of mass-energy in the Universe. There are many other examples. These understandings are confirmed by the new observations that they successfully predict — gravitational waves are a recent example.

B. Beyond DHQM?

Despite its successes some find DHQM unsatisfactory by standards for physical theory beyond logical consistency and consistency with experiment and observation. The intuition of others suggests that in domains where the predictions of quantum mechanics have not yet been fully tested an experimental inconsistency will emerge and a different theory will be needed. For example, perhaps the interference between “macroscopically” different configurations predicted by quantum mechanics will not be observed on large distance scales. e.g. [58]. And indeed the application of DHQM to cosmology is an enormous and mostly untested extrapolation. What is needed to meet such standards, or to resolve such experimental inconsistencies should they develop, is not further research on DHQM itself, but rather new and conceptually different theoretical frameworks. It would be of great interest
to have serious and compelling alternatives to DHQM e.g. if only to suggest decisive experimental tests both of DHQM and other formulations of quantum mechanics. We need more research both theoretically and experimentally!

C. The Relation Between DHQM and CQM

Did we derive CQM from DHQM in this paper? We did not. Even assuming classical spacetime that would require having a general analysis of measurement situations and the formation of accessible records of their outcomes not to mention the quantitative analysis of measurement models.

We did suggest in Section III, especially Section III-F, how measurement situations could be analyzed in DHQM using measurement models based on decoherent sets of histories describing the interaction between a measurement apparatus and a measured subsystem. But we found no evidence that DHQM supports a general second law of state vector reduction.\textsuperscript{12}

Progress can be made by examining more and different measurement models such as those in \cite{9} (Sections 9 and 10) and \cite{17}. There is still much to do.

D. Concluding Manifesto

The author ends this work by quoting the concluding paragraph of his first paper on DHQM with Murray Gell-Mann \cite{6}: “We conclude that resolution of the problems of interpretation presented by quantum mechanics is not to be accomplished by further intense scrutiny of the subject as it applies to reproducible laboratory situations, but rather through an examination of the origin of the Universe and its subsequent history. Quantum mechanics is best and most fundamentally understood in the context of quantum cosmology.”

\textsuperscript{12} And indeed the author has not been able to identify decisive experimental evidence for a general second law applicable to all measurement situations outside simple systems like the Stern-Gerlach model.
V. APPENDIX A: COPENHAGEN QUANTUM MECHANICS AND DECOHERENT HISTORIES QUANTUM MECHANICS.

Another perspective on the author’s view on the relationship between CQM and DHQM is provided by the following modestly edited excerpt from the conclusion of a paper with Murray Gell-Mann: “Quasiclassical Coarse Graining and Thermodynamic Entropy” 8

This appendix is concerned with the relation between our approach to quantum mechanics, based on coarse-grained decoherent histories of a closed system, and the approximate quantum mechanics of measured subsystems, as in the “Copenhagen interpretation.” The latter formulation postulates (implicitly for most authors or explicitly in the case of Landau and Lifshitz 55) a classical world and a quantum world, with a movable boundary between the two. Observers and their measuring apparatus make use of the classical world, so that the results of a “measurement” are ultimately expressed in one or more “c-numbers”.

We have emphasized that this widely taught interpretation, although successful, cannot be the fundamental one because it seems to require a physicist outside the system making measurements (often repeated ones) of it. That would seem to rule out any application to the universe, so that quantum cosmology would be excluded. Also billions of years went by with no physicist in the offing. Are we to believe that quantum mechanics did not apply to those times?

In this discussion, we will concentrate on how the Copenhagen approach fits in with ours as a set of special cases and how the “classical world” can be replaced by a quasiclassical realm. Such a realm is not postulated but rather is explained as an emergent feature of the universe characterized by $H$, $|\Psi\rangle$, and the enormously long sequences of accidents (outcomes of chance events) that constitute the coarse-grained decoherent histories. The material in the preceding sections can be regarded as a discussion of how quasiclassical realms emerge.

