



# Quanta and Qualia

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## Abstract

I sketch a line of thought about consciousness and physics that gives some motivation for the hypothesis that conscious observers deviate—perhaps only very subtly and slightly—from quantum dynamics. Although it is hard to know just how much credence to give this line of thought, it does add motivation for a stronger and more comprehensive programme of quantum experiments involving quantum observers.

**Keywords** Quantum theory · Consciousness · Bell experiments · Beables

## 1 Introduction

I describe below my current stances on consciousness and its relationship to physics, which have been strongly influenced in particular by James [1]. Briefly, I am among those persuaded that there is a hard problem of consciousness, and that in Chalmers' terms it appears to be strongly emergent [2] from, or in other words inexplicable by, the currently understood laws of physics. This means I reject the counter-view that consciousness is a weakly emergent consequence of brain activity—that is, a consequence that may initially seem surprising but in principle is entirely explicable by aspects of neuroscience that are reducible to known physical facts and laws.

One strong reason for doing so is that a complete scientific model of consciousness appears to require, among other things, some sort of data selection principle, characterising the subset of information about material substrates of consciousness (such as our brains) that has correlates in conscious states (such as our conscious minds). The known laws of physics are not of a type that allows any such principle to be derived. I enlarge on this below. Another way of framing the essential point is the conceivability argument for the logical possibility of a consciousness-free universe,

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materially identical to ours and following the same known laws of physics, but inhabited by “philosophical zombies” [3,4] who act as we do but are aware of nothing; I find this equally persuasive. A further compelling argument is the knowledge argument [5,6]: someone can have knowledge of all the known facts about and laws governing the material world and yet, in the absence of first-hand experience, not know what particular types of experience are like.

The scale of the explanatory gap between the known laws of physics and conscious experience seems most evident to me when we take a cosmological perspective and consider consciousness in the context of Darwinian evolution. Our consciousnesses seem very well designed to maximize our survival chances; they also seem designed to allow us to report and discuss our conscious states with others. None of this appears explicable by the known laws of physics [1,7].

Of course, these positions are all highly debatable and have been criticised and defended by many. ( See e.g. Refs. [2,4–12] and references therein for some expositions and reviews.) My goal here is not to make new cases for them. Nor do I want to suggest that they necessarily imply that there must be new physical laws explaining every aspect of consciousness. Consciousness poses formidable problems for physics, including explaining the brute fact of its existence, qualitative and quantitative aspects of conscious experience, the relationship between consciousness and matter, the evolutionary or cosmological origins of consciousness, and the evolution of human consciousness from some presumably primitive form. It is not clear that any of the standard positions on consciousness (e.g. [3,13]) is necessarily the right starting point for resolving all these problems, nor does it seem realistic to expect any new proposal to tackle them all at once.

This leaves a risk of succumbing to a form of learned<sup>1</sup> helplessness, given a voluminous literature in which every plausible argument is opposed by plausible counterarguments and every interesting position has potentially insurmountable difficulties. A better alternative than intellectual paralysis may be to accept our present framings of the problems may be conceptually inadequate and to look for lines of thought that might suggest different ways of thinking about the relationship between physics (as presently understood) and consciousness.

I suggest here that, in particular, current developments in the foundations of physics could suggest possible ways of acquiring new empirical evidence about the relationship between physics and consciousness. First, I will sketch in a bit more detail the stances summarised above, and then try to say something about their potential implications for quantum theory and experimental tests involving conscious observers.

1. Consciousness—the collection of perceptions, sensations, thoughts, emotions, thoughts about perceptions, and so on, that we experience—is a natural phenomenon. We say something about the world when we say that we are conscious, just as we do when we say that the Earth is roughly round and that solid objects tend to fall towards it. Saying that an individual’s brain runs algorithms that include models of the individual, or that their body tends to respond in a relatively predictable way to stimuli, also says something about the world—but it does not say or logically imply anything about their consciousness, including its existence.

<sup>1</sup> in both senses of the term

2. One of the main goals of physics is to give compressed descriptions of natural phenomena.<sup>2</sup> Physical laws reduce a very large set of data to a much smaller set. For example, Newton’s laws of gravity and of motion not only characterise and quantify how and when solid objects fall towards the Earth, but give us a unified description that includes the large-scale behaviour of liquids and gases, the motion of celestial and terrestrial bodies, and laws governing tides and atmospheres. So it is a reasonable ambition for physics to look for a compressed, lawlike description of consciousness.
3. The only certain examples we have, our brains and nervous systems, suggest that consciousness is intimately bound up with the properties of matter. So a reasonable ansatz, or starting point, for a lawlike description of consciousness would be a relatively compressed set of rules from which we can infer that when a physical system is in state  $S$  its consciousness is in state  $C(S)$ . We certainly want to allow that  $C(S)$  may be empty, since we don’t want to assume that every physical system is conscious.<sup>3</sup> We should also allow for the possibility of a physical system having more than one separate consciousness, since a human family or a city appear to be examples, and perhaps even a single human or animal brain can be. So really we should say “its consciousness is in state  $C(S)$ , or its consciousnesses are in states  $C_i(S)$  for a list  $i$  in some index set  $I(S)$ ”. For brevity we leave this implicit below.
4. By the admittedly high standards of successful laws of physics, we don’t have any remotely satisfactory lawlike description of consciousness. We can say the waking human brain is generally conscious, and that specific types of consciousness—visual imagery, or smell, or formulating speech—are associated with activities in various regions of the brain (generally many such regions for any given activity). These seem like raw observational data that any theory should aim to explain. Perhaps, more charitably, they could also be seen as steps towards high level laws in a high level description, which should eventually be superseded by more fundamental laws. In physical terms they seem roughly comparable to the observations that stones fall to the ground, birds go up in the air when they flap their wings hard and clouds tend to float around in the sky. That is, they are generally true, though slightly vague, statements about quite complex physical systems. The history of physics encourages us to try to describe the underlying phenomena better—more completely, more simply, more precisely—by formulating simple and precise mathematical laws governing a smaller range of more elementary objects or quantities.<sup>4</sup>

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<sup>2</sup> Some might say this is *the* goal of physics.

<sup>3</sup> Nor do we want to exclude this possibility.

