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Quantum physics and human language

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Abstract

Human languages employ constructions that tacitly assume specific properties of the limited range of phenomena they evolved to describe. These assumed properties are true features of that limited context, but may not be general or precise properties of all the physical situations allowed by fundamental physics. In brief, human languages contain ‘excess baggage’ that must be qualified, discarded, or otherwise reformed to give a clear account in the context of fundamental physics of even the everyday phenomena that the languages evolved to describe. The surest route to clarity is to express the constructions of human languages in the language of fundamental physical theory, not the other way around. These ideas are illustrated by an analysis of the verb ‘to happen’ and the word ‘reality’ in special relativity and the modern quantum mechanics of closed systems.

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‘Mind and world . . . have evolved together and in consequence are something of a mutual fit.’

—Wm James, 1893 [1]

‘We are deceived at every level by our introspection.’

—F H C Crick, 1979 [2]

1. Introduction

Human languages are features of particular kinds of information gathering and utilizing systems (IGUSes)¹, living late in the universe, dwelling on a minor planet, circling a garden-variety star, that is but one of about ten billion stars in a galaxy that is but one of about a hundred billion other galaxies within the visible universe. Human languages are thus

¹ The term IGUS is broad enough to include both single representatives of biological species that have evolved naturally and certain kinds of mechanical devices. It includes human beings, both individually and collectively as members of groups, cultures and civilizations. It includes intelligent beings that we might meet in the future. For more discussion see [3].

features of our universe but very special ones. Languages evolved over the history of our species through a combination of frozen accidents and selection by both physical and cultural evolutionary pressures. Human languages are adapted to provide certain highly coarse-grained descriptions of the quasiclassical realm of everyday experience—the ‘world’ to which James presumably referred in the above quote. Yet, human languages are not restricted to such quasiclassical descriptions. Suitably extended, they also permit the discussion of regimes under exploration in contemporary fundamental physics that are characterized by concepts that can be quite far from those native to the quasiclassical realm. This essay explores some aspects of the tension between the domains in which human languages evolved and those to which they can be applied. In particular, we have in mind applications to the modern quantum mechanics of closed systems, most generally the universe as a whole. This deals not only with quasiclassical realms but many mutually incompatible ones as well.

The theses of this essay are these: human languages employ constructions that tacitly assume properties of the limited range of phenomena they evolved to describe. These assumed properties are true features of that limited context, but may not be general properties of all the physical situations allowed by fundamental physics. In brief, human languages contain ‘excess baggage’ that must be qualified, discarded, or otherwise reformed to give a clear account in the context of fundamental physics of even the everyday phenomena that the languages evolved to describe.

It is no more surprising to find that human language contains tacit assumptions than it is to discover that we possess a useless appendix. Indeed these limitations of language are evidence for its evolution just as our appendix is evidence for human evolution. Rather, the important circumstance is that the flexible, open-ended, nature of human language allows it to be employed in the discussion of concepts very far from those it evolved to describe with only a few precautions and modifications. This essay is concerned with those precautions and modifications.

The surest route to clarity is to express the constructions of human languages in the language of fundamental physical theory, not the other way around. Alternatively the constructions can be qualified so that tacit assumptions are made explicit. By ‘human language’ here we mean roughly the language of everyday discourse. By ‘language of physics’ we mean roughly the language, terms, concepts, and mathematics found in physics textbooks. Making a precise distinction will not be necessary because we will do that explicitly in specific examples.

There are many different physical theories that could be used to illustrate these theses, many different linguistic constructions that could be considered, and certainly many different human languages. For simplicity and clarity we shall focus on limited examples of each of these possibilities.

We will consider just one human language—English—and hope that our analysis of the connection between English and physics extends to other human languages in an essentially equivalent way. Assuming this equivalence we shall refer just to ‘human language’—singular rather than plural.

We shall consider just two linguistic constructions. The first is the use of the verb ‘to happen’ in its various forms: ‘happened’, ‘is happening’ and ‘will happen’. Other existential verbs ‘to be’, ‘to exist’, etc may be treated similarly. The other construction is the word ‘reality’.

We shall consider just two theories: the quantum theory of closed systems [3–5] and special relativity. Clarifying the quantum mechanics of closed systems is the objective of this essay. But special relativity provides a simple, uncontroversial example².

² It should be noted that none of these considerations is necessary to discuss the work of G Ghirardi as for example in [6].

When we refer to ‘quantum mechanics’ or ‘quantum theory’ in this essay, we mean the decoherent (or consistent) histories quantum mechanics of closed systems, most generally the universe [3–5]. This is a modern synthesis of the ideas of many that extends the work begun by Everett. Decoherent histories quantum theory is logically consistent, consistent with experiment as far as is known, applicable to cosmology, consistent with the rest of modern physics such as special relativity, and generalizable to include quantum gravity (e.g. as in [7]). It incorporates Copenhagen quantum theory as an approximation appropriate for measurement situations. It may not be the only theory with these properties, but is the most promising of those currently available in the author’s opinion.

Briefly the discussion will be as follows: a conflict arises between special relativity and the use of ‘happened’, ‘is happening’ and ‘will happen’ in human language. These constructions tacitly assume that there is a division of spacetime into past, present and future. But special relativity does not provide a unique such division, but rather many of them. The resulting conflict can be resolved by abandoning ‘to happen’ and using the language of special relativity. Alternatively spacetime can be conventionally divided into past, present and future and the use of ‘to happen’ qualified to refer to that convention.

In quantum mechanics, ‘happened’, ‘is happening’ and ‘will happen’ are probabilistic statements to be qualified with the relevant probability, e.g. ‘happened with probability p ’. These probabilities are constructed from those that quantum mechanics assigns to a set of alternative histories of the universe. Human language tacitly assumes that there is a unique such set, mostly the histories of the quasiclassical realm. But quantum theory exhibits many alternative sets of histories to describe past, present and future which may be incompatible roughly in the sense that position and momentum are incompatible. The resulting conflict can be resolved by replacing statements which involve ‘to happen’ with statements about quantum-mechanical probabilities. Alternatively, ‘to happen’ can be qualified to refer to the particular set of histories which define those probabilities.

This essay is based on the author’s experience in explaining and teaching the quantum mechanics of closed systems along with some modest reflection on the subject. It is intended for *physicists* as a practical guide to a clearer understanding of this area by dealing with some of the linguistic tangles that naturally arise. No new physics is considered, only issues concerning the discussion of physics. The ideas expressed are merely the author’s opinions on routes to clarity. Others may find different routes work better. This essay is therefore not a review of all that has been written on these questions. In particular, there is a long history of discussion of related questions in philosophy and linguistics, but this essay does not pretend to address any of the deep issues that may arise there (see, e.g., [8]).

The paper is structured as follows: section 2 discusses the use of ‘to happen’ in the context of special relativity. Section 3 discusses the use of ‘to happen’ in the quantum-mechanical context where there are many mutually incompatible decoherent sets of coarse-grained alternative histories of the universe. Section 4 ventures to discuss the implications of this for our notions of reality. Section 5 discusses dispensable words and what to do about them. Section 6 concludes with practical advice on achieving clarity.

