BUZZWORDS

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A modestly edited and reformated appendix from the author's lectures *The Quantum Mechanics of Cosmology* in *Quantum Cosmology and Baby Universes: Proceedings of the 1989 Jerusalem Winter School for Theoretical Physics* (edited by S. Coleman, J. Hartle, T. Piran, and S. Weinberg), World Scientific, Singapore (1991). Discussion to review some notation has been added, and some parts have been deleted because they relied too heavily on the main text. The references have for the most part have been left as they were in 1991. Where possible the original equation numbers have been preserved. The whole thing is on this site.

Only a casual inspection of the literature reveals that many interpreters of quantum mechanics who agree completely on the algorithms for quantum mechanical prediction, disagree, often passionately, on the words with which they describe these algorithms. This is the "words problem" of quantum mechanics. The agreement on the algorithms for prediction suggests that such disagreements may have as much to do with people as they do with physics. This does not mean that such issues are unimportant because such diverging attitudes may motivate different directions for further research. However, it is important to distinguish such motivation from properties of the theory as it now exists.

A few "buzzwords" characterize the words problem for quantum mechanics. They are phrases like "reduction of the wave packet", "many worlds", "non-locality", "state", etc. These are words that evoke or challenge some of the core assumptions that guide physicists in their work. To avoid confusion among the variety of preconceived meanings commonly held for such terms, they have been avoided in the preceding discussion. Now, in this appendix, it seems appropriate to return to a brief discussion of the author's attitudes and preferences concerning these words (*circa* mid-1990). These comments are are not essential to the main discussion. The text's discussion of the quantum mechanical process of prediction for closed systems is self-contained as far as it goes and the material in this appendix may be dispensed with. Alternatively, the reader may choose different words with which to surround the discussion and different attitudes to it. In this spirit no attempt has been made to describe, discuss, confront, or refer to other discussions of these words.

-1. Histories: The discussion of buzzwords is in the context of decoherent histories quantum theory (DH) which is explained at various levels at many different places on this site. But we begin with a bare bones review of in the notation used. The reader familiar with this can immediately skip the next two sections.

We consider a closed system described by a Hamiltonian H and a quantum state $|\Psi\rangle$.

Alternatives at one moment of time can be reduced to a set of yes/no questions. For example, alternative positions of the Earth's center-of-mass can be reduced to asking, "Is it in this region – yes or no?", "Is it in that region – yes or no?", etc. An exhaustive set of yes/no alternatives at one time is represented in the Heisenberg picture by an exhaustive set of orthogonal projection operators $\{P_\alpha(t)\}$, $\alpha = 1, 2, 3 \cdots$. These satisfy

$$\sum\nolimits_\alpha P_\alpha(t) = I, \text{ and } P_\alpha(t)\, P_\beta(t) = \delta_{\alpha\beta} P_\alpha(t) \ , \tag{1}$$

showing that they represent an exhaustive set of exclusive alternatives. In the Heisenberg picture, the operators $P_\alpha(t)$ evolve with time according to

$$P_\alpha(t) = e^{+iHt/\hbar} P_\alpha(0)\, e^{-iHt/\hbar}\,. \tag{2}$$

The state $|\Psi\rangle$ is unchanging in time.

An simple kind of set of histories is specified by sets of single time alternatives $\{P^1_{\alpha_1}(t_1)\}$, $\{P^2_{\alpha_2}(t_2)\}, \cdots, \{P^n_{\alpha_n}(t_n)\}$ at a sequence of times $t_1 < t_2 < \cdots < t_n$. 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 α 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 *chain or class operator*

$$C_\alpha \equiv P^n_{\alpha_n}(t_n) \cdots P^1_{\alpha_1}(t_1)\,. \tag{3}$$

For any individual history α, there is a *branch state vector* defined by

$$|\Psi_\alpha\rangle = C_\alpha |\Psi\rangle\,. \tag{4}$$

When probabilities can be consistently assigned to the individual histories in a set, they are given by

$$p(\alpha) = \parallel |\Psi_\alpha\rangle \parallel^2 = \parallel C_\alpha|\Psi\rangle \parallel^2 = ||P^n_{\alpha_n}(t_n)\cdots P^1_{\alpha_1}(t_1)|\Psi\rangle||^2. \tag{5}$$

Negligible interference between the branches of a set

$$\langle\Psi_\alpha|\Psi_\beta\rangle \approx 0 \quad , \quad \alpha \neq \beta\,, \tag{6}$$

is a sufficient condition for the probabilities (5) to be consistent with the rules of probability theory. Sets of histories for which (6) is satisfied are said to "decohere". The orthogonality of the branches is approximate in realistic situations. But we mean by (6) equality to an accuracy that defines probabilities well beyond the standard to which they can be checked or, indeed, the physical situation modeled.