<sup>4</sup> This remains true even if one believes that some properties of consciousness are necessarily beyond the possible scope of physical explanation, so long as one accepts that there are at least *some* aspects that could be characterised by simpler laws. For example, one might consistently believe there is no hope for a physical explanation of the nature of the sensory experience of seeing red, and still hope for simpler laws characterising when a physical system is conscious, or conscious of images, or even conscious of redness, and perhaps even for laws quantifying some information theoretic measures of its consciousness. The history of physics encourages us to try to formulate mathematical descriptions for those aspects of natural phenomena that appear as though they may allow this, even if other aspects presently resist description. For example, investigating the biomechanics and neurology of animals was worthwhile even in an era where there seemed no obvious prospect of understanding the nature or origin of life.

5. The sort of law suggested so far is consistent with consciousness being an epiphenomenon [7,12], that is, having physical causes or correlates but no effects on the material world. Suppose that the laws of physics are complete, or complete enough to describe physics in many regimes, including the behaviour of matter on Earth. Or at least that they are completable, in the sense that there is an as yet undiscovered unified theory  $T$  of the sort physicists conventionally imagine. That is, one that includes quantum theory and gravity, and fully describes the dynamics of matter, fields and spacetime, perhaps also including a theory of initial conditions and/or other constraints—but which makes no reference to consciousness. And suppose, just to simplify the language of the discussion, that  $T$  allows a sort of effective reductionism in many contexts, so that with appropriate modelling, which in principle can be justified from the fundamental principles of  $T$ , we can describe physical systems  $S$  interacting with their environment  $E(S)$ , modelled in a way derived from the laws of physics encapsulated in  $T$ . In shorthand, we say such systems  $S$  follow the laws of physics given by  $T$ . Now, some of these physical systems  $S$ —human brains, for example—have associated non-empty consciousnesses  $C(S)$ . But by (conventional) hypothesis,  $S$  follows the laws of physics given by  $T$  whatever the form of its consciousness  $C(S)$ . We don't need to know anything about  $C(S)$  to predict the physical behaviour of  $S$ , or any of its physical properties (other than those of  $C(S)$  itself). Indeed, we don't even need to be aware of the phenomenon of consciousness in order to predict the physical behaviour of  $S$ . On the view given so far, then, a complete understanding of the physics of  $S$  involves understanding  $T$ , deriving the predictions that  $T$  makes for  $S$ , and then adding, as an extra interesting detail, that  $S$  has a particular (maybe empty) form of consciousness  $C(S)$ . This detail is generally time-dependent, our experiences tell us: as the physical state of  $S$  changes over time, the consciousness  $C(S)$  generally also changes.<sup>5</sup>
6. However, if consciousness is an epiphenomenon, and its epiphenomenal association with the material world is described by simple laws, then it is very hard to understand how and why we evolved to have rich consciousnesses that contain a great deal of data highly relevant to our survival. Darwinian evolution takes place in the material physical world. If consciousness hitches a free ride on that world, then there is no particular need *a priori* for evolutionarily successful creatures to be conscious [1]. Even if they are, there is no need for their consciousnesses to contain data relevant to survival. We could equally well be agilely escaping a tiger while conscious of nothing, or aware only of the fermion numbers of our patellae, or any other physical variables associated with our material selves. On the epiphenomenal view of consciousness, the laws of physics encoded in  $T$  are all that is relevant to our body and brain functions during the escape; they are also all that is

<sup>5</sup> Quite what sort of time-dependent story about  $C(S)$  should emerge for conscious spatially extended objects  $S$  is very unclear. It seems as though  $C(S)$  should be associated with the worldtube of  $S$  rather than any fixed worldline, and then it seems that neither proper time or any other single time parameter is adequate to characterise the dependence of  $C(S)$ . Given that our only empirical examples, our own consciousnesses, seem (?) to be associated with a single time parameter, even though our brains occupy appreciable spatial regions, we have no real basis for speculating further about more general possibilities. We thus tentatively file this under “questions that might one day be addressable if there is real progress on a physical theory of consciousness”.

relevant to describing the evolution of those body and brain functions over aeons that include successful and tragic encounters with tigers by earlier generations. All that we need to explain our evolved traits is that our direct ancestors tended to be over-represented in the successful encounters (et cetera).

7. It is also very hard to understand how, if consciousness is purely an epiphenomenon, we can talk about the contents of our conscious minds, listen to ourselves doing so, and feel that we accurately represented ourselves [14].
8. As if these problems for the epiphenomenal view of consciousness were not devastating enough, they can be sharpened further [1]. Not only do our consciousnesses contain a great deal of information about the world relevant to our survival, but the information is associated with qualitative types of experience that seem designed to encourage evolutionarily advantageous behaviour. It seems to be logically possible, and arguably even natural, to think of epiphenomenal consciousnesses as value neutral—simply registering aspects of the exterior and interior world without associating any form of judgement on them. Indeed, some aspects of our own consciousnesses seem to be close to neutral. For example, we feel that many—though by no means all—visual images give us data without associating much aversion or attraction. However highly pleasant and unpleasant sensations, pleasures and pains, play very significant roles in our conscious lives. Moreover, these roles *seem* to be important to our survival. By and large, the pleasures seem associated with evolutionarily advantageous activities (food, drink, friendship, bonding, raising of status, sex, . . .), and the pains with disadvantageous ones (raging thirst, injury, lowering of status, rejection, . . .). Yet, on an epiphenomenal view, there seems no possibility of an evolutionary explanation for these correlations. Evolution of our material selves explains that the laws of physics encoded in  $T$  caused our brains and bodies to tend to seek out evolutionary advantageous activities and avoid disadvantageous ones. It does not then matter whether our epiphenomenal consciousnesses find the former pleasurable and the latter painful, or vice versa.
9. So, consciousness is not an epiphenomenon.<sup>6</sup>

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<sup>6</sup> Or else the laws of physics and the laws of epiphenomenal consciousness were apparently designed together to give us the false and useless but pleasing sense of being in conscious control of our actions. I find it hard to take this possibility seriously. Epiphenomenalism *per se* does have advocates [7, 12]. However, the relevant position here is stronger than standard epiphenomenalism. It is that there are succinct physical laws *and* separate succinct laws describing how the contents of consciousnesses are connected epiphenomenally to their material substrates, and that the second types of law just happen to imply that consciousnesses have the sense of controlling evolutionarily relevant behaviour in evolutionarily favourable ways, even though in fact all the relevant behaviour is already physically determined. Since almost all succinct epiphenomenal laws that one could imagine do not have this property, and all of them are equally logically consistent, this seems to me entirely implausible.