2. Spacetime

Up here, on length scales much greater than the Planck length, the world is four-dimensional with a classical spacetime geometry. There is neither a unique notion of space nor a unique notion of time. Rather, from each point in spacetime, there is a family of timelike directions and three times as many spacelike directions. Spacetime geometry is curved by mass–energy according to the laws of general relativity, but in sufficiently small patches every geometry is

well-approximated by the flat spacetime of special relativity. To simplify our discussion we begin by restricting attention to a patch of spacetime where this approximation holds.

First, recall a few basic facts about flat spacetime. Events occur at points. At each point Q there is a light cone consisting of two parts: The future light cone is the three-dimensional surface generated by light rays emerging from Q . The past light cone is similarly defined by light rays converging on Q . (The labels ‘past’ and ‘future’ are conventional, but may be conveniently specified by the directions towards the big bang and away from it.) Points inside the light cone of Q are timelike separated from it; points outside it are spacelike separated.

The centre of mass of a localized IGUS such as ourselves describes a timelike world line whose points can be labelled by the timelike distance along the curve also known as proper time.

Consider an event A on your world line and another event B elsewhere. Suppose you are located along your world line at event A . Could you answer the questions: ‘Will B happen in the future?’; ‘Is B happening now?’; and ‘Did B happen in the past?’ You cannot because these questions are meaningless in special relativity without further qualifications. The questions presume that spacetime can be divided into past, present (now), and future just on the basis of the location of A in spacetime. There is no such division.

More specifically, imagine there are astronauts on Saturn’s moon Titan. Questions like ‘What are the astronauts doing now?’ or ‘Did they begin breakfast half an hour ago?’ are meaningless without further qualifications. The light travel time between Titan and Earth can be over an hour implying a comparable special relativistic ambiguity in the notion of simultaneity. There is thus a conflict between familiar constructions of human language and the facts of special relativity.

The simplest resolution of the conflict is to discard the verbs like, ‘to happen’ and to formulate physically meaningful questions in the language of physics. Questions like ‘Is B in my future light cone at A ’, ‘Is B spacelike separated from me at A ’, and ‘Is B in my past light cone at A ?’ do make sense and have unambiguous answers³.

Another route to resolving the conflict is to retain the verb ‘to happen’ but to qualify its usage in some conventional way. Specifically, we could divide spacetime up into a spacelike surface S containing A , the future of S , and the past of S . Then the questions ‘Will B happen in the future of S ’, ‘Is B happening on S ’, and ‘Did B happen in the past of S ?’ do make sense and have definite answers depending on where B is in spacetime. They are made meaningful by the qualifications referring to the spacelike surface S . However, there are an arbitrarily large number of spacelike surfaces containing A and the answers to the questions can be different for other spacelike surface S' when B is spacelike separated from A . Unqualified constructions involving ‘to happen’ are meaningless, when qualified they have many different meanings⁴.

Introducing a coordinate system in our patch of spacetime is another arbitrary way of fixing a convention to give ‘to happen’ a qualified meaning. Riemann normal coordinates based at the point A are a simple example if they cover the whole patch. If the geometry of the patch happens to be exactly flat, these reduce to a choice of a particular Lorentz frame. Past, present and future are now defined by the timelike coordinate (call it t) being greater than, equal to, or less than its value at A . As a bonus, a coordinate system provides a convention for

³ ‘Is’ here is understood in a tenseless, four-dimensional sense referring to the properties of spacetime. In a similar way ‘happen’ is sometimes used (mostly by physicists) in a four-dimensional sense of occurring in spacetime. That usage will not be discussed in this essay but can be a further source of confusion.

⁴ Using the language of physics and employing appropriate qualifications are not the only ways of resolving the conflict between special relativity and human language. Raphael Sorkin tells the author that there have been various proposals for *reforming* human language. These include redefining ‘now’ to mean ‘spacelike’ and using adverbs rather than verb forms to indicate tense, as in ‘It happens spacelike’. The author guesses that the two resolutions discussed in the text have better chances of success.

answering further questions of the form ‘Does B occur before C or afterward?’ which would be ambiguous if unqualified when B and C are spacelike separated.

The satellites comprising the global positioning system (GPS) are an example of a collective IGUS that effectively employs a coordinate system to define temporal relations. Both the special relativistic effects arising from the velocities of the satellites, and the general relativistic effects arising from the slight curvature of spacetime in the vicinity of the Earth are important for GPS operation [9]. The system would fail in about an hour if these were not both accounted for. Precise agreement among the satellites on a notion of simultaneity is needed. To define that the GPS uses a version of a standard set of coordinates for the weak field metric of general relativity, centred in the Earth, with spatial axes pointing towards fixed stars, and the time coordinate normalized so that that on the Earth’s geoid (approximately the ocean surface) it coincides with the time of clocks co-rotating with the Earth there. It is unlikely that the satellites are employing the verb ‘to happen’ in any communication. But, if they did, they could define it by the time of their effective coordinate system.

Human IGUSes were using constructions like ‘will happen’, ‘is happening’ and ‘did happen’ long before they had accurate clocks, and certainly before there was a precise notion of coordinate system. How would the notion of ‘present’ or ‘now’ that is implicit in these constructions be described in the language of physics? The author has discussed the physics of ‘now’ in [10]. The next few paragraphs summarize some of these ideas.

Human IGUSes have an individual notion of ‘now’ which can be modelled as a feature of their conscious focus on their most recently acquired information. This is already an approximate idea only defined up to the time scale of human perception⁵ which we denote by τ_* . Individual IGUSes can agree on ‘what is happening now’ by reporting their current observations and checking the reports they receive against their individual notions of ‘now’. The result is an approximate, imprecise, common present useful in everyday circumstances.

Agreement on a common present can be reached by a group of IGUSes in a patch where spacetime is approximately flat if the following contingencies are met.

- (1) The relative velocities of the IGUSes are small compared to the velocity of light.
- (2) The light travel time between IGUSes in a Lorentz frame in which they are nearly at rest is small compared to the time scale τ_* characterizing perception.
- (3) The time scale for perception τ_* is short compared to the time scales on which interesting features of the IGUSes’ environment vary.

Contingency (2), based on (1), means that special relativistic ambiguities in the meaning of simultaneity are negligible in the construction of a common present. Contingency (3) means that the ambiguity in the ‘now’ of each IGUS is negligible in this construction. Condition (1) means that agreement can be reached over an interesting length of time.

Under these contingencies, a collection of IGUSes can construct a common present, but it is a present that is local, approximate and contingent on their relation to each other and to their environment. All the contingencies are easily satisfied for human IGUSes on Earth. However, astronauts on Titan will not be able to participate in this common ‘now’; contingency (2) will be violated. Further conventions will be needed to use the verb ‘to happen’ in talking to them.

