The World as Wavefunction

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There may be a way to maintain a monistic wavefunction ontology, but it is certainly not *trivial* to see what that way is

(Maudlin ([2010], p.129, his emphasis)

ABSTRACT

Murray Gell-Mann and James Hartle have made an original proposal for a version of decoherent histories quantum mechanics which is specifically tailored so as not to imply the emergence of multiple quasi-classical worlds. I argue that there is an explanatory gap in the proposal but that there remains an important insight. That insight might be used to tackle what can be seen as an outstanding problem for Hugh Everett III's '"relative state" formulation' of quantum mechanics. At least, so long as that view is understood to give ontic priority to the wavefunction. The argument employs a recent novel analysis of self-location within any sort of multiverse, which also suggests a solution to the cosmological measure problem.

1 All Coherence Gone

'A quantum universe can be described by many decohering sets of alternative coarse-grained histories - many realms'. So wrote Jim Hartle ([2010], p. 94). Characterized in that way, decoherent histories quantum mechanics (DHqm) is suggestive of Hugh Everett III's '"relative state" formulation' (RSqm) in the version currently championed by theorists such as Simon Saunders and David Wallace[1]. But Hartle and Murray Gell-Mann, both involved in the development of DHqm, have long been reluctant to concede that many realms, multitudes of emergent quasi-classical worlds, exist. And that's understandable; the idea that we have vast numbers of doppelgangers living divergent lives on other planets which are constantly emerging from an underlying physical reality can seem a somewhat extravagant hypothesis which is to be avoided if possible.[2]

Of course, it may well be that our universe is spatially infinite. Contemporary cosmology supposes that we inhabit a causally isolated region with a current radius of about forty-one billion lightyears. The visible firmament is on our past lightcone, a hypersurface of that so-called Hubble sphere. A spatially infinite universe may well contain a countable infinity of such Hubble spheres which are perfectly isomorphic to the one we suppose ourselves to inhabit[3]. That would also yield hosts of doppelgangers living parallel and divergent lives. But it appears to be a contingent matter whether a spatially infinite universe contains infinitely many galaxies. In that case, maybe we have multitudinous doppelgangers and maybe not. But many see RSqm as entailing that similar legions exist as a physically necessary consequence of quantum mechanics. Furthermore, if Hartle's realms were real, that can seem to imply that we and our environment are constantly branching into myriad worlds which would

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[1] For discussion and references see Saunders ([2010a], pp. 8-12) and Wallace ([2010a]), ([2012], pp. ???).

[2] For a recent argument that RSqm is not in fact committed to the existence of a mulititude of quasi-classical worlds see Barratt ([2011]).

[3] On the assumption of the 'Bekenstein bound', which entails that the number of possible observable physical states in a finite volume of space is finite.

conventionally be described as possible rather than actual[4]. In trying to free DHqm of this spectre Gell-Mann wrote:

> To use the language we [he and Hartle] recommend is to address the familiar notion that a given system can have different possible histories, each with its own probability, it is not necessary to become queasy trying to conceive of many 'parallel universes', all equally real. ([1994], p. 138)

Decoupling DHqm from RSqm has not proved so easy, but in a new paper Gell-Mann and Hartle ([2011]) claim to have achieved their goal of having DHqm without the many worlds which they take to be entailed by RSqm. Their argument turns on a concept of 'extended probabilities'. These have values outside the range 0-1 but are precisely related to conventional probabilities with values within that range (*ibid*., p. 4, eqn. 2.2). The extended probabilities apply to fine-grained histories and it is the decoherent coarse-graining of sets of fine-grained histories which yield the conventional probabilities attaching to coarse-grained histories. The upshot is a novel account of, for instance, a two-slit experiment. For an electron arriving at the detector screen as part of the interference pattern it is true that it passed though only one of the slits. But it is not possible to assign probabilities to the electron having passed through the left slit or the right slit. Only extended probabilities can be assigned to these fine-grained alternatives, implying that it would be impossible in principle to settle a bet on which of the alternatives actually occurred (*ibid*., p. 3).