It is worth adding here that even a very slight causal effect of consciousness on the material world—if we could make sense of such a hypothesis—could allow the possibility of countering this specific objection. This is not because it would make it true that we are in conscious control of our actions in the pleasing but naive way that we tend to intuit: a very small effect would presumably not make much difference to this. However, it might leave room for an explanation of how the sense of conscious control and the associated causal physical mechanisms could have co-evolved, over the history of life on Earth, through the slow accumulation of small effects.

## 2 Backward or Onward?

At this point, one really needs to pause and take a breath, because the terrain is not going to become easier if one presses further. Following the logic of the argument so far, there should be a physical theory of consciousness, but it should not be an epiphenomenal theory. But are there any other coherent options? And even if there might possibly be, how could they do any better in explaining the puzzles of the evolution of consciousness? Even if one is willing to dream up equations somehow trying to characterize a dynamical interaction between conscious states and familiar material physical states, would they not necessarily work equally well if we relabelled painful states as pleasurable and vice versa?

When an argument runs into such difficulties, one should question one's premises. Perhaps the whole line of thinking about consciousness we have set out is just misguided? Perhaps one of the other standard lines of thought<sup>7</sup> is more promising after all? Well, perhaps. A review is beyond my scope here. But I'm not convinced: it seems to me they also end up either falsely<sup>8</sup> denying any possibility of scientific progress on the hard problem or creating insoluble puzzles of their own.

At the very least, it is clear from the literature that each position on consciousness finds thoughtful critics who believe they can identify deep problems. If every line of thought runs into deep problems, one should arguably pursue the one that offers most hope of bringing new data. I will now argue that the one I have set out does at least suggest the possibility of experimental progress on the problem of consciousness, and with that, the possibility of saying at least something more about how consciousness evolved. I don't see how to take it far enough to sketch any plausible conjecture about a satisfactory solution to the problem of pain and pleasure. Still, even a small chance of experimental progress is worth pursuing, especially given the huge implications. And if there is experimental progress, perhaps it will bring conceptual and theoretical progress, in the new light of which these puzzles might seem less daunting.

People must, I imagine, once have thought it pointless to ask why stones always fall, birds sometimes fly, and clouds generally float in the sky. Those were just part of the definition of stones, birds, and clouds. It must have seemed useless to such people to speculate that we might be able to understand all this falling, flying and floating better if stones, birds, clouds and everything else in the natural world turned out to be made up of smaller constituents. After all, even if they were, it must have seemed that we would just be left asking essentially the same question: why do stone-constituents fall (at least when assembled into stones) whereas bird-constituents sometimes fly (at least when assembled into birds), and so on. In a sense, on this last point, they were right. Even now, we *do* still ask why the laws of general relativity and quantum theory hold and not others. But even if the essence of the question is in some sense still the same, its form has changed as our understanding developed, from an obstinate gatekeeper seemingly preventing progress to a faithfully helpful guide along the long path to modern physics.

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<sup>7</sup> See the references cited above for discussions.

<sup>8</sup> I claim "falsely" is a statement of fact, not opinion. Whether they are right or wrong, the sort of ideas sketched in this paper show that there *could* be a testable scientific theory of consciousness.

So, let us continue.

### 3 Quanta and Qualia

#### 3.1 Quantum Theory and the Brain

The hard problem of consciousness was a problem when we believed the world was described by classical physics.<sup>9</sup> It may still be a problem if and when quantum theory and general relativity are superseded. There is no compelling reason of principle to believe that quantum theory is the right theory in which to try to formulate a theory of consciousness, or that the problems of quantum theory must have anything to do with the problem of consciousness.

That said, physics is where it is. Quantum theory is our best current fundamental theory. It works extremely successfully in describing microscopic physics and some aspects of macroscopic physics. But it still has problems. One is the long-standing problem of finding some description of objective reality consistent with quantum theory.<sup>10</sup> Another is that we cannot rigorously define physically relevant field theories in four dimensions, even in Minkowski space. And, of course, we do not know how to unify quantum theory and general relativity.

In summary, despite all quantum theory's successes, there are still reasons to question whether it completely describes all of physics. So, let us start by supposing that quantum theory applies pretty well to systems like human brains. However, let us keep an open mind on whether it captures absolutely everything that physics can say about them—since this has certainly not been well tested—and see where this takes us.

#### 3.2 Qualia

According to one popular line of thought (see e.g. [4,15,16]) our consciousnesses can be thought of as composed of very large numbers of individual sensation-components, or qualia. The analogy here is with (what was once) the atomic hypothesis: that matter, in all its rich variety, can be understood as composed of various types of elementary objects, atoms, in various proportions and combinations. Modern chemistry eventually led to the classification of the elements, and hence the elementary atoms, and to the postulated understanding of (macroscopic terrestrial) matter as combinations of atoms. Similarly, one might think, visual perceptions can maybe be understood as

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<sup>9</sup> This is meant as an intellectual point, not a historical statement about discussions of consciousness. The term “hard problem” was coined by Chalmers 1995 [4,8]. Many earlier discussions of the mind-body problem cover some of the same ground as Chalmers; the intellectual history is reviewed in Ref. [4] and the other general references cited earlier. However, regardless of how precisely it was recognised, by whom, or when, the problem *existed* in the era of classical physics. To put it another way, if we believed today that the world were described by classical physics, we should still be discussing the hard problem. It is possible that quantum theory may ultimately shed new light on consciousness, or vice versa. It is even possible that at a fundamental level the formulation of quantum theory might turn out to require consciousness as a physical primitive. But it is not the case that quantum theory introduced the hard problem into physics.

<sup>10</sup> Of course, this too is keenly debated. For some reviews and discussions, see for example Refs. [33–36].

some combination of a finite number of colour and relationship qualia, emotions as combinations of finitely many elementary emotional qualia, and so on.