The purpose of this section was not to analyse human linguistic constructions in any detail. Rather, it was to emphasize that certain of these constructions referring to time are ambiguous even in the context of our understanding of the physics of spacetime through special and general relativity. The existence of such ambiguities is not surprising given that the language evolved to describe limited and specific circumstances in which conditions (1)–(3) hold. The language implicitly assumes certain features of these limited circumstances summarized roughly by the

⁵ This is of order 0.1 s, e.g. [11].

three contingencies above. The ambiguities can be resolved either by replacing parts of the human language with the language of physics, or by using that language to specify conventions that resolve the ambiguity.

As our understanding of spacetime progresses to ever more general contexts, the ambiguities in the use of human language can be expected to become larger. In a quantum theory of gravity, there is no fixed spacetime geometry. Rather, geometry is a quantum variable, fluctuating and without definite value. Then, even statements like ‘This happened in my past light cone’ become meaningless without further qualification. Beyond that, some explorers expect that spacetime will only be an coarse-grained phenomenon of some deeper level of description [12]. How will ‘to happen’ be unambiguously defined then?

3. The quantum mechanics of closed systems

3.1. A model universe

To keep the discussion manageable, we consider a closed quantum system, most generally, the universe, in the approximation that gross quantum fluctuations in the geometry of spacetime can be neglected. The closed system can then be thought of as a large (say $\gtrsim 20\,000$ Mpc), perhaps expanding, box of quantum fields moving in a fixed background spacetime. Everything is contained within the box, in particular galaxies, planets, observers and observed (if any), measured subsystems, and the apparatus that measures them. This is a model of the most general physical context for prediction.

The fixed background spacetime means that the notions of time are fixed and that the usual apparatus of Hilbert space, states and operators can be employed in a quantum description of the box. The essential theoretical inputs to the process of prediction are the Hamiltonian H governing evolution and the initial quantum state $|\Psi\rangle$. These are assumed to be fixed and given by fundamental theory. We assume that H , $|\Psi\rangle$, and the operators representing alternatives can be described in terms of a set of fundamental fields and their conjugate momenta. For definiteness, we work in a fixed Lorentz frame whose time is t .

All the special relativistic concerns regarding the use of ‘to happen’ discussed in section 2 arise in this context, but we resolve these by fixing the Lorentz frame in order to concentrate on quantum-mechanical issues.

For the reader not familiar with it, a simplified, bare-bones account of the quantum mechanics of closed systems is given in appendix A. However, very little of even the modest detail given there is necessary for the present discussion. The points essential for the present discussion are as follows.

- (1) The assumed inputs are theories of the quantum dynamics (H) and the initial quantum state $|\Psi\rangle$.
- (2) The outputs are the probabilities of the individual members of sets of alternative coarse-grained histories of the closed system. Consistent probabilities are predicted only for sets of histories for which there is negligible quantum interference between all pairs of histories in the set as a consequence of H and $|\Psi\rangle$. Such sets of histories are said to *decohere* and are called *realms* for short.
- (3) There are no non-trivial completely fine-grained realms. Coarse graining is therefore necessary for decoherence. Some realms are *compatible* in the sense that they can be related by the operations of fine and coarse graining. But quantum theory also exhibits *incompatible* realms. Two realms are mutually *incompatible* if there is no common finer-grained realm of which they are both coarse grainings. Realms defined by coarse grainings of incompatible variables such as position and momentum provide simple examples.

- (4) *Quasiclassical realms*⁶ exhibit the regularities of classical physics and in particular the approximate correlations in time summarized by effective classical equations of motion. At a sufficiently fine-grained level, quasiclassical realms are defined by coarse grainings of familiar *quasiclassical variables* such as averages of energy, momentum and number over suitable volumes. The quasiclassical realms of everyday experience are a subset of the totality of realms provided by quantum theory for a description of the universe.
- (5) Quantum theory does not distinguish between its different realms, although IGUSes may distinguish between them by their utility, as for example in the almost exclusive focus of human IGUSes on quasiclassical realms.

If any of this is not immediately clear, the reader should consult appendix A.

3.2. Probabilities

Probabilities are measures of ignorance in classical physics, but in quantum physics they are fundamental. This subsection is devoted to reconciling human language which incorporates assumptions of classical certainty with a probabilistic fundamental theory. To this end, we restrict the discussion of this subsection to one realm. We begin by reviewing a little notation explained more fully in appendix A.

We consider histories that are sequences alternatives labelled by $\alpha_1, \alpha_2, \dots, \alpha_n$ at a series of times t_1, t_2, \dots, t_n . The probabilities of these are given by

$$p(\alpha_n, \dots, \alpha_1) = \|P_{\alpha_n}^n(t_n) \cdots P_{\alpha_1}^1(t_1)|\Psi\rangle\|^2 \quad (3.1)$$

where the $P_{\alpha_k}^k(t_k)$ are Heisenberg picture projections onto these alternatives. The label k denotes the particular exhaustive *set* of exclusive alternatives, α_k labels the particular alternative within the set, and t_k is the time. To conserve on notation, we denote individual histories by $\alpha \equiv (\alpha_1, \alpha_2, \dots, \alpha_n)$ and denote the corresponding chains of projections by C_α so that

$$p(\alpha) = \|C_\alpha|\Psi\rangle\|^2 \quad (3.2)$$

is a shorthand for (3.1).

Conditional probabilities for alternatives α given another alternative β are constructed in the usual way

$$p(\alpha|\beta) \equiv p(\alpha, \beta)/p(\beta). \quad (3.3)$$

Most useful probabilities are conditional. Suppose, for instance, we know certain data d about the universe at a present time t_0 represented by a projection $P_d(t_0)$. The predictions for future histories of the universe given these data are specified by the conditional probabilities

$$p(\alpha_{\text{fut}}|d) = \frac{\|C_{\alpha_{\text{fut}}}P_d(t_0)|\Psi\rangle\|^2}{\|P_d(t_0)|\Psi\rangle\|^2} \quad (3.4)$$

where the $\{C_{\alpha_{\text{fut}}}\}$ represent an exhaustive set of alternative histories to the future of t_0 . Similarly, the probabilities for retrodiction of the past are given by

$$p(\beta_{\text{pst}}|d) = \frac{\|P_d(t_0)C_{\beta_{\text{pst}}}\Psi\rangle\|^2}{\|P_d(t_0)|\Psi\rangle\|^2} \quad (3.5)$$

where $\{C_{\beta_{\text{pst}}}\}$ represent an exhaustive set of alternative histories to the past of t_0 . In each case, we assume that the set of histories consisting of P_d and the C 's is decoherent.

⁶ We use the term *quasiclassical realm* to emphasize that the classical behaviour is probabilistic and on occasion significantly interrupted by quantum mechanics.

The alternatives $P_d(t_0)$ can refer to the data possessed by an IGUS at a time t_0 along its own history. Similarly, α_{fut} and β_{pst} can refer to data possessed by that IGUS in the future or past of t_0 . Thus, it is possible to provide probabilities that answer questions like ‘Given that I observe a tree here today, what is the probability that there was a tree here yesterday?’ or ‘Given that I observe a tree here today, what is the probability that I will observe a tree here tomorrow?’, or even ‘Given that I observe a tree here today, what is the probability that there is a tree here today?’ (This the probability that our observations do not deceive us.)