Downstream from the slits, the characteristic interference pattern in the waveform of the electron is to be understood as the coarse-graining of an ensemble of fine-grained histories. The squared modulus of amplitude yields conventional probabilities but the waveform is to be understood as describing a *notional* (imaginary) ensemble of fine-grained histories *only one of which exists*. Here 'history' is being used in the sense of a temporally extended object, not merely a description. The single extant electron is somewhere but only an

[4] Some RSqm theorists suggest that branching can be understood in terms of the divergence of previously isomorphic universes. I shall say more about that in the final section.

extended probability can be assigned to any possible region where that electron may be. The idea that the ensemble of fine-grained histories is an imaginary theoretical device and only one of those histories actually exists is central to Gell-Mann's and Hartle's attempt to avoid the many worlds of RSqm. As they put it:

> This real history is described by embedding it in an ensemble of comparable imagined fine-grained histories, not unlike the familiar ensemble of statistical mechanics. (*ibid*., p. 1)

Describing the fine-grained histories requires a choice of preferred variables and Gell-Mann and Hartle write:

> The fine-grained histories are described by a preferred set of variables which we take to be those of a sum-over-histories formulation of quantum mechanics. They are histories of particle positions in the case of particles, four-dimensional field configurations — both bosonic and fermionic — in the case of quantum field theory, and histories of geometries and fields in the case of semiclassical quantum gravity. Histories of these variables are assumed to be the most refined description of the system possible.
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> A strong case can be made that these histories are adequate for the prediction of all observable quantities. (*ibid.*, p. 3)

But, accepting that assumption, there still seems to be a problem with Gell-Mann's and Hartle's proposal. Their one true fine-grained history is rather like a lone ant in an anthill. The erratic path which the ant follows may well be identical to that of an ant interacting with a host of fellows, the ant may move as if it were one of a community even if it's all alone, but if no such community exists any *causal explanation* of why the ant moves thus and so looks obscure. There's a fundamental difference between the proposed notional ensemble and the 'familiar ensemble of statistical mechanics'. It is that for the classical system there is a simple dynamics internal to one instance of the ensemble. But Gell-Mann's and Hartle's unique fine-grained history has no such simple internal dynamics. As they put it:

> The set of all fine-grained histories between an arbitrary pair of times t_0 and t_f is the set of all such paths $\{q^i(t)\}$ between these two times. They are continuous but typically non-differentiable. (*ibid*., p.3)

The unique fine-grained history is only calculable because it behaves *as if* it were interacting with other members of the ensemble. Histories which have not decohered *interfere* non-negligibly. But if Gell-Mann and Hartle were right then quantum interference would not exist as a physical process. It would be purely imaginary. Now, it may be possible in some sense that there is one fine-grained history with an internal dynamics which is extremely complex and which is describable as if it were one of an ensemble of histories mutually interacting in a way described by the evolution of the wavefunction. But, on the face of it, isn't it more plausible that the dynamics of each fine-grained history is what it is because the mutually interacting ensemble *exists*?

I shall not attempt to press that point further. What I'm concerned to show here is that *if* the ensemble of fine-grained histories is regarded as extant rather than imaginary then Gell-Mann's and Hartle's work may help to resolve what some have seen an outstanding problem for RSqm. It has long been overlooked by many working with Everett's relative state interpretation that it provides no coherent realist account of what's going on in the paradigm two-slit experiment. According to RSqm what passes through the slits is the *wavefunction* of the electron. But what, precisely, is that? Tim Maudlin ([2010]) stresses that this fundamental ontological question remains unanswered. In what follows I'm going to argue that Gell-Mann's and Hartle's characterization of fine-grained histories in terms of extended probabilities, coupled with a novel interpretation of the location of an observer within a multiverse, can yield an answer to the question which Maudlin poses. The assumption that the Gell-Mann/Hartle ensemble exists, rather than just one element of it, need not in any way threaten Hartle's claim that 'Extended probabilities give a simple and general way of formulating quantum theory ([2008], p. 1).[5]

2 Self-Location in a Multiverse

Maudlin's problem has to do with the constitution of philosophers' tables and chairs. It can seem that according to RSqm they are nothing but seething masses of wavefunction. But if Gell-Mann's and Hartle's one fine-grained history really were all that exists then a table could, for instance, be understood as being constituted by a temporal fragment of a history involving particles with definite, albeit non-differentiable, trajectories. The wavefunction would be banished, so to speak, to the domain of the notional ensemble.

However, if the GMH ensemble (Gell-Mann/Hartle) were taken as extant rather than notional then the wavefunction would become instantiated by that multiplicity of fine-grained histories. For the wavefunction is the origin of the dynamics of a single fine-grained history by way of that history interacting with its fellows. The trajectory of a particle in a fine-grained history is calculated by Gell-Mann and Hartle *as if* that history were but one element of a causally interacting ensemble. But if the ensemble exists the dynamics of a fine-grained history is just a physical part of the actual dynamical evolution of the ensemble, which is the instantiation of the wavefunction.