There is absolutely no evidence in favour of this qualia-as-atoms-of-consciousness model. If consciousness is indeed something that can be modelled in any scientifically familiar way, it could be as a field, or a manifold. It could also, of course, be that there is some mathematical model that looks nothing like anything we have encountered in physics so far. Still, if we are going to speculate about the relationship of consciousness to the rest of physics at all, we need some language, and the qualia model gives a useful way of thinking about how a connection might be made. So we will use it, while emphasizing that our tentative conclusions are meant to apply more generally. The same fundamental questions arise whether consciousness is built from atomic qualia or described by some other quantities. And, importantly, the same conclusions follow.

### 3.3 Qualia from Quantum States: A Cartoon

Whatever our consciousnesses are, they are almost certainly not identical to the physical states that give complete descriptions of our brains. Even on a classical description, the vast majority of the information encoded in a configuration space description of the brain's physical state does not appear to be carried by the associated consciousness. This is true even of the highly coarse grained descriptions that arise in a higher level neuroscientific model of the brain. For example, we are not aware of whether or not neurons only involved in governing unconscious processes are firing, nor are we aware of most of the complex sequences of firings that produce conscious images.

The brain contains roughly  $10^{11}$  neurons, firing on average roughly  $10^2$  times per second, giving roughly  $10^{13}$  discrete signals per second. At a finer physical level, it contains about  $10^{26}$  atoms, and tracking their coordinates (in a classical model) would require  $10^{78}$  independent parameters. As far as we can measure it, the bit rate of information needed to describe our conscious states of mind is far smaller than these numbers. For example, lexical decision tasks may take us only of the order of 100 bits per second of information processing [17], not all of which is conscious. The number of details we can attend to per second in visual images also appears relatively small in comparison. For example, recognizing one object drawn from a class of  $\approx 10^5$  takes us of order 100 ms [18].

Admittedly, we cannot be at all precise on this point without a precise description of the range of possible conscious mind states. Perhaps our emotional spectra are far richer than we generally credit. Introspection cannot be precisely calibrated. We cannot definitively refute the hypothesis that conscious mind states are described by more than  $10^{13}$  binary parameters or even more than  $10^{78}$  continuous parameters, nor that every neuron firing or even every atom moving in the brain subtly modulates our conscious state. But these seem very unlikely: most of these parameters seem to be irrelevant to describing consciousness, since most microscopic details of the brain's structure and operation do not seem to have conscious correlates. So I will take it as a reasonable working hypothesis that very many different complete brain states appear to map to the same conscious mind state, and that we can reasonably model possible



human conscious mind states, as they evolve in time, by significantly fewer than  $10^{13}$  discrete signals per second.<sup>11</sup> If so, any physical theory of consciousness must involve, among other things, a great deal of data selection.

Perhaps we can model this as a *data selection principle*: some rule that maps the large amount of information contained in a parametrised description of the complete physical state of the brain to a smaller amount of information contained in a hypothetical parametrised description<sup>12</sup> of the contents of the associated conscious mind.

I am not sure that anyone currently has any compellingly plausible idea as to how this might work in any detail.<sup>13</sup> Certainly I don't. So let me instead give a cartoon: not an idea to be taken seriously, but an illustration of the sort of thing that would count as a data selection principle. Suppose that nature has fixed a cubic lattice with a certain scale  $L$ , where  $L$  is larger than a small molecule and maybe not much larger than a neuron.<sup>14</sup> Suppose that nature is described by some version of quantum theory in which collapses are objectively defined localized events in space-time—for example, some versions of Copenhagen quantum theory, or a dynamical collapse model. Suppose moreover that this version of quantum theory allows us to define a wave function on any given spacelike hypersurface, from some theory of the initial conditions. Suppose also that it allows us to define local density matrices in a spatial region by tracing out from the wave function the degrees of freedom corresponding to other regions of a spacelike hypersurface in the limiting case where that hypersurface tends to the past light cone of a region.<sup>15</sup> We then take the expectation value of the mass density defined by the local density matrix describing the quantum state of matter within each volume  $L^3$  cube as one component of a primitive physical ontology, which describes physical states to which conscious mind states may be attached. We update these density matrices at each time interval  $L/c$ , supposing that nature has also fixed a one-dimensional lattice in time.

We suppose further that conscious mind states are composed of combinations of elementary qualia, which supervene on the physical ontology in a lawlike way. Specifically, we suppose there is some local rule according to which a quale  $Q_j$  is associated with the cube  $C$  at discrete time point  $T$  provided that the configuration of local density

<sup>11</sup> Precise measures of information would need a probability distribution on the set of possible states. In principle, we could get some probability distribution on human brain states from neuroscientific models derived from observational data in typical environments. We could also get an upper bound on the information contained in conscious mind states, if the set of such states is finite, by assuming they are equiprobable.

<sup>12</sup> We give a cartoon of such a description below just to illustrate one way to begin thinking about possibilities.

<sup>13</sup> Some noteworthy discussions of the relationship between consciousness and physics include Refs. [23,37–39].

<sup>14</sup> Any readers who want to pay this crude cartoon the honour of worrying about its consistency with special relativity could imagine that this story works only where large enough local collections of matter define a local inertial frame to a good enough approximation. We could then replace the assumption of a global lattice with a patchwork of local lattices, locally defined in the relevant inertial frames. To extend the cartoon a bit further we could (for example) add the rule that if there is no such frame, then there are no qualia, and no local consciousness.

<sup>15</sup> For example, in Copenhagen quantum theory, this construction means that the effects of measurements inside the past light cone are taken into account in constructing the local density matrix, while those outside the past light cone are not.

matrices for nearby and recent cubes (within distance  $NL$  and within past time  $NL/c$ , for some number  $N > 1$ ) satisfies some property  $P_j(\rho_1, \dots, \rho_M)$ . Here  $M \approx 8N^4$  is the number of nearby and recent cubes,  $\rho_i$  are the mass density expectation values in these cubes,  $j \in J$  is an index over the possible types of quale (which we might perhaps take to be finite), and the properties  $P_j$  are sets of mathematical constraints (which to simplify the cartoon we might take to be exclusive, so that each cube is associated with at most one quale). If none of the constraints  $P_j$  hold, then there is no quale associated with the given cube at the given time. The consciousness  $C(S)$  associated at any given time with a system  $S$  to which these rules are applied is the collection of all the qualia defined at that time.