Like all assertions in a probabilistic theory, those involving the verb ‘to happen’ should always be qualified by a probability. For instance, from present data that include texts giving 55 BC as the date of the Roman invasion of Britain we would like to infer that Caesar did invade Britain in 55 BC. But the probability for this is not unity. There is some probability that the texts are forgeries, or contain propagating mistakes, or that the ink on their pages made a quantum transition from a configuration spelling a different date. If the probability is sufficiently close to unity we say simply that the Roman invasion of Britain *happened* in 55 BC. Similar qualifications are needed for ‘is happening’ and ‘will happen’.

This need for qualifying ‘happen’ because of probabilities is a trivial observation. Such qualifications are generally needed in classical physics as well. Probabilities are inescapable as a practical matter because of ignorance of present data or inability to determine classical evolution. Quantum fluctuations add one more source of uncertainty which is often negligible in everyday circumstances, as in probability for the date of the Roman invasion of Britain. In the next section we consider a more serious reason for qualification.

3.3. Incompatible realms

Human IGUSes focus almost exclusively on coarse-grainings of the quasiclassical realm. Our senses are adapted to perceive quasiclassical variables and our language is adapted to describe quasiclassical histories⁷.

As we have already mentioned, the quantum universe exhibits distinct realms which are incompatible in the sense that there is no finer-grained realm of which they are coarse-grainings. Questions, answers, predictions, retrodictions, etc are all in the context of a particular realm which must be specified to understand what they mean.

Consider by way of example the reconstruction of a past history of the universe from data we have gathered in the present together with the theory of the initial state⁸. As mentioned above, that is accomplished by retrodicting the probabilities of past events from the given present data using the conditional probabilities (3.5).

Suppose present data are given in quasiclassical variables. The most familiar and useful retrodictions from these data are made using quasiclassical past histories. With these we retrodict the date 55 BC for the first Roman invasion of Britain from present textual records. We use present observations of the planets to reconstruct their past trajectories. We use fossil records to estimate that there is a high probability that dinosaurs roamed the Earth 150 million years ago. We infer that matter and radiation were in thermal equilibrium at the beginning of the universe from the present values of the Hubble constant, spatial curvature and the temperature of the cosmic background radiation. These are all past histories that are members of quasiclassical realms based on coarse-grainings of quasiclassical variables.

But in quantum theory there is no unique past conditioned on given present data. Incompatible past realms can provide different stories of what happened. A striking, if

⁷ Explanation for our quasiclassical focus can be sought in the physical structure of human IGUSes and the origin of that structure.

⁸ For more on the reconstruction of the past in quantum mechanics, see [13].

artificial, example of this is provided by the three-box model introduced by Aharonov and Vaidman for a different purpose [14].

Consider a particle that can be in one of three boxes, A , B , C in corresponding orthogonal states $|A\rangle$, $|B\rangle$ and $|C\rangle$. For simplicity, take the Hamiltonian to be zero, and suppose the system to initially be in the state

$$|\Psi\rangle \equiv \frac{1}{\sqrt{3}}(|A\rangle + |B\rangle + |C\rangle). \quad (3.6)$$

Suppose for present data at t_0 the particle is in the state

$$|\Phi\rangle \equiv \frac{1}{\sqrt{3}}(|A\rangle + |B\rangle - |C\rangle). \quad (3.7)$$

Denote the projection operators on $|\Phi\rangle$, $|A\rangle$, $|B\rangle$, $|C\rangle$ by P_Φ , P_A , P_B , P_C respectively. Denote by \bar{A} the negation of A ('not in box A ') represented by the projection $P_{\bar{A}} = I - P_A$. The negations $\bar{\Phi}$, \bar{B} , \bar{C} and their projections $P_{\bar{\Phi}}$, $P_{\bar{B}}$, and $P_{\bar{C}}$ are similarly defined.

From the present data $|\Phi\rangle$ and the initial condition $|\Psi\rangle$ let us ask whether the particle was in the box A at a time earlier than t_0 . (The exact values of the times are unimportant since $H = 0$. Only the order matters.) The relevant past realm consists of the histories

$$P_\Phi P_A, \quad P_\Phi P_{\bar{A}}, \quad P_{\bar{\Phi}} P_A, \quad P_{\bar{\Phi}} P_{\bar{A}}, \quad (3.8)$$

and is easily checked to decohere exactly. The conditional probabilities for A and \bar{A} given Φ can be calculated from (3.5) with $P_d = P_\Phi$ and $\{C_\alpha\} = \{P_A, P_{\bar{A}}\}$. The result is

$$p(A|\Phi) = 1, \quad p(\bar{A}|\Phi) = 0. \quad (3.9)$$

Thus, we can say *in this past realm* that the event that the particle was in box A in the past happened.

But an examination of (3.6) and (3.7) shows that both initial condition and present data are symmetric under interchange of A and B . Therefore, using the decoherent set of histories

$$P_\Phi P_B, \quad P_\Phi P_{\bar{B}}, \quad P_{\bar{\Phi}} P_B, \quad P_{\bar{\Phi}} P_{\bar{B}} \quad (3.10)$$

we can compute

$$p(B|\Phi) = 1, \quad p(\bar{B}|\Phi) = 0. \quad (3.11)$$

Thus, we can say *in this past realm* that the event that the particle was in box B happened.

There is no contradiction because the sets of histories (3.8) and (3.10) are incompatible realms. The finer-grained set of histories describing both A and B is

$$P_\Phi P_A P_B, \quad P_\Phi P_A P_{\bar{B}}, \quad P_\Phi P_{\bar{A}} P_B, \dots, \text{etc.} \quad (3.12)$$

But this set does not decohere. The inference 'if in A then not in B ' cannot be drawn since there are no consistent probabilities for it.

Equations (3.8) and (3.10) do not exhaust the possible realms defining possible pasts for the present data P_Φ . For example, we could consider

$$P_\Phi P_\Psi, \quad P_\Phi P_{\bar{\Psi}}, \quad P_{\bar{\Phi}} P_\Psi, \quad P_{\bar{\Phi}} P_{\bar{\Psi}}. \quad (3.13)$$

This is trivially decoherent with easily anticipated probabilities, but also clearly distinct from (3.8) and (3.10). In this past realm we could say that P_Ψ happened rather than anything about the above alternatives.

The usual use of 'happened' assumes that there is only one realm. In a theory that permits incompatible pasts, its use must be reformed. As with the other conflicts between human language and fundamental physics discussed in this paper, there are two routes to improving precision and clarity. One is to use the language of physics and speak of the past in terms of the conditional probabilities in different past realms. The other route is to qualify 'happen' so

it refers to a particular realm. For instance, in the three-box example we could say that ‘the event that the particle was in box *A* happened in the realm that referred to *A*’ (or whatever other characterization of (3.8) one prefers) and similarly for *B*.