This framework is easily generalized to use an initial density matrix ρ instead of a pure state $|\Psi\rangle$. Decoherence of histories $\{C_\alpha\}$ and their probabilities $p(\alpha)$are summarized in the single equation:

$$D(\alpha,\beta) \equiv Tr[C_\alpha \rho C^\dagger\alpha] \approx \delta_{\alpha\beta} p(\alpha) \tag{7}$$

Explicitly, the probabilities for the histories in a decoherent set are

$$p(\alpha_n, \cdots, \alpha_1) = Tr[P^n_{\alpha_n}(t_n)\cdots P^1_{\alpha_1}(t_1)\rho P^1_{\alpha_1}(t_1)\cdots P^n_{\alpha_n}(t_n)]\ . \tag{8}$$

0. Prediction and Retrodiction. The joint probabilities $p(\alpha_n t_n, \cdots, \alpha_1 t_1)$ in (8) for the individual histories in a decohering set are the raw material for prediction and retrodiction in quantum cosmology.

The conditional probability for *predicting* alternatives $\alpha_{k+1}, \cdots, \alpha_n$, given that the alternatives $\alpha_1, \cdots, \alpha_k$ have already happened, is

$$p(\alpha_n t_n, \cdots, \alpha_{k+1} t_{k+1}|\alpha_k t_k, \cdots, \alpha_1 t_1) = \frac{p(\alpha_n t_n, \cdots, \alpha_1 t_1)}{p(\alpha_k t_k, \cdots, \alpha_1 t_1)}\quad . \tag{II.3.2}$$

The probability that $\alpha_{n-1}, \cdots, \alpha_1$ happened in the *past*, given an alternative α_n at the present time t_n, is

$$p(\alpha_{n-1}t_{n-1}, \cdots, \alpha_1 t_1 | \alpha_n t_n) = \frac{p(\alpha_n t_n, \cdots, \alpha_1 t_1)}{p(\alpha_n t_n)} \quad . \tag{II.3.3}$$

Future predictions can all be obtained from an effective density matrix summarizing information about what has happened. If ρ_{eff} is defined by

$$\rho_{\text{eff}}(t_k) \equiv \frac{P^k_{\alpha_k}(t_k) \cdots P^1_{\alpha_1}(t_1)\rho P^1_{\alpha_1}(t_1) \cdots P^k_{\alpha_k}(t_k)}{Tr[P^k_{\alpha_k}(t_k) \cdots P^1_{\alpha_1}(t_1)\rho P^1_{\alpha_1}(t_1) \cdots P^k_{\alpha_k}(t_k)]} \quad , \tag{II.3.4}$$

then

$$\begin{aligned} &p(\alpha_n t_n, \cdots, \alpha_{k+1} t_{k+1} | \alpha_k t_k, \cdots, \alpha_1 t_1) \\ &= Tr[P^n_{\alpha_n}(t_n) \cdots P^{k+1}_{\alpha_{k+1}}(t_{k+1})\rho_{\text{eff}}(t_k) P^{k+1}_{\alpha_{k+1}}(t_{k+1}) \cdots P^n_{\alpha_n}(t_n)] \ . \end{aligned} \tag{II.3.5}$$

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 hiistory require knowledge of *both* present records *and* the initial condition of the universe.

1. State. In classical physics there is a description of a system at a moment of time that is all that is necessary to both predict the future *and* retrodict the past. As already mentioned, the most closely analogous notion in quantum mechanics is the effective density matrix, $\rho_{\text{eff}}(t)$, of eq. (II.3.4)

$$\rho_{\text{eff}}(t_k) = \frac{P^k_{\alpha_k}(t_k) \cdots P^1_{\alpha_1}(t_1)\rho P^1_{\alpha_1}(t_1) \cdots P^k_{\alpha_k}(t_k)}{Tr[P^k_{\alpha_k}(t_k) \cdots P^1_{\alpha_1}(t_1)\rho P^1_{\alpha_1}(t_1) \cdots P^k_{\alpha_k}(t_k)]} \quad , \tag{II.3.4}$$

expressed either in the Heisenberg picture, a here, or in the Schrödinger picture. This quantum mechanical notion of "state at a moment of time", has a very different character from the classical analog. The future may be predicted from ρ_{eff} *alone* but to retrodict the past requires, *in addition*, a knowledge of the initial condition. The quantum mechanical notion of state is, therefore, already considerably weaker in its power to summarize probabilities than its classical analog for deterministic theories.