Within our cartoon, this rule is meant to be fundamental, not tailored to the specifics of human brains. It is supposed to give us a general algorithm for identifying  $C(S)$  for any system  $S$ . So we really should extend the cartoon to give some cartoon-level story about how we can tell whether qualia are part of the same consciousness or not. Perhaps we could do that by adding a second scale  $K$ , and saying that any pair of qualia separated by no more than  $K$  cubes, at any given time, form part of the same consciousness, and that belonging to the same consciousness is a transitive relation on qualia. In other words, a pair of qualia belong to different consciousnesses if and only if they are not joined by a path through the qualia that takes no more than  $K$  cubes for each step.<sup>16</sup>

For anything like this to work, even at the cartoon level, one would have to find properties  $P_j$  that tend to be correlated with specific conscious qualia when those properties apply to human brains and (perhaps) central nervous systems, so that postulating that the qualia supervene on brain matter gives a good description of our conscious mind states. The  $P_j$  should also not have the property that these supervenience postulates also imply additional qualia from (at the very least) most of the matter surrounding our brains and central nervous systems: if they did, we would not be able to speak of separate single consciousnesses associated with each brain. One would also need some plausible description of elementary qualia  $j \in J$ . And then, much harder still, one would need that the  $P_j$  actually produce the right sort of collections of qualia—corresponding to the sort of things we actually consciously experience—for the enormous variety of brains and brain states for which we have experience (direct or reported). It does not matter for the cartoon whether or not the  $P_j$  imply that things other than brains—modern computers, large rocks, spiral nebulae—are also conscious.

Obviously, I am not suggesting any of this is actually possible. The aim of this sketch is not to speculate about an actual theory of consciousness but just to give a concrete, albeit incredible, illustration that allows us to develop a particular line of thought further. Whatever the fundamental physical theory of consciousness – if there is one—

<sup>16</sup> The so-called combination problem [40], first raised by William James [41], is widely thought to be an obstacle to any satisfactory theory of consciousness involving novel rules attaching elements of consciousness to simple physical system. Chalmers [42] has argued that the combination problem has several aspects. If one thinks of this cartoon as a sort of panprotopsychist model, the rule that transitively connects qualia separated by no more than  $K$  cubes illustrates that panprotopsychist laws (at least at cartoon level) can deal with what Chalmers calls the subject combination problem. Other aspects, especially the quality combination problem, remain problematic.

looks like, I am pretty sure it does not resemble this cartoon. But suppose, just for the sake of the argument, that it were possible to make the cartoon work. We would then have a theory of consciousness, including a classification of qualia and a data selection principle. The description of the  $P_j$  would, we need to assume, be significantly simpler than just a dictionary of all the brain states and corresponding conscious states that we can identify. (If it isn't, then it doesn't produce a compressed description of the empirical data about consciousness, and so it doesn't define a useful theory.) In that sense, we would have a significantly better understanding of consciousness.<sup>17</sup>

However, our theory, as described, would be of consciousness as an epiphenomenon. It could possibly nonetheless represent a very substantial advance in our understanding of consciousness, if it turned out to describe the rich variety of our experiences from a simple set of principles  $P_j$ . But it could not explain how and why humans had evolved to produce brains that just happen to produce conditions in which many  $P_j$  tend to apply, and in which the corresponding qualia produce the sort of consciousnesses we have. So, on the anti-epiphenomenal view we have outlined above, it could not be fundamentally correct: at best it might be a good approximation.

### 3.4 Improving the Cartoon?

Any explanation of why humans and other animals evolved to become conscious has to run one of two ways.

One is that human evolution can be understood purely in terms of the familiar material laws of physics, and it is just a nice property of consciousness that it resides in highly evolved creatures that are continually processing information about their environments and acting on it. If one believes this is a satisfactory definition of, or a self-evident property of, consciousness, one can be happy with this explanation. As noted above, I don't, so I'm not.

The other is that familiar materialist explanations of evolution alone are not adequate and that something about consciousness itself gives an extra evolutionary advantage. This needs an extra mechanism that implies that, in some sense, conscious creatures tend to prevail in competition with unconscious ones. More than that, since a binary division between conscious and unconscious creatures doesn't give enough room for an evolutionary story, it needs to imply, in some sense, that more conscious creatures tend to prevail in competition with less conscious ones.

Having (perhaps foolhardily!) chosen to reject the first type of explanation in this discussion, we have to try for the second. We can translate "more (less) conscious" into "having more (fewer) qualia" in our cartoon. Then, fortunately for our cartoon narrative, there is at least an available option, already explored in a different connection

<sup>17</sup> This is not to say we would have solved the existing puzzles concerning the relationship of consciousness and physics. Indeed, a theory of this type would raise new puzzles: for example, why the lawlike supervenience of qualia on a quantum-derived ontology takes this particular form. Nonetheless, we would be able to make predictions we cannot presently make about the conscious mind states associated with brain states. We could also test them, insofar as any predictions about conscious states are testable, by adding the assumption that conscious states are often reliably reported. That is, we could see whether the predicted conscious mind states agree with our descriptions of our own mind states and with the descriptions others give of theirs.

[19] as a natural way of defining generalizations of quantum theory. According to our cartoon, we can (in principle) calculate the probability  $P_q(D)$  of any distribution  $D$  of qualia, from quantum dynamics and the relevant measurement or collapse postulate and from knowledge of the constraints defining the properties  $P_j$ . (The suffix  $q$  stands for quantum here.) We can do this for any system  $S$ , or in principle (given a good enough quantum theory that incorporates gravity and describes cosmology) for the entire universe. As noted, if our cartoon were actually correct, this calculation would give the correct predictions for an epiphenomenal model of consciousness. But we can change the model, and make it *non-epiphenomenally* dependent on quantum theory, if we postulate instead that the true probability distribution  $P_{\text{true}}(D)$  of distributions of qualia is a modified version of  $P_q(D)$ .

For instance, following the ideas of Ref. [19], we could postulate that

$$P_{\text{true}}(D) = C P_q(D) A(D), \quad (1)$$

where  $C$  is a constant that ensures the rescaled probabilities sum to 1 and  $A(D)$  is some weight factor that depends only on properties of the qualia distribution  $D$ .<sup>18</sup> To be clear: if we take quantum theory as ultimately a theory for predicting the experiences of observers, this means postulating that quantum theory is at least subtly incorrect. But the deviation could be very small and subtle, if  $A(D)$  depends only slightly and subtly on  $D$ .