If ‘happened’ means high probability for an event in the past conditioned on certain present data, the above examples show that different events can have happened in different incompatible pasts, even seemingly contradictory events. If someone asks you ‘What happened yesterday?’ you should strictly speaking respond with the question ‘In what realm?’.

It should be stressed, however, that the same event cannot have happened in one realm and not have happened in another. The probability for a past history is given uniquely by (3.5) in all the realms of which it is a member. If it is high in one realm, it is high in all the others. In this sense ‘happened’ is non-contextual.

Needless to say, similar considerations apply to ‘happening’ and ‘will happen’. We next turn to the implications of all this for the word ‘reality’.

4. Reality

The words ‘real’ and ‘reality’ are used in many different ways in human language. In the following we attempt to draw crude distinctions between a few of these without suggesting that other distinctions are not possible. The general point is that notions of reality reside in the models (schemata) that IGUSes construct of the world around them, both individually and collectively. Different models have different notions of reality. Therefore, when using the words ‘real’ or ‘reality’ it is important for clarity to specify which model is being referred to.

4.1. *Everyday physical reality*

Everyday notions of physical reality arise from the agreement among human IGUSes, both individually and collectively, on their observations and on the models of the world (schemata) that they infer from them. These models are formed from the gathered data by processes of selection, communication and schematization, consistent with built-in biases. The models are constantly updated as the IGUSes acquire new information, integrate it with previous experience, infer new useful regularities, and check the model against other schemata. The everyday notions of physical reality reside in these models. This is the reality of tables and chairs, stars and galaxies, biological species, fellow humans, and the records of experiments revealing quantum phenomena, among many other things. These are the notions of reality that human language evolved to describe and assist in constructing. Explaining the regularities found in such models is an important objective of science. The limits of physical reality are illustrated by the lack of agreement on mirages and illusions, and by the delusions of schizophrenics who are said to be ‘out of touch with reality’. In human language, this everyday physical reality is often what is meant when the word is used without qualification.

How do we understand the agreement among human IGUSes on the facts of their physical reality in a quantum universe characterized fundamentally by the distributed probabilities of the alternative histories of a vast number of incompatible realms? The simplest explanation is that human IGUSes are all making observations utilizing coarse-grainings of the quasiclassical realms in order to exploit the quasiclassical regularities that these realms exhibit. They thus are adapted to develop schemata in more or less the same way. Occasionally they slip up as when they are subject to delusions, or see canals on Mars, or find ghosts under the bed. But they agree, by and large. Indeed, we could not function in social units without this agreement; the ability to construct a common physical reality must have been a highly adaptive trait. Plausibly, many other IGUSes on Earth, such as dolphins and ants, make use of similar coarse grainings.

If we find intelligent life on other planets, will they have the same notion of physical reality that we do? It is plausible that many kinds of IGUSes will have evolved to exploit the regularities of quasiclassical realms as we have. In that case, we can expect to reach agreement with them. But could there be IGUSes focused on coarse-grainings of a distinct, incompatible realm with a correspondingly different notion of physical reality? The statistics of the schemata of extra-terrestrial IGUSes will constitute a test of the conjecture of the adaptive utility of the quasiclassical realms.

Closer to home, we imagine that we could construct mechanical IGUSes (robots) that have notions of reality differing from the human kind. Even restricting to input data streams that are coarse grainings of a quasiclassical realm, we imagine that we could construct robots that create different schemata from that data. For instance the built-in biases for selecting what to schematize and the rules for how to schematize could both be varied. A thermostat is a very simple example of an IGUS with a restricted schema. It should be possible to construct IGUSes (robots) with schemata that do not employ our past, present future organization of temporal information⁹ [10]. Science fiction abounds with robots that construct different schemata. It is also not beyond possibility that we could construct robots utilizing non-quasiclassical input data streams. Such robots would consequently have qualitatively different schemata and qualitatively different notions of everyday reality.

4.2. *The realities of physical theories*

As Bohr said, ‘the task of science is both to extend the range our experience and reduce it to order’ [15]. Elementary notions of physical reality are extended by fundamental physical theories. These are realities that are agreed to by physicists and reside in the physics literature. Indeed, there is very little, if any, distinction between the model itself and the notion of reality which follows from it¹⁰.

We hope that the reality of our fundamental theoretical frameworks is objective because they summarize the universal regularities of the universe independently of any selection by us. In particular we hope that they would be agreed to by other IGUSes we might meet that are interested in physics whether they share our notion of everyday physical reality or not.

The everyday physical reality described in section A is an approximate, particular feature of these fundamental models arising from particular coarse grainings and particular initial conditions. Characterizing the emergence of physical reality already raises interesting questions in classical physics and more profound ones in quantum mechanics.

A fundamental classical model for the universe would consist of the fine-grained histories of particles and fields evolving from an initial condition according to deterministic laws. These fine-grained histories can be specified by giving the coordinates and momenta of both particles and fields as a function of time¹¹. An initial condition could be specified by giving a distribution function for these variables at an initial time. The important point for present considerations is that the reality of classical theory consists of a unique family of fine-grained histories.

⁹ Our conscious focus on the most recently acquired data are plausibly the reason that the present is sometimes characterized as more ‘real’ than the imperfectly recorded past and the unknown future. What is meant presumably is that present data figure more prominently and accurately in robot’s schema. However, the ‘NS’ robot of [10] would treat the past and present equally, and the ‘AB’ robot would have some premonitions of the future.

¹⁰ That is possibly the reason that ‘reality’ is so little discussed in physics textbooks—it is already implicit in the model under discussion.

¹¹ More precisely they are specified by giving these values on a foliating family of spacelike surfaces in a curved spacetime obeying the Einstein equation when general relativity is taken into account.

The constituents of the everyday notion of physical reality are not atoms, molecules and electromagnetic fields, but rather tables and chairs, stars and galaxies, etc more generally the forms, velocities and locations of individual objects. Indeed such notions were used by our species long before atoms, molecules and fields were discovered. Rather, everyday physical reality arises from the fundamental classical model by appropriate coarse-graining. For instance, coarse-graining by quasiclassical variables such as the averages over suitable volumes of densities of approximately conserved quantities such as energy, momentum and number leads to phenomenological equations of motion such as the Navier–Stokes equation for a wide class of initial conditions (see, e.g. [16]). Further coarse-graining is needed to define individual physical objects such as particular trees. The important point is that everyday physical reality is an approximate feature of classical physics contingent on particular choices of coarse-graining.

The story of the emergence of everyday physical reality from the quasiclassical realms in quantum theory is similar to that in classical physics. The coarse-grainings defining the relevant sets of histories are the same. The two new features are the following: first the initial quantum state must be such that the set of coarse-grained histories decoheres. Second, the correlations in time that define classical determinism are now only approximate—occurring with high probability in particular initial states¹².