In that case our local environment would seem to be constituted by a sort of minimal slice of wavefunction. The idea would be this. If the ensemble exists then the one coarse-grained history which we inhabit would be underlain by a multitude of mutually interacting fine-grained histories. But presumably our own bodies and brains would be constituted by elements of only one of those fine-grained histories. Again, to be clear, the term 'history' here is being used in the sense in which Gell-Mann and Hartle use it, that is to say as being a temporally extended object.

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[5] For an alternative approach to providing a fundamental ontology for RSqm see Wallace and Timpson ([2010]).

Each of us would have a multitude of doppelgangers in environments which were isomorphic at the coarse-grained level but anisomorphic at the fine-grained level. For a bunch of such doppelgangers about to observe an electron detected at the screen of a two-slit apparatus there would be some doppelgangers relative to each of whom the relevant electron in each of their fine-grained histories had gone through the left slit and some relative to whom the relevant electron in their fine-grained history had gone through the right slit.

On this picture our philosophers' table is constituted by a minimal slice of wavefunction in the sense that we as observers are only ever instantiated by one fine-grained history, even if the other fine-grained histories of the ensemble exist. The table which a given observer sees would be a table sharing a particular fine-grained history with that observer. But a change of perspective is possible which allows the *whole* wavefunction, not just a minimal slice of it, to inhabit our observed environment. The inspiration comes from reflection on a genre of discussion which has been prominent in analytic philosophy of mind in recent decades involving thought experiments to do with Twin Earth[6]. We are asked to imagine two matched doppelgangers, each on one of two nearly isomorphic Earthlike planets. Because these thought experiments are directed towards understanding the relation between a creature's mentality and its environment, a restricted environmental anisomorphism is usually introduced.

Until recently it has been universally assumed that in a Twin Earth setup there are two numerically distinct subjects, one on each planet, and the discussion focuses on whether or not aspects of the representational content of the subjects' minds differs in virtue of the environmental anisomorphism. However, it turns out that it's possible to interpret the setup as involving a single subject with a single mental life which is doubly instantiated, just as any matched pair of objects on the planets instantiate one and the same physical form. The full details of this novel interpretation of doppelgangers are to be found in Tappenden ([2011b]) and it would be inappropriate to set out the arguments at length here, but I shall outline the salient points.

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[6] See Putnam ([1975]) for the seminal paper.

For the sake of simplicity, begin by imagining that the twinned planets are perfectly isomorphic. One on your left and one on your right. On the planets are a matched pair of doppelgangers, $\text{Doppelganger}_{\text{Left}}$ and $\text{Doppelganger}_{\text{Right}}$ (D_L and D_R). Imagine being able to speak with these doppelgangers. What you get back is apparently two streams of perfectly isomorphic verbal behaviour. The idea now is that you understand the responses not to be two numerically distinct loci of verbal performance, but a single locus. The single verbal performance is doubly instantiated, it's instantiated by the sonic emissions of both D_L and D_R.

There is a single subject, Una, who in some sense has a single body. But that body is somehow constituted by both D_L and D_R. Getting to understand the constitution of objects in Una's environment, including her own body, is an important part of interpreting Una as being a single subject. On this unitary interpretation of doppelgangers, as opposed to the conventional plural interpretation, D_L and D_R do not constitute loci of minds. There is a single mind which is instantiated by some sort of composite of D_L and D_R. The nature of the composition is central to what follows.

Bear in mind that it is not only Una's *verbal* performance which gives us a window on her as a subject. All her intentional behaviours are likewise instantiated by composites of the muscular articulations of D_L and D_R. When Una reaches out to pluck an apple D_L and D_R show arm-moving-applewise articulations. So all the objects in Una's environment which she indicates and refers to in her behaviours are somehow to be understood as composites of isomorphic pairs of counterpart objects on the two isomorphic planets. The 'apple' which Una plucks must somehow be a composite of the $\text{apple}_{\text{Left}}$ and the $\text{apple}_{\text{Right}}$.

Imagine that we interpret Una as thinking of a table that it is round. On a standard representational view of mind it is supposed that Una entertains the thought because she deploys a mental representation. It is perhaps most plausible that that representation is manifest as a cerebral process[7]. On that assumption, in

[7] 'Extended mind' theorists currently claim that some mental representations may be constituted by elements of an organism's local environment but that is controversial and anyway does not affect the central idea here. See Menary ([2010]) for disparate views on the issue.