Now, if  $A(D)$  is chosen to favour, even very slightly, distributions with more qualia, we have the potential beginnings of an explanation for the evolution of primate-level consciousness from primitive qualia. For such an explanation to work, we need that the postulated properties  $P_j$  somehow just happen to involve relations among mass density expectation values that are useful for, or naturally fit into the context of, the types of information processing that animal brains carry out—gathering information correlated with their bodies and environments, computing relevant features, and generating responses.<sup>19</sup>

But given that (big<sup>20</sup>) assumption, we can see that there would be selection pressure towards creatures whose information processing capacities use such relations in their information processing systems, and then selection pressure in favour of those whose systems generate more qualia.<sup>21</sup>

<sup>18</sup> This is not the most general possibility, but general enough for the present discussion.

<sup>19</sup> “Information” here is meant in the slightly informal sense standardly used in discussing biological intelligence. It is very hard to quantify precisely the information in an animal’s environment, or its representation of that environment, or its behavioural responses. Nonetheless it is generally agreed that relatively simple information-theoretic models give us good analogies, and widely expected that the analogies could in principle be made to approach representations of reality more and more closely as more complexity is introduced. Underlying this expectation is the assumption—with which most neuroscientists and physicists are very comfortable—that the known laws of physics completely describe animal behaviour.

<sup>20</sup> Though it *is* a very big assumption to make, it is still much less contrived than the dogmatic assumption that we must have consciousnesses of *exactly* the sort we have, given the information processing that we do.

<sup>21</sup> Stretching credulity even further, if  $A(D)$  were somehow chosen to favour qualia of particular types (which tend to be “pleasant”) and disfavour qualia of other types (which tend to be “painful”), we might also have at least the potential beginning of a story about how creatures came to embed in their information

One can only make full sense of this cartoon theory as we have phrased it, with a postulate of the form (1), in a block universe picture, since equation (1) defines the probability distribution for the complete configuration of all qualia throughout space and time.<sup>22</sup> Block universe theories of this type are logically consistent, but they can have unusual and counter-intuitive implications, including effects that appear to agents within the theory to be reverse causation and spacelike signalling. They also do not generally reduce to equally simple theories applicable to subsystems of the universe. For example, the behaviour of a conscious individual, or an finite ecosystem, cannot generally be modelled using only its initial state and some simple analogue of Eqn. (1). There *are* nonetheless theoretical reasons to consider some types of block universe theory, since they suggest possible solutions to the quantum measurement/reality problem.<sup>23</sup> That said, like the earlier part of the cartoon, our block universe qualia cartoon theory is meant only as an existence theorem, not a serious theoretical proposal.<sup>24</sup>

## 4 Summary and Discussion

Every line of thought on the relationship of consciousness to physics runs into deep trouble. Because of this, we are inclined to place some (albeit weak) credence that the line of thought we have outlined may not be entirely orthogonal to the truth, despite its own evident problems. We stress again that none of the details of our cartoons are

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processing systems some subsystems that generate pleasant qualia (which are favoured by our hypothetical postulate, and which are located so that they correspond to evolutionarily favourable activities) and some that generate painful qualia (which are disfavoured, and located so that they correspond to unfavourable activities). But our comments earlier apply: there seems no reason why this would not equally well work for evolution—although not so happily for us, its conscious products—with the pleasure-pain polarities reversed. The best I can offer is the thought that that the pleasure-pain problem might somehow look different and less fundamentally threatening if we understood the actual details of the interaction between material states and conscious states. But we don't have a theory of consciousness, and so I don't see how this could work. Maybe, of course, it just doesn't: maybe the pleasure-pain problem actually is insoluble in this approach, or perhaps in any approach.

<sup>22</sup> This leaves us with the problem of the psychological perception of time, since those qualia must nonetheless give conscious creatures the impression of a flow of time associated with a succession of experiences. But this is a deep problem in any view of consciousness and physics. It also, of course, leaves us with the usual gap between standard language and fundamental ontology in talking about processes within a block universe. For example, “the evolution of primate-level consciousness” is shorthand for something like “the sequential appearance of low-level, increasingly more complex, and primate-level consciousnesses at increasing cosmological times measured from the presumably highly ordered singularity conventionally referred to as the beginning of the universe”.

<sup>23</sup> One line of thought on this can be found in Refs. [43,44]; see also references therein for other discussions.

<sup>24</sup> Among the very odd features of the block universe rule (1), as stated, is that it implies that the bias towards consciousness in evolutionary selection arises from a calculation that depends on the global distribution of consciousness in space and time. For example, the weight bias between alternatives that would produce either descendent  $d_1$  or  $d_2$ , with differing numbers of lifetime qualia does not in general reduce to a ratio of the weights associated with the qualia they produce over their lifetimes,  $A(C(d_1))/A(C(d_2))$ . It does not even reduce to a ratio of the form  $A(T_1)/A(T_2)$ , defined by the weights associated with the qualia their entire trees of descendents  $T_i$  produce. One has also to consider the effects of  $T_1$  and  $T_2$  on other future conscious lifeforms and evaluate the ratio of weights  $A(D_1)/A(D_2)$  associated with the full qualia distributions  $D_i$  over all future space-time arising if  $d_i$  is the descendent. A version of the rule in which the weight function  $A$  is chosen so that  $A(D_1)/A(D_2) = A(C(d_1))/A(C(d_2))$  would probably improve the cartoon somewhat.

meant to be taken seriously. What we do take seriously, at a weak level of credence, is the suggestion that we could make some progress on understanding the problem of the evolution of consciousness if we supposed that consciousnesses alter (albeit perhaps very slightly and subtly) quantum probabilities. A further reason for taking this seriously (still at a weak level of credence) is an aesthetic preference for theories in which fundamental quantities (here qualia and quanta) genuinely interact, rather than one being purely dependent on the other. The same point was used to motivate inventing and testing generalizations of quantum theory in a different context in Ref. [19].<sup>25</sup>

What are the implications? Broadly, to add some support to tests of quantum theory that involve conscious observers. For example, perhaps this line of thought adds a little to the motivation for interferometry experiments involving viruses [20], or ultimately bacteria or larger creatures.<sup>26</sup> Existing intuitions that such experiments might be worthwhile are mostly based on the idea [21] that quantum collapse may be connected to, or even directly caused by, consciousness. Chalmers and McQueen [22] have recently formulated a more precise version of this proposal, invoking the hypothesis of Tononi and collaborators [23] that what they term integrated information could define a measure of consciousness.<sup>27</sup> Our discussion gives another weak reason for speculating that the direct involvement of conscious observers might possibly alter something relevant to interferometry and other experiments.