What is very different from classical physics is the reality of the fundamental quantum theory. There are no non-trivial fine-grained decoherent sets of histories for quantum theory as there are for classical physics [21]. Coarse-graining is necessary for decoherence, and there are many different coarse-grainings not all of which are compatible. As we have already discussed, quantum theory therefore provides many mutually incompatible realms of which the quasiclassical ones are a small subset. The theory does not distinguish between these, although IGUSes may do so. In the three-box example in section 3.3, the past realm that refers to box *A* is no more or less ‘real’ than the incompatible past realm that refers to box *B*. The reality of quantum theory may be said to consist of all the different possible realms¹³.

To use the word ‘reality’ in the context of quantum theory without qualification is to risk confusing everyday physical reality which is constructed from quasiclassical realms with the reality of quantum theory which consists of all realms.

4.3. Other realities

Human IGUSes exhibit a wide range of individual notions of reality that go beyond physical reality by incorporating in their schemata the supernatural, prejudice, revelation, hearsay, wishful thinking and the like along with scientific evidence. Today one can find human IGUSes of different persuasions on the reality of UFOs, paranormal phenomena and biological evolution. Beyond these individual notions, there are many other kinds of agreed-upon models constructed by human IGUSes, each defining a notion of reality. For instance, a notion of mathematical reality arises from the agreement of mathematicians on axioms which, as Gödel put it [23], ‘force themselves on us as being true’.¹⁴

4.4. Usage

The above discussion probably does not exhaust the uses of the word ‘reality’ in human language. But it does illustrate that its meanings are diverse. What they seem to have in

¹² For some further discussion and models, see e.g. [17–20].

¹³ The far reaching consequences of this generalization of the reality of classical theory have been stressed in [22].

¹⁴ When we encounter other intelligent beings we can confidently predict that they will have the same arithmetic that we do. But will they have ZFC?

common is an agreement by at least some IGUSes on a model for some class of coarse-grained physical phenomena. This diversity of meanings can lead to confusion if the word is used without qualification. In particular it is important to distinguish between everyday physical reality and the notions of reality provided fundamental physical theory. That is especially the case if everyday experience is special and contingent among many other possibilities as is in quantum theory. The trend in fundamental physics today seems to lie in the direction of increasing disparity between everyday physical reality and the reality of the fundamental theory. If that trend continues, maintaining appropriate linguistic qualifications will become even more necessary for clarity.

5. Dispensible words

Dispensable words are ones that can be added to or deleted from an exposition of a physical theory without affecting the theory's experimentally verifiable predictions or its utility. Such words can be important for motivation, for evoking analogies, for building intuition and for suggesting future research. In short, they can help understanding. But they can also be confusing, the source of false problems, and an obstacle to understanding. Not surprisingly, some dispensable words arise from natural constructions in human language. Also, not surprisingly, many of the confusing dispensable words occur in quantum theory¹⁵.

It is useful to know when language describing a theory is dispensable and when it is not. In particular, a question of whether or not dispensable words are appropriate will not be settled by experiment.

There is a simple test for dispensable words: dispense with them and see if the predictions of the theory are unchanged. The author has usually found that dispensing with the dispensables is a route to clarity. This section illustrates these ideas with two examples from quantum mechanics.

5.1. Probabilities 'to happen'

Consider the two sentences, 'The probability of rain this afternoon is 80%' and 'The probability for rain to happen this afternoon is 80%'. To the author these two sentences mean the same thing in any understanding of probability of which he is aware. His decision whether or not to carry an umbrella would be the same under either assertion. The words 'to happen' are dispensable.

Qualifying 'the probability of *A*' so that it becomes 'the probability of *A* to happen' can be a source of confusion because it suggests to some that 'happening' is a physical process. Indeed, some have held that quantum theory is incomplete until it explains why, in a set of alternatives for which it supplies probabilities, one of them 'happens' (or is observed). Quantum theory as developed here has no such mechanism and yet is consistent with all experiment, as far as we know, through the probabilities which are its only output.

5.2. Equally real histories

Another candidate for dispensable words is the statement, 'all the histories in a given realm are equally real'.¹⁶ This statement has a simple meaning if 'real' is understood to refer to the theoretical model—the reality of the theory as discussed in section 4.3. In that context

¹⁵ For one reason this might be so, see [24].

¹⁶ This is a translation of the statement 'all the other worlds are equally real' where what is meant by world is what is called history here even if it consists only of an alternative at one time.

the statement could be rephrased as ‘quantum mechanics does not distinguish between the histories in a given realm except by their probabilities’. Indeed, using the word ‘real’ in this sense, it would be possible to correctly say that ‘all the realms of quantum theory are equally real’. This could be similarly rephrased as ‘quantum theory does not distinguish between different realms’. In each case, the first statement can be replaced by the second without affecting the predictions of the theory for experiment. The second formulations are easier to understand for many physicists. But all these statements are dispensable as the exposition of quantum theory given in this paper shows.

Deutsch [25] especially has stressed the naturalness and interpretative value of the equal status of histories in a given realm, for instance, for understanding the power of quantum computation. Such advantages, however great, do not alter that fact that words like ‘all the other histories are equally real’ can be dispensed with without affecting the experimental implications of the theory.

As discussed in section 4, the linguistic difficulty with using the word ‘real’ is that it can mean different things in different circumstances even in physics. Maintaining that ‘all the histories in a set are equally real’ risks confusion unless the meaning of ‘real’ is explained. The author’s experience is that otherwise it can be confused with the everyday physical reality discussed in section 4.1. The resulting conflict can be an obstacle for some to accepting Everett’s powerful and natural idea of taking the state of the universe seriously.

6. Advice

The aim of fundamental physics is to find the laws governing the regularities exhibited universally by *all* physical systems, without exception, without qualification and without approximation. The search for these laws has been seriously underway at least since the time of Newton. Classical mechanics, Newtonian gravity, Maxwell’s electrodynamics, the atomic theory of matter, special and general relativity, quantum field theory, superstring theory, the quantum theory of geometry and quantum cosmology are just some of the milestones in the history of this search. As new regimes of experiment and observation have been explored, more general theoretical frameworks have evolved. Old theories have become effective theories applicable in limited circumstances of the extended context.

Excess theoretical baggage is typically shed in this process of generalization [26]. Ideas that were once accepted as fundamental, general, and inescapable have come to be seen as consequent, special and dispensable. Examples from the history of physics are an Earth centred cosmology, a single universal time, an exact second law of thermodynamics, fixed Euclidean spatial geometry, and a quantum mechanics restricted to measurements. These ideas were not true general features of the world, but only perceived to be general because of our special universe, our special place in it, and the limited range of our experience.

Over this history, the models provided by fundamental physical theory have moved far beyond our everyday notions of physical reality¹⁷. The evolution of physical theory beyond everyday notions of physical reality has complicated its description using a human language that is adapted to that everyday reality. That has been the subject of this essay.

¹⁷ Excess baggage in the language of physics is also typically shed in the process of extension and generalization of physical theory. Indeed, the relationship between the languages of two effective theories often presents problems similar to those between the human language and the language of physics that we have discussed. For example, applying the language of classical physics to quantum-mechanical situations can lead to paradoxes which can be resolved by sticking to the language of quantum theory [4, 27]. By and large, however, these physics linguistic problems have not caused much difficulty and, in any event, are not the subject of this essay.