Una's case what constitutes the *single* mental representation she deploys is some sort of composite involving the *pair* of relevant isomorphic cerebral processes going on in the heads of the two doppelgangers.

Ordinarily, for a mental representation to represent a table's being round it is supposed to be the vehicle of a representational content which is expressed by the proposition 'T is round' where T is the table in question. How the representation comes to bear its content is controversial but need not concern us. However, in Una's case it appears that what she's thinking about is not a table but a composite of isomorphic tables. So in order to coherently interpret Una as a single subject it is necessary to understand her as thinking not about a table but about what might be called a 2-table, where a 2-table does not just include any old pair of isomorphic tables but rather a corresponding pair of isomorphs on matched planets of the Twin Earth genre. Clearly that genre of multiverse may contain any number of isomorphic worlds of the sort Una's doppelgangers inhabit so there's scope for 3-tables, 4-tables and so on, assuming that worlds are understood as finite and causally isolated, like Hubble spheres.

So we might attribute the content expressed by '$_2$T is round' to Una's mental representation, where $_2$T is the 2-table in question. But this raises a problem. It makes no sense to say of a *pair* of tables that it is round. What is needed is to modify the predicate. The appropriate modification is to introduce the idea that an n-table is n-round if and only if each of its component tables is round. So we attribute the content '$_2$T is 2-round' to Una's mental representation. A 2-table is 2-round if and only if each of its two component tables is round. A two-table is an object which constitutes what appears to Una as a table and it consists of two isomorphic components, one on each planet. Where the conventional plural interpretation of doppelgangers would suppose that there were two subjects with matched bodies on a pair of isomorphic planets each thinking of a local table that it is round, on the novel unitary interpretation we have the single subject, Una, thinking of a single 2-table that it is 2-round.

The unitary interpretation can be applied to understanding the thoughts, speech and intentional actions of a single subject spanning any number of isomorphic worlds. But this is from a third-person point of view. We imagine the interpreter as somehow standing outside that multiverse; the god's eye perspective. But how might we think of ourselves as inhabiting a multiverse where each of us spans a multitude of isomorphic worlds?

Surely we must take it that what we see as a table is a table, not an n-table. Putting ourselves in Una's shoes we cannot admit that what we take to be a table is not a table. So a way has to be found to understand how a table in our environment could somehow be constituted by isomorphic physical objects, each in a different world.

Bearing in mind that the model being using here is that of spatially separated worlds akin to isomorphic Hubble spheres it would seem that a round table in our observed environment cannot be round in virtue of being an *aggregate* of round objects. If we observed a table to weigh a dozen kilograms that table could not be a spatial aggregate of a multitude of objects each weighing a dozen kilograms. The weight of a spatial aggregate is the sum of the weights of its parts.

In the domain of classical physics objects can only be aggregates of spatial and temporal parts. Later we shall see that in quantum physics a further type of aggregate is available but in the meantime it will be instructive to remain in the classical domain. There, the way forward is to suppose that an object in our environment may be a *set* of isomorphic *elements.* Willard Van Orman Quine once proposed that any particular, such as a table, could be understood as being a self-membered singleton set ([1969], pp. 31-2). Adapting this to the classical model before us, the idea now is that a table in our environment may be a multipleton set, reducing to being a self-membered singleton if there's no multiverse. But if we span a number n of isomorphic worlds we can imagine that any number of them might suddenly disappear. We have as yet no solution to David Hume's problem of how any sort of physical necessitation can exist and so in positing a classical multiverse we cannot exclude the possibility of any particular world in that multiverse coming to a sudden end. And given that any particular world can end at any time there is the possibility of us being left spanning any sample of the original collection but still faced with a table. So any *subset* of the original table must also be a table.

Any table we're left with could then be understood to have some *observable* property if and only if each of its subsets had that property. It's necessary to introduce the qualification 'observable' because clearly the number of elements constituting a table which is a multipleton set cannot be the same for each of its subset tables. However, it's plausible that if we were to span a multitude of isomorphic worlds the magnitude of that multitude would not be observable; if the number of worlds should change we would not notice any difference. Later, we shall see that changes in the number of worlds which we span can be understood to be related to the concept of physical probability but for the moment, just thinking about a philosopher's table sitting still with a MacBook atop, let's take the number of worlds we span at any given moment as unobservable.

This leads to the following proposal for the constitution of objects in our environment if we are to coherently understand ourselves as being single subjects spanning a multitude of classical worlds. Corresponding matched objects in isomorphic worlds can be called 'parallel world counterparts'.