Our discussion perhaps also adds a little to the motivation for long range Bell experiments in which human observers make (their best attempt at) free random choices of measurement outcomes, and observe the outcomes directly, with separations large enough that the combined choice processes and observations on the two wings are spacelike separated. This added motivation is presently weak, since we have given no specific motivation in this discussion for looking at Bell experiments in particular. A perhaps stronger motivation comes from combining the hypotheses that wave function collapse requires consciousness and that collapse results propagate causally in the future light cone. This leads to a consistent theory, if one assumes either that measurements can never be precisely specified or that collapses are never perfect pro-

<sup>25</sup> There are interesting parallels between the beable hypothesis [45] and the qualia hypothesis. Bell's notion of beable—a mathematical quantity in a physical theory that directly corresponds to an element of physical reality—is intended to give a language to highlight a general class of possible solutions to the quantum reality problem: what, precisely, could be the sample space for which we calculate probabilities for a closed quantum system? Similarly, the notion of qualia identifies hypothetical elementary quantities that could be characterised by a theory of consciousness that addresses the hard problem. In both cases, whether the relevant problem really *is* a problem is controversial, with thoughtful people on both sides. For those who think both problems are real and may lead to new science, parsimony might suggest that qualia can be understood in terms of—perhaps as functions of—beables. A more radical option would be to identify beables and qualia, which would imply that quantum theory is ultimately about conscious perceptions (though not necessarily only those of familiar living creatures).

<sup>26</sup> Among the further uncertainties here are that it is far from clear why we should expect viruses or bacteria to have any sort of consciousness.

<sup>27</sup> To the best of my knowledge there is currently no empirical evidence for the integrated information hypothesis, and its plausibility is debated. However, Chalmers and McQueen's point applies quite generally. Any well-defined measure of consciousness would allow a more precise formulation of Wigner's idea and hence an analysis of whether experimental tests could be feasible in the foreseeable future.

jections, and implies a loophole (the so-called “collapse locality loophole”) in all Bell experiments to date [24,25].

(It is worth parenthetically mentioning here that some [26,27] have suggested that Bell experiments involving conscious observers can also be motivated by some form of “free will” hypothesis. Discussions of free will in connection with physics are, if anything, even more contentious than those of consciousness, and it is beyond my scope to try to add to them here, beyond pointing readers to recent relevant work. Roughly speaking, as I understand it, the main ideas are that (a) superdeterminism could explain the observed violation of Bell inequalities in Bell experiments to date, (b) there are possible motivations for considering models in which superdeterminism applies to the material world but not to the outcomes of freely made human decisions. One such motivation, discussed by Hardy [26] is some form of dualism, in which human decisions have the effect of unpredictable interventions into the material world, whose effects propagate into but not outside the future light cone of the decision point. On this view, it is possible we might see different results in Bell experiments in which the measurements on the two wings arise from spacelike separated free choices by observers. Retarded Bell inequalities formalising mathematically the hypothesis to be tested were defined by Hardy [28]. An extended discussion is given in Ref. [26], where Hardy reviews the history of work and ideas in this direction and sets out a detailed experimental proposal, while also noting problems with and arguments against the relevant hypotheses. While Hardy expresses strong credence that Bell experiments will continue to give standard results, he stresses the point, also made below, that the payoff of a surprising result is sufficiently large to justify the experiments.

Arguments that free will should play a fundamental role in physics have also recently been made by Gisin [29].)

In the longer term, if and when quantum technology advances to the point that direct tests of quantum theory (not necessarily interferometric tests) on macroscopic objects are possible, our discussion does give a clear motivation for carrying them out on animals and humans.

To be clear, neither I nor (as far as I am aware) any author mentioned here insist or even predict that quantum theory will be violated in any of these experiments. The arguments that consciousness might have a role in quantum physics are admittedly problematic, even if the counterarguments also are. And most of the interesting theoretical ideas about quantum theory over the last fifty years involve formulations in which observers play no special role.

But, to be provocatively quantitative, on the grounds that deep puzzles in physics have often led to big surprises and that consensus views tend to be overconfident, I would still give credence of perhaps 15% that *something* specifically to do with consciousness causes deviations from quantum theory, with perhaps 3% credence that this will be experimentally detectable within the next fifty years. No doubt many physicists would give much lower figures. Still—as the existential risk community in particular has emphasized (e.g. [30–32]) – if one assigns non-zero probabilities, however small and uncertain, to events with large costs or benefits, one should pay close attention to the expectation values. The potential benefits here include making some progress in understanding the relationship between physics and consciousness. That would also offer some hope of getting data to guide us in the ethical questions

we already face (how rich are the consciousnesses of animals?) and those we likely will (are human-level AI programmes, or human brain emulations?). It could also significantly change our understanding of the physics of computation, with potentially large implications for the future of intelligence. Even if one has very weak levels of credence (say 0.01%) for any current ideas on the physics of consciousness, it seems to me the large potential implications still suggest that more work should be carried out on possible experiments on conscious or plausibly conscious observers, and their possible theoretical motivations.