By way of conclusion the author offers a few words of advice on routes to clarity in the face of the disparity between the languages of fundamental physics and that of human IGUSes. This advice is not directed to how to *find* a fundamental theory. Rather it is only about how to deal with the conflicts with human language that may arise.

- *Identify theoretical excess baggage.* Remember that ideas that were fundamental and obvious in one theory can become emergent and dispensible in a more general one. The idea that there is a unique past, present and future defined by physics is one example that we have discussed. Another is the idea that there should be a unique theoretical reality specified by one decoherent set of alternative fine-grained histories rather than many different ones that may be incompatible and yet fit into a consistent theoretical framework.
- *Identify linguistic excess baggage.* Remember that human language can contain tacit assumptions that reflect the limited context in which it evolved. We have discussed examples associated with ‘to happen’ and ‘reality’. Linguistic excess baggage can be dispensed with in favour of the more precise language of physics. *To clearly discuss quantum theory, learn to speak the language of quantum mechanics.* Alternatively linguistic excess baggage can be qualified so that tacit assumptions become explicit.
- *Identify dispensible language.* Remember that an exposition of a theory can contain language that can be dispensed with without affecting its experimental predictions. Examples are the use of ‘to happen’ to qualify probabilities and the use of ‘all equally real’ to qualify sets of histories. The author often finds it useful to drop dispensible language in introducing quantum theory. That is especially the case if the audience carries its own linguistic baggage which conflicts with the dispensible language making it an obstacle to understanding and acceptance. However, do not forget that adding interpretative but dispensible language can be an important route to insight, motivation and understanding. Either way, it is important to recognize when language is dispensible and when it is not. In arguments concerning the interpretation of the theory one then understands which statements are experimentally verifiable and which are not.
- *Beware of introspection.* Remember that human beings are physical systems in the universe that have a long, specific, evolutionary history. That evolution is consistent with the universal laws of physics. But the present nature of these IGUSes has far more to do with the frozen accidents of their evolution than with those fundamental laws. As a consequence, introspection is unlikely to be a good guide to their character. That is especially the case if introspection is seen to require precise representations in the fundamental theory for constructions of the human language. To take an extreme example, some have concluded from the strong impression of ‘now’ held by human IGUSes that the fundamental theory *must* incorporate it despite the overwhelming body of experimental evidence against preferred frames with figures of merit approaching 10^{-21} [28], and despite the possibility of constructing IGUSes which do not prefer the present [10]. Rather, ‘now’ can be seen as a feature of how certain IGUSes process temporal information as described in section 2.
- *Beware of agendas.* Remember that the basic criteria for physical theory are logical consistency and consistency with experiment. Agendas for physical theory motivate research as in the quest for unification or a selection principle that would distinguish one realm from all others [22, 29]. But if a theory that is logically consistent and consistent with experiment disagrees with your agenda that should not be called a problem for the theory, it is more likely to be a problem with your agenda.

It seems likely that there are limits to quantum theory and the validity of its principle of superposition as there have been for every other candidate for a fundamental theory to date. The remarkable fact about the history of this most successful of all physical theories is that, despite the limited range over which it has been experimentally verified, there are no alternative theories that are consistent with these experiments, consistent with the rest of modern physics, but which differ their predictions in domains not yet tested. As Steve Weinberg puts it: ‘It is striking that it has not so far been possible to find a logically consistent theory that is close to quantum mechanics other than quantum mechanics itself’ [30].

Alternatives to quantum theory would be of great interest if only to guide experiment. Given the trend in the development of fundamental theory, it is very possible that the disparity between human language and the language of fundamental physics will increase as quantum theory is replaced or extended. If that is the case, careful analyses of the relationship between human language and the language of physics of the kind sketched all too superficially in this essay will be increasingly important for clarity of understanding.

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Appendix. The quantum mechanics of a closed system

This appendix gives a simplified, bare-bones account of some essential elements of the modern synthesis of ideas constituting the quantum mechanics of closed systems [3–5] using the model closed box described in section 3.1.

Realms

The most general objective of a quantum theory of a closed system is the prediction of probabilities for the individual members of exhaustive sets of coarse-grained alternative time histories of the system. For instance, we might be interested in alternative histories of the centre of mass of the Earth in its progress around the Sun, or in histories of the correlation between the registrations of measuring apparatus and a measured subsystem. Alternatives at one moment of time can always be reduced to a set of yes/no questions. For example, alternative positions of the Earth’s centre 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 is represented in the Heisenberg picture by an exhaustive set of orthogonal projection operators $\{P_\alpha(t)\}$, $\alpha = 1, 2, 3, \dots$. These satisfy

$$\sum_{\alpha} P_{\alpha}(t) = I, \quad \text{and} \quad P_{\alpha}(t)P_{\beta}(t) = \delta_{\alpha\beta}P_{\alpha}(t) \quad (\text{A.1})$$

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

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

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

An important kind of set of histories is specified by a series of sets of alternatives $\{P_{\alpha_1}^1(t_1)\}, \{P_{\alpha_2}^2(t_2)\}, \dots, \{P_{\alpha_n}^n(t_n)\}$ at a sequence of times $t_1 < t_2 < \dots < t_n$. 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, etc¹⁸. An individual history c_α in such a set is a particular sequence of alternatives $(\alpha_1, \alpha_2, \dots, \alpha_n) \equiv \alpha$ and is represented by the corresponding chain of projections called a *class operator*

$$C_\alpha \equiv P_{\alpha_n}^n(t_n) \cdots P_{\alpha_1}^1(t_1). \quad (\text{A.3})$$

Such a set of histories is generally *coarse-grained* because alternatives are specified at some times and not at every time, and because the alternatives at a given time are projections onto subspaces with dimension greater than one and not projections onto a complete set of states. *Fine-grained* sets of histories consist of one-dimensional projections at each and every time.

Operations of fine- and coarse-graining may be defined on sets of histories. A set of histories $\{c_\alpha\}$ may be *coarse-grained* by partitioning it into exhaustive and exclusive classes $\bar{c}_{\bar{\alpha}}, \bar{\alpha} = 1, 2, \dots$. Each class consists of some number of histories in the finer-grained set, and every finer-grained history is in some class. Suppose, for example, that the position of the Earth's centre of mass is specified by dividing space into cubical regions of a certain size. A coarser-grained description of position could consist of larger regions made up of unions of the smaller ones. *Fine-graining* is the inverse operation of dividing sets of histories up into smaller classes. The class operator $\bar{C}_{\bar{\alpha}}$ for a history in a coarse-graining of a set whose class operators are $\{C_\alpha\}$ is related to those operators by summation, namely

$$\bar{C}_{\bar{\alpha}} = \sum_{\alpha \in \bar{\alpha}} C_\alpha \quad (\text{A.4})$$

where the sum defining $\bar{C}_{\bar{\alpha}}$ for the class $\bar{c}_{\bar{\alpha}}$ is the sum over the C_α for all finer-grained histories contained within it.