It is important to distinguish the notions of "state at a moment of time" represented by $\rho_{\text{eff}}(t)$ from the initial condition of the system represented by the initial Heisenberg ρ. Both are commonly referred to as the "state of the system". However, while an initial condition, or its equivalent, is an essential feature of the quantum mechanical process of prediction, a notion of "state at a moment of time" is not. The familiar theory may be organized without this notion just in terms of histories. When, as in quantum theories of spacetime, there is no well defined notion of time it is unlikely that it is possible to introduce a notion of "state at a moment of time".

2. Reduction of the Wave Packet. Two senses of this phrase can be distinguished. The first concerns the updating of probabilities by an $IGUS$ on acquisition of information. The second concerns the evolution in time of the effective density matrix, $\rho_{\text{eff}}(t)$, corresponding to the notion of "state at a moment of time". I shall consider these senses separately, for the quantum mechanics of closed systems.

Much has been made of the renormalization of joint probabilities that occurs in the calculation of the conditional probabilities for prediction eq. (II.3.2) and retrodiction eq. (II.3.3). An *IGUS* utilizing these formulae would update the conditional probabilities of interest as new information is acquired (or perhaps lost). There is, however, nothing specifically quantum mechanical about such updating; 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. All probabilities are available to the *IGUS*, but, as new information is acquired, new conditional probabilities become relevant for prediction and retrodiction.

For those quantum mechanics of closed systems that permit the construction, according to (II.3.4), of an effective density matrix, $\rho_{\rm eff}(t)$, to summarize present information for future prediction, the process of the reassessment of probabilities described above can be mirrored in its "evolution" according to the following rule: The effective density matrix, $\rho_{\rm eff}(t)$, is constant in the Heisenberg picture between two successive times when data is acquired, t_k and t_{k+1}. When new information is acquired at t_{k+1}, $\rho_{\rm eff}(t)$ changes by the action of a new projection on each side of (II.3.4) and division by a new normalizing factor. One could say that "the state of the system is reduced"[1] at t_{k+1}. It might be clearer to say that a new set of conditional probabilities has become appropriate for future predictions and therefore a new $\rho_{\rm eff}(t)$ is relevant.

It should be clear that in the quantum mechanics of a closed system this "second law of evolution" for $\rho_{\rm eff}(t)$ has no special, fundamental status in the theory 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, it is possible to formulate the quantum mechanics of a closed system without ever mentioning "measurement", "an effective density matrix", its "reduction" or its "evolution". Further, as in the framework for quantum spacetime there may be quantum mechanical theories where it is not possible to introduce an effective density matrix at all, much less discuss its "evolution" or "reduction".

Two remarks may be useful concerning the "reduction of the wave packet" in the Copenhagen approximation. First, again, the quantum mechanics of a subsystem under observation may be formulated directly in terms of probabilities for histories without an effective density matrix or its reduction. To introduce these notions is, therefore, to some extent a choice of words. Second, and more importantly, the association of the "reduction" with "measurement" is a special property of the ideal measurement model. This has suggested to some that there is a physical mechanism behind the reduction of the wave packet. However, in the more general situations in which a closed system is considered, there is no necessary association of "reduction" with a measurement situation.

Do the Everett class of interpretations eliminate the "reduction of the wave packet"? Some have said so (Everett 1957, DeWitt 1970). The argument is crudely that only probabilities for correlations at one moment of time — the "marvelous moment now" — are of interest. For these $\rho_{\rm eff} = \rho$ and no further reduction need be contemplated. However, in general, probabilities for histories involving more than one time are of interest and for

[1] Typically it is not reduced very much! The P's of a coarse graining of a typical *IGUS* fix almost none of the variables of the whole universe and therefore correspond to very large subspaces of its Hilbert space. Most variables are still available, untouched, for future projections.

cosmology they are essential. For these sequences of projections are necessary. Then, the Everett interpretation *can*, if one so chooses, be formulated in terms of a $\rho_{\rm eff}(t)$ that is "reduced". On the other hand, the "reduction of the wave packet" is not a necessary element of a quantum mechanics of cosmology. If one chooses, it need never be mentioned. It is, thus, no less necessary or more necessary in the Everett class of formulations than it is in the Copenhagen approximation to it. It's a matter of words. In a generalized quantum mechanics these words may not even be possible.