Concrete Sets

> Any environmental object O is a set of self-membered singletons which are parallel world counterparts and O possesses some observable property F if and only if all the subsets of O possess F. Tappenden ([2011b], p. 133)[8]

According to Concrete Sets, if we inhabit a multiverse consisting of a number n of isomorphic worlds then any table we observe in our local environment has n! subsets which are all isomorphic tables and our table is round because all its subset tables are round. The idea has so far been applied to thought experiments of the Twin Earth genre where quantum mechanics is not an issue. I shall come to

[8] This proposal is incompatible with David Lewis's Main Thesis in his *Parts of Classes* ([1991], p.7), which is not a problem in itself but worth mentioning given the celebrity of Lewis's engaging idea.

applying the idea to an ensemble of fine-grained histories later. But first it will be useful to pursue these thoughts further in a classical context.

3 A Classical Model for Linear Superposition

Return to the god's eye view of our two isomorphic planets, one on the left and one on the right, and imagine that Una reports seeing a black box before her. What we see from our detached perspective is two matched black boxes and we can understand Una as speaking truly if we take her to be referring to a 2-black 2-box. But suppose that, unbeknown to Una, the interiors of the matched black boxes are causally isolated from their surrounding environments allowing a contained anisomorphism between the two planets. One box contains a black cat and the other contains a white cat. Una's 2-box thus harbours a 2-cat since each component box contains a cat, but the 2-cat is neither 2-black nor 2-white since the component cats are neither both black nor both white. The 2-colour of the 2-cat can thus be said to be indeterminate.

Imagine now what would plausibly happen if Una were to unmask the contents of her 2-box. On the left planet D_L's retinas would register an image of a black cat and on the right planet D_R's retinas would register an image of a white cat. We could expect Una to undergo personal fission into a subject seeing a black cat and a subject seeing a white cat. The analogy with the RSqm fission account of what would happen to a subject unveiling Schrödinger's proverbial boxed cat is unmistakable. There has been much discussion of how an informed subject about to make an observation using, say, a Stern-Gerlach apparatus to measure spin should understand their predicament if believing RSqm[9]. Here I shall simply assume that such a subject can intelligibly suppose that their situation is in some sense like that of a subject who believes that a stochastic process takes place and expects to see either one or the other possible outcome with a given probability. Since it is difficult to see how such analyses can be understood in terms of genuine probabilities I shall speak of fission-probability (f-probability) for

[9] For a variety of views see Saunders and Wallace ([2008]); Greaves and Myrvold ([2010]); Saunders ([2010b]); Papineau ([2010]); Tappenden ([2011a]).

branching contexts. F-probabilities take values 0-1 and guide betting behaviour in the same way as probabilities, setting aside some bizarre and controversial exceptions.[10]

To be clear about this, the idea is that on a currently defensible view of RSqm the following holds. If a subject knows that s/he will undergo personal fission into subjects observing different outcomes A, B, C… then prior to fission the subject can intelligibly assign f-probabilities to observing A, observing B, observing C and so on. Such an observer must assign a *probability* of 1 to seeing each outcome simultaneously as distinct persons. That is hard to imagine but nonetheless the claim is that the informed pre-fission subject can make assignments of f-probabilities to the outcomes A, B, C, etc. which can serve to guide behaviours, such as betting, in a similar way to probabilities. Understanding transtemporal identity in fission contexts, how it is that an observer prior to an observation can expect to retain their personal identity through fission, need not pose a problem[11]. There then arises the question of what values the f-probabilities should take. For RSqm much work has gone into attempting to show that those values should be equal to the relevant squared moduli of amplitude.[12]

So, if Una were to be informed about her situation prior to opening the 2-box, the analogy with RSqm would suggest that she should regard her situation as somehow being like that of being able to assign probabilities to the seeing of a black or a white cat. Since Una is to fission into two subjects a first thought might be that she should assign an f-probability of ½ to each outcome. But on further reflection this becomes problematic. For suppose Una spanned three isomorphic planets and were faced with a 3-box where two component boxes contained matched black cats and the third contained a white cat. We should still, on the unitary interpretation of doppelgangers, expect that Una would fission into one observer seeing a black cat and one seeing a white cat. Which might again suggest that if informed she should suppose the situation as being somehow like having a

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[10] For some discussion of these exceptions see Papineau ([2003]), Tappenden ([2004], [2011a], pp.118-21), Price ([2010]), Wallace ([2012], pp. ??)