We say that a ‘measurement situation’ exists if some variables (including such quantum-mechanical variables as electron spin) come into high correlation with a quasiclassical realm. In this connection we have often referred to fission tracks in mica. Fissionable impurities can undergo radioactive decay and produce fission tracks with randomly distributed definite directions. The tracks are there irrespective of the presence of an “observer”. It makes no difference if a physicist or other human or a chinchilla or a cockroach looks at the tracks. Decoherence of the alternative tracks induced by interaction with the other variables in
the universe is what allows tracks to exist independent of “observation” by an “observer”. All those other variables are effectively doing the “observing”... The same is true of the successive positions of the Moon in its orbit not depending on the presence of “observers” and for density fluctuations in the early universe existing when there were no observers around to measure them.

The idea of “collapse of the wave function” corresponds to the notion of variables coming into high correlation with a quasiclassical realm, with its decoherent histories that give true probabilities. The relevant histories are defined only through the projections that occur in the expressions for these probabilities [cf (2.1)]. Without projections, there are no questions and no probabilities. In many cases conditional probabilities are of interest. The collapse of the probabilities that occurs in their construction is no different from the collapse that occurs at a horse race when a particular horse wins and future probabilities for further races conditioned on that event become relevant.

The so-called “second law of evolution”, in which a state is ‘reduced’ by the action of a projection, and the probabilities renormalized to give ones conditioned on that projection, is thus not some mysterious feature of the measurement process. Rather it is a natural consequence of the quantum mechanics of decoherent histories, dealing with alternatives much more general than mere measurement outcomes.

There is thus no actual conflict between the Copenhagen formulation of quantum theory and the more general quantum mechanics of closed systems DHQM. Copenhagen quantum theory is an approximation to the more general theory that is appropriate for the special case of measurement situations. DHQM rather is a generalization of CQM. That connection means that the experimental successes of CQM support DHQM as well.

In our opinion decoherent histories quantum theory advances our understanding in the following ways among many others:

- Decoherent histories quantum mechanics extends the domain of applicability of quantum theory to histories of features of the universe irrespective of whether they are receiving attention of observers and in particular to histories describing the evolution of the universe in cosmology.

- The place of classical physics in a quantum universe is correctly understood as a property of a particular class of sets of decoherent coarse-grained alternative histories —
the quasiclassical realms \[9, 14\]. In particular, the limits of a quasiclassical description can be explored. Decoherence may fail if the graining is too fine. Predictability is limited by quantum noise and by the major branchings that arise from the amplification of quantum phenomena as in a measurement situation. Finally, we cannot expect a quasiclassical description of the universe in its earliest moments where the very geometry of spacetime may be undergoing large quantum fluctuations.

- Decoherent histories quantum mechanics provides new connections such as the relation between the coarse graining characterizing quasiclassical realms and the coarse graining characterizing the usual thermodynamic entropy of chemistry and physics.

- Decoherent histories quantum theory helps with understanding the Copenhagen approximation. For example, measurement was characterized as an “irreversible act of amplification”, “the creation of a record”, or as “a connection with macroscopic variables”. But these were inevitably imprecise ideas. How much did the entropy have to increase, how long did the record have to last, what exactly was meant by “macroscopic”? Making these ideas precise was a central problem for a theory in which measurement is fundamental. But it is less central in a theory where measurements are just special, approximate situations among many others. Then characterizations such as those above are not false, but true in an approximation that need not be exactly defined.

- Irreversibility clearly plays an important role in science as illustrated here by the two famous applications to quantum-mechanical measurement situations and to thermodynamics. It is not an absolute concept but context-dependent like so much else in quantum mechanics and statistical mechanics. It is highly dependent on coarse graining, as in the case of the document shredding. This was typically carried out in one dimension until the seizure by Iranian “students” of the U.S. Embassy in Tehran in 1979, when classified documents were put together and published. Very soon, in many parts of the world, there was a switch to two-dimensional shredding, which still appears to be secure today. It would now be labeled as irreversible just as the one-dimensional one was previously. The shredding and mixing of shreds clearly increased the entropy of the documents, in both cases by an amount dependent on the coarse grainings involved. Irreversibility is not absolute but dependent on the effort or cost involved in
reversal.

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