3. The Measurement Problem. Quantum mechanics does not predict a particular history for a closed system; it predicts the probabilities of a *set of alternative* histories. This is the case even when the histories constitute a quasiclassical realm[2] and refer to the "macroscopic" description of objects consisting of many particles. Some describe this state of affairs as the "quantum measurement problem" or even the "quantum measurement paradox". However, such words can be confusing because there is no evidence that quantum mechanics is logically inconsistent, no evidence that it is inconsistent with experiment, and no evidence of known phenomena that could not be described in quantum mechanical terms.

Therefore, If there is a "quantum measurement problem"nothing said in this exposition of quantum mechanics will resolve it. It is not a problem *within* quantum mechanics; rather it seems to be a problem that certain researchers have *with* quantum mechanics[3] Some find quantum mechanics unsatisfactory by some standard for physical theory beyond logical consistency and consistency with experiment. The intuition of others suggests that in situations 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. What is needed to meet such standards, or to resolve such experimental inconsistencies, should they develop, is not further research on quantum mechanics itself, but rather a new and conceptually different theoretical framework. It would be of great interest to have serious and compelling alternative theories if only to suggest decisive experimental tests of quantum mechanics.

4. Many Worlds. Quantum mechanics describes *sets of alternative* histories of the universe and within a given set one cannot assign "reality" simultaneously to different alternatives because they are contradictory. Everett (1957), DeWitt (1970) 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 over another except through its probability.

The author prefers the term "many histories" to "many worlds" as less confusing and less inflammatory. However, either set of words, and no doubt others as well, may be used to describe this theoretical framework without affecting its predictive content.

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[2] At the time this was originally written we called this a 'quasiclassical domain'. We changed to 'realm' to avoid any confusion with terminology like 'ferromagnetic domains'. The word 'realm' is a shorthand for 'decoherent set of alternative coarse-grained histories'.

[3] Indeed, there seem to be diverse opinions among the most well known interpreters of quantum mechanics as to whether there even is a quantum measurement problem and, what it means and how important it is. See e.g. [10].

5. Non-Locality. In an EPR or EPRB situation a choice of measurements, say σ_x or σ_y for a given electron, is correlated with the behavior of σ_x or σ_y respectively for another electron because the two together are in a singlet spin state even though widely separated. A situation in which an $IGUS$ measures the x-component of the spin decoheres from one in which the y-component is chosen, but in each case there is also a correlation between the information obtained about one spin and the information obtained about the other. This behavior is called "non-local" by some authors. 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. Ghirardi, Rimini, and Weber, 1980, Jordan, 1983.)

Consider a measurement situation. In a particular Lorentz frame, let $\{s^1_{\alpha_1}(t_1)\}$ correspond to a set of alternatives at time t_1 but localized in space. For example, the projection operators $s^1_{\alpha_1}(t_1)$ might be projections onto ranges of field averages at time t_1 over a certain spatial region R_1. Let $\{s^2_{\alpha_2}(t_2)\}$ be another set of alternatives at a later time t_2 defined for a region R_2 *every point of which is spacelike separated from every point of* R_1. Let the initial density matrix of the measured system be ρ_s. These alternatives are assumed to decohere because they are measured as described in Section II.10.

If no measurement is carried out at time t_1, the probability of finding alternative α_2 at the later time t_2 is

$$p_{\text{no meas}}(\alpha_2) = tr\left[s^1_{\alpha_2}(t_2)\rho_s\right] \ . \tag{A.2}$$

If a measurement is carried out at time t_1, but the results are not known (because they cannot be independently signaled from R_1 to R_2 faster than the speed of light) then probability of finding alternative α_2 is

$$p_{\text{meas}}(\alpha_2) = \sum_{\alpha_1} p(\alpha_2, \alpha_1) = \sum_{\alpha_1} tr\left[s^2_{\alpha_2} t_2) s^1_{\alpha_1}(t_1)\rho_s s^1_{\alpha_1}(t_1) s^2_{\alpha_2}(t_2)\right] \tag{A.3}$$