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## References

1. James, W.: Are we automata? *Mind* **4**, 1–22 (1879)
2. Chalmers, D.J.: Strong and weak emergence. In: Davies, P., Clayton, P. (eds.) *The Re-emergence of Emergence*. Oxford University Press, Oxford (2006)
3. Gennaro, R.J.: Consciousness. *The Internet Encyclopedia of Philosophy* (2018). <http://www.iep.utm.edu/>
4. Chalmers, D.J.: *The Conscious Mind: In Search of a Fundamental Theory*. Oxford University Press, Oxford (1996)
5. Nida-Rümelin, M.: Qualia: the knowledge argument. In: *The Stanford Encyclopedia of Philosophy* (Summer 2015 Edition) (2015). <https://plato.stanford.edu/archives/sum2015/entries/qualia-knowledge/>
6. Alter, T.: The knowledge argument against physicalism. In: *The Internet Encyclopedia of Philosophy* (2017). <http://www.iep.utm.edu/>
7. Robinson, W.: Epiphenomenalism. In: *The Stanford Encyclopedia of Philosophy* (Fall 2015 Edition) (2015a). <https://plato.stanford.edu/archives/fall2015/entries/epiphenomenalism/>
8. Chalmers, D.J.: Facing up to the problem of consciousness. *J. Conscious. Stud.* **2**(3), 200–219 (1995)
9. Dennett, D.C.: *Consciousness Explained* (1993)
10. Glynn, I.: *An Anatomy of Thought: The Origin and Machinery of the Mind*. Oxford University Press, Oxford (2003)
11. Weisberg, J.: The hard problem of consciousness. In: *The Internet Encyclopedia of Philosophy* (2017). <http://www.iep.utm.edu/hard-con/>
12. Walter, S.: Epiphenomenalism. In: *The Internet Encyclopedia of Philosophy* (2017). <http://www.iep.utm.edu/epipheno/>
13. Van Gulick, R.: Consciousness. In: Zalta, E.N. (ed), *The Stanford Encyclopedia of Philosophy*. Metaphysics Research Lab, Stanford University, spring 2018 edition (2018)
14. Robinson, W.: Epiphenomenalism: self-stultification. In: *The Stanford Encyclopedia of Philosophy* (Fall 2015 Edition) (2015b). <https://plato.stanford.edu/entries/epiphenomenalism/#SelStu>
15. Lewis, C.I.: *Mind and the World-Order: Outline of a Theory of Knowledge*. Courier Corporation, London (1929)
16. Schrödinger, E.: *What is Life?: With Mind and Matter and Autobiographical Sketches*. Cambridge University Press, Cambridge (1992)
17. del Prado Martín, F.M.: Macroscopic thermodynamics of reaction times. *J. Math. Psychol.* **55**(4), 302–319 (2011)



18. Biederman, I.: Recognition-by-components: a theory of human image understanding. *Psychol. Rev.* **94**(2), 115 (1987)
19. Kent, A.: Beable-guided quantum theories: generalizing quantum probability laws. *Phys. Rev. A* **87**(2), 022105 (2013)
20. Arndt, M., Nairz, O., Zeilinger, A.: Interferometry with macromolecules: quantum paradigms tested in the mesoscopic world. In: *Quantum [Un] Speakables*, pp. 333–350. Springer (2002)
21. Wigner, E.P.: Remarks on the mind-body problem. In: Good, I.J. (ed.) *The Scientist Speculates*. Heineman, London (1961)
22. Chalmers, D.: Dirty secrets of consciousness. In: *Talk at FQXi 5th International Conference, Banff, August 2016* (2016)
23. Oizumi, M., Albantakis, L., Tononi, G.: From the phenomenology to the mechanisms of consciousness: integrated information theory 3.0. *PLoS Comput. Biol.* **10**(5), e1003588 (2014)
24. Kent, A.: Causal quantum theory and the collapse locality loophole. *Phys. Rev. A* **72**(1), 012107 (2005)
25. Salart, D., Baas, A., van Houwelingen, J.A.W., Gisin, N., Zbinden, H.: Spacelike separation in a Bell test assuming gravitationally induced collapses. *Phys. Rev. Lett.* **100**(22), 220404 (2008)
26. Hardy, L.: Proposal to use humans to switch settings in a Bell experiment. [arXiv:1705.04620](https://arxiv.org/abs/1705.04620) (2017)
27. BIG Bell Test Collaboration et al.: Challenging local realism with human choices (2018). [arXiv:1805.04431](https://arxiv.org/abs/1805.04431)
28. Hardy, L.: Bell inequalities with retarded settings (2015). [arXiv:1508.06900](https://arxiv.org/abs/1508.06900)
29. Gisin, N.: Time really passes, science can't deny that (2015). [arXiv:1602.01497](https://arxiv.org/abs/1602.01497)
30. Kent, A.: A critical look at risk assessments for global catastrophes. *Risk Anal.* **24**(1), 157–168 (2004)
31. Bostrom, N., Cirkovic, M.M.: *Global Catastrophic Risks*. Oxford University Press, Oxford (2011)
32. Bostrom, N.: Existential risk prevention as global priority. *Glob. Policy* **4**(1), 15–31 (2013)
33. Saunders, S., Barrett, J., Kent, A., Wallace, D.: *Many Worlds?: Everett, Quantum Theory, & Reality*. OUP, Oxford (2010)
34. Schlosshauer, M.A.: *Decoherence: And the Quantum-to-Classical Transition*. Springer, New York (2007)
35. Fuchs, C.A.: Notes on a Paulian idea: Foundational, historical, anecdotal, and forward-looking thoughts on the quantum: Selected correspondence, 1995-2001 (2003)
36. Cushing, J.T., Fine, A., Goldstein, S.: *Bohmian Mechanics and Quantum Theory: An Appraisal*, vol. 184. Springer, New York (2013)
37. Tononi, G., Edelman, G.M.: Consciousness and complexity. *Science* **282**(5395), 1846–1851 (1998)
38. Crick, F., Koch, C.: A framework for consciousness. *Nat. Neurosci.* **6**(2), 119–126 (2003)
39. Tegmark, M.: Consciousness as a state of matter (2014). [arXiv:1401.1219](https://arxiv.org/abs/1401.1219)
40. Seager, W.: Consciousness, information and panpsychism. *J. Conscious. Stud.* **2**(3), 272–288 (1995)
41. James, W.: *The Principles of Psychology*. Read Books Ltd, Worcestershire (2013)
42. Chalmers, D.J.: The combination problem for panpsychism. In: *Perspectives: Contemporary Panpsychism* (2013)
43. Kent, A.: Lorentzian quantum reality: postulates and toy models. *Philos. Trans. R. Soc. A* **373**(2047), 20140241 (2015)
44. Kent, A.: Quantum reality via late time photodetection (2016). [arXiv:1608.04805](https://arxiv.org/abs/1608.04805)
45. Bell, J.S.: The theory of local beables. *Epistemol. Lett.* **9**, 11–24 (1976)