For any set of histories $\{c_\alpha\}$, there is a *branch state vector* for each history in the set defined by

$$|\Psi_\alpha\rangle = C_\alpha |\Psi\rangle. \quad (\text{A.5})$$

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

$$p(\alpha) = \|\Psi_\alpha\|^2 = \|C_\alpha |\Psi\rangle\|^2. \quad (\text{A.6})$$

However, quantum interference prevents consistent probabilities from being assigned to every set of alternative histories that may be described. The two-slit experiment provides an elementary example: an electron emitted by a source can pass through either of two slits on its way to detection at a farther screen. It is not possible to consistently assign probabilities to the two histories distinguished by which slit the electron goes through. Because of interference, the probability to arrive at a point on the screen would not be the sum of the probabilities to arrive there by going through each of the slits. In quantum theory, probabilities are squares of amplitudes and the square of a sum is not generally the sum of the squares. On the other hand, if other interactions of the electron destroy the interference between the two histories (as when a measurement determines which slit it passes through) then probabilities can be consistently assigned.

¹⁸ In general realistic sets of histories will be *branch dependent* with sets of projections at a given time depending on the particular sequence of previous alternatives, but we ignore this in the present simplified exposition.

Negligible interference between the branches of a set

$$\langle \Psi_\alpha | \Psi_\beta \rangle \approx 0, \quad \alpha \neq \beta \quad (\text{A.7})$$

is a sufficient condition for the probabilities (A.6) to be consistent with the rules of probability theory. Specifically, as a consequence of the decoherence condition (A.7), the probabilities (A.6) obey the most general form of the probability sum rules

$$p(\bar{\alpha}) \approx \sum_{\alpha \in \bar{\alpha}} p(\alpha) \quad (\text{A.8})$$

for any coarse-graining $\{\bar{c}_{\bar{\alpha}}\}$ of the $\{c_\alpha\}$. Sets of histories obeying (A.7) are said to (medium) decohere¹⁹. These are sets for which quantum mechanics makes predictions. They are determined through (A.6) by the Hamiltonian H and the quantum state of the universe $|\Psi\rangle$. We use the term *realm* as a synonym for a *decoherent set of alternative coarse-grained histories*.

A coarse-graining of a decoherent set is again decoherent. A fine-graining of a decoherent set risks losing decoherence. An important mechanism of decoherence is the dissipation of phase coherence between branches into variables not followed by the coarse-graining. Consider by way of example, a dust grain in a superposition of two positions deep in interstellar space [35]. In our universe, about 10^{11} cosmic background photons scatter from the dust grain each second. The two positions become correlated with different, nearly orthogonal states of the photons. Coarse-grainings that follow only the position of the dust grain at a few times therefore correspond to branch state vectors that are nearly orthogonal and satisfy (A.7). The orthogonality is approximate but in realistic situations sufficient to define consistent probabilities well beyond the standard to which they can be checked or, indeed, the physical situation modelled [36].

Measurements and observers play no fundamental role in this general formulation of quantum theory. Measurement situations can, of course, be described [36, 37]. In a typical measurement situation, one subsystem of the universe (the measured subsystem) interacts with another (the apparatus). A variable of the measured subsystem, not otherwise decohering, becomes correlated with a variable of the apparatus which decoheres because of its interaction with the rest of the universe. The correlation thus effects the decoherence of the measured variables so that probabilities can be predicted for its values. With suitable idealizations and assumptions, probabilities for the measured outcomes are given to an excellent approximation by usual textbook quantum theory. But, in a set of histories where they decohere, probabilities can be assigned to the position of the Moon when it is not receiving the attention of observers and to the values of density fluctuations in the early universe when there were neither measurements taking place nor observers to carry them out.

The probabilities of the histories of the possible *decoherent* sets of coarse-grained histories and the conditional probabilities constructed from them are the totality of predictions of the quantum mechanics of a closed system given the Hamiltonian H and initial state $|\Psi\rangle$.

Incompatible realms

Coarse-graining is generally necessary for decoherence. There are only trivial decoherent sets of completely fine-grained histories [21].

¹⁹ For a discussion of the linear positive, weak, medium and strong decoherence conditions, see [31–33]. However, as L Diósi has shown [34], medium decoherence is the weakest of this chain that is consistent with elementary notions of the independence of isolated systems.

A completely fine-grained set of histories can be coarse-grained in many different ways to yield a decoherent set whose probabilities can be employed in the processes of prediction and retrodiction. Further, there are many different completely fine-grained sets to start from corresponding to the different possible choices of one-dimensional projections at each time arising from different complete sets of commuting observables. Once coarse-grained enough to achieve decoherence, further coarse graining preserves it. Some decoherent sets can be organized into families connected by the operations of fine and coarse graining. Such sets are said to be *compatible*.

Realms for which there is no common finer-grained decoherent sets are *incompatible*. We may not draw inferences by combining probabilities from incompatible realms²⁰. That would implicitly assume that there are the probabilities of a finer-grained description which is not available. Incompatible realms provide different descriptions of the universe. All of the totality of incompatible realms are necessary to give a complete account of the universe because they are, in principle, equally available for exhibiting regularities and constructing explanations. Quantum theory does not distinguish one of these realms over another without further criteria.

Incompatibility is not inconsistency in the sense of making different predictions for the same history. The probability of a history c_α is given by (A.6) in all the realms of which it is a member.

Quasiclassical realms

While quantum theory permits a great many incompatible descriptions of a closed system by different realms, we as human observers utilize mainly realms that are coarse-grainings of one family of compatible sets—the quasiclassical realms of everyday experience. These are the sets of decoherent histories whose probabilities manifest the classical regularities of the universe that are exploitable in our various pursuits, in particular, to get food, reproduce, avoid destruction and achieve recognition. These are the sets of histories defined by quasiclassical alternatives which our perception is adapted to distinguish.

Quasiclassical realms are defined as coarse-graining specifying ranges of values of the variables of classical physics. These include the averages over small volumes of approximately conserved quantities such as energy, momentum and various kinds of particle species. We call such variables *quasiclassical variables*. The useful properties of quasiclassical realms follow from the approximate conservation of the variables that define them. In particular quasiclassical realms exhibit correlations in time governed by the approximate deterministic laws of motion of classical physics. In our quantum universe, classical laws are applicable over a wide range of time, place, scale and epoch.

More specifically, by a *quasiclassical realm* we mean an exhaustive set of mutually exclusive coarse-grained alternative histories, that obey a realistic principle of decoherence, that consist largely of related but branch-dependent projections onto ranges of quasiclassical variables at a succession of times, with individual histories exhibiting patterns of correlation implied by closed sets of effective equations of motion subject to frequent small fluctuations and occasional major branchings (as in measurement situations). By a *family of quasiclassical realms* we mean a set of compatible ones that are all coarse grainings of a common one. Thus defined, the quasiclassical realms are a feature of our universe that arise from its quantum state and dynamics which we are adapted to exploit [21].

²⁰ As the work of R Griffiths [4] especially has shown, essentially all inconsistencies alleged against consistent histories quantum mechanics arise from violating this logical prohibition.

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