In general (A.3) and (A.2) will not be equal because of interference. This is consistent because they correspond to two physically distinct situations: In the situation described (A.2) no measurement was made at time t_1. A measurement was made in that described by (A.3). However, in the case of spacelike separated regions R_2 and R_1, the local operators $s^k_{\alpha_2}(t_2)$ and $s^k_{\alpha_1}(t_1)$ *commute* by relativistic causality. The operators $s^1_{\alpha_1}(t_1)$ in (A.3) can therefore be moved to the outside of the trace, moved from one side of ρ_s to the other by the trace's cyclic property, and eliminated using $(s^1_{\alpha_1})^2 = s^1_{\alpha_1}$ and $\sum_{\alpha_1} s^1_{\alpha_1} = 1$. Thus, the relativistic causality of the underlying fields implies

$$p_{\text{meas}}(\alpha_2) = p_{\text{no meas}}(\alpha_2), \tag{$A.4$}$$

so that by a local analysis of the second measurement one cannot tell whether the first was even carried out, much less gain any information about its outcome if it was.

6. Reality. Quantum mechanics prefers no one set of histories to another except by such criteria as decoherence and classicality. Quantum mechanics prefers no one history to another in a given set of alternative decohering histories except by probability. Thus, the only element of the theory that might conceivably lay claim to the title of a unique, absolute, independent "reality" is the collection of all *sets* of alternative coarse-grained histories of the universe, or what is essentially the same thing, its initial condition.[4,5] Yet, to use the word "reality" in this way is contentious, for this notion has no relation to the familiar "reality" of our impressions. What are these impressions and how are they described quantum mechanically? The familiar sense of reality arises, it seems, from the agreement among many and varied collections of *IGUS*es on the values of the quasiclassical variables in a quasiclassical realm and the experience that this agreement is largely independent of circumstance, position, and time. In quantum mechanics this agreement would be described as follows: A coarse graining can be associated with each *IGUS* which includes certain quasiclassical projection operators that the *IGUS* can perceive and projection operators (not necessarily quasiclassical) that describe the *IGUS*'s memory in which these perceptions are registered. To have a good memory means that there is a nearly full correlation between the operators describing the *IGUS*'s memory and the quasiclassical operators of the quasiclassical realm. Perception is thus a particular type of measurement situation. Agreement among several *IGUS*es means that there is a correlation between the various memories and common projection operators of a quasiclassical realm. The correlations will not be perfect. There may be fluctuations and, indeed, situations where there is a correlation between an *IGUS*es memory and some *other* part of its memory rather than the appropriate quasiclassical variable describe symptons of schizophrenia commonly described as "loss of contact with reality". Despite such anomalies, the agreement that exists would seem to be the source of our impression of an independent "reality".

The focus by *IGUS*es on the quasiclassical operators of a quasiclassical realm can be explained by understanding evolution of *IGUS*es in the universe. That is the only way of understanding why *IGUS*es employ the coarse grainings they do. If, as a consequence of the initial conditions of the universe and the dynamics of the fundamental fields, there is an essentially unique quasiclassical realm, then it is plausible that human *IGUS*es are features of this realm that our particular universe presents. The coarse grainings describing what *IGUS*es perceive are then *all coarser grainings of the coarse graining defining the essentially unique quasiclassical realm*. *IGUS*es agree because they are perceiving the same quasiclassical projection operators. Thus, although quantum mechanics prefers no one set of histories to another, or one history in a given set to another, but *IGUS*es do.

Thus, if an essentially unique set of decohering alternative histories with high classicality is an emergent feature of our universe it would seem reasonable to associate the term "reality" in its familiar sense with that set of histories or with the individual history in the set correlated with our present memory. Reality would then be an *approximate* notion contingent on the approximate standard for decoherence, the initial condition of the universe, and the dynamics of the elementary fields. Universes for which no quasiclassical realmss were emergent would have no such notion of "reality". The evolution, perceptions, and behavior of *IGUS*es in a universe for which there is more than one quasiclassical realm are open and very interesting questions. Thus, a central question for serious theoretical research in quantum cosmology is whether our universe exhibits more than one quasiclassical realm

[4] This would imply that "all the alternative *sets* of decohering histories are equally real".

[5] As Bohm (1952), deBroglie (1956), Bell (1981), and others have demonstrated, it is possible to use words to describe quantum mechanics that themselves specify a "reality". However, the predictions of quantum mechanics appear to be unaffected by this choice. If that is the case, then such issues as the existence of quasiclassical realms or the description of the reality of familiar experience remain as issues in the alternative descriptions.

and, if so, the consequences of this fact for the evolution and behavior of $IGUS$es and the evolution of their notions of "reality".

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[10] M. Schlosshauer, *Elegance and Enigma: The Quantum Interviews*, (Springer, Heidelberg, 2011).