[11] For two alternative approaches to this see Saunders and Wallace ([2008]) and Tappenden ([2011a], p. 115).

[12] This work was begun in Deutsch ([1999]). For its most recent manifestation see Wallace ([2010b], [2012], pp.??).

fifty-fifty chance of seeing black or white. And yet it's tempting to think that the *proportions* of parallel planets containing counterpart black cats and white cats might somehow be analogous to the squared moduli of amplitude in the quantum-mechanical case.

This suspicion can find some backing, for suppose that Una spans some very large finite number of parallel planets. The infinite case brings with it the notorious measure problem of cosmology of which I'll say more shortly. And now, into the classical model, let's introduce the idea of an irreducibly stochastic process which selects whether a boxed cat on a given planet is black or white. We can imagine that Una's multi-box is equipped with a multi-button and when she presses the multi-button a stochastic process takes place on each planet. And suppose that on each planet the stochastic process is such that there's a two-thirds chance of the cat turning out black and a one-third chance of its turning out white. For a large number of planets there'll be a high probability that the proportions across the set will be two-thirds for black cats and one-third for white cats.

Now, by way of a lemma, let's for a moment abandon the unitary interpretation of doppelgangers and revert to the standard plural interpretation. In that case we have one subject on each planet where a stochastic process takes place and if each of those subjects were well-informed of the setup and were to state their chance of seeing a black cat, they would be speaking truly if they were to say that the probability of seeing a black cat was two-thirds.

But if we now revert to the unitary interpretation of doppelgangers the only way for it to be consistent is for Una to be interpreted as speaking truly if she says that her situation is somehow like that of there being a probability of *two-thirds* that she will see a black cat. That must be so because when Una speaks here vocal behaviour is isomorphic to the verbal behaviours of her constituent doppelgangers, when those doppelgangers are understood to be loci of verbal performance according to the standard plural interpretation. The unitary interpretation is only possible if Una's verbal behaviour can be understood to refer to something in her environment which corresponds to what is taken to be in the environments of her constituent doppelgangers on the plural interpretation. So Una, well-informed about her predicament, must be interpreted as assigning an f-probability of two-thirds to seeing a black cat, despite expecting to fission into only *two* subjects, one seeing a black cat and the other seeing a white cat.

If talk of f-probabilities in branching scenarios is acceptable then it should be possible on the unitary interpretation to take Una as speaking of f-probabilities rather than probabilities. But this alternative would collapse if the f-probabilities of the unitary interpretation were not numerically equal to the probabilities of the standard plural interpretation. Rational betting behaviours could not then intelligibly be the same on the two interpretations. One might say, 'so much the worse for the unitary interpretation' but that wouldn't be justified because in the situation where Una fissions into two subjects making different observations *there is no overriding reason* to suppose that she should assign an f-probability of ½ to seeing one or the other outcome. And so there is no justification for throwing out the unitary interpretation of doppelgangers on those grounds.

To emphasise this point, think again about the comparison with RSqm. If a quantum measurement is set up which has two outcomes, one with square modulus of amplitude equal to two-thirds and the other one-third then RSqm demands that those values determine the prior f-probabilities. The intuition that a subject should assign f-probabilities of a half to each outcome because the upstream subject expects to fission into two downstream subjects is trumped by the arguments which entail that it's the Born rule which determines f-probabilities. Likewise, the argument which I've just given for the classical analogue can counter a similar naïve intuition.

The classical setup does not *require* that Una has a multi-button which initiates a stochastic process. I just used that idea for ease of exposition. Stochasticity could simply be introduced in determining the 'initial conditions' for classical worlds, as in any classical deterministic theory. In that case the picture which emerges for the classical model is that if we have a large collection of worlds which are parallel up to a point but with differing initial conditions then an observer spanning a fibre-bundle of linear histories of such worlds will be subject to personal fission when observing differing phenomena as that fibre-bundle of parallel histories differentiates into sub-bundles of divergent histories. And the proportions of worlds in branching sub-bundles will tend to be numerically equal to the informed subject's f-probability assignments if the initial number of worlds is large but finite. However, there is now no need to confine the classical model to finitude.

4 Resolving the Cosmological Measure Problem

How are f-probabilities in the classical model to be understood when a subject spans an infinite number of worlds? As is well known, the concept of proportion cannot apply to infinite collections. But the unitary interpretation of doppelgangers offers a neat solution to this problem since its coherence depends on any utterance made by the unified subject being qualitatively identical to those attributed to the individuals D_{Left} , D_{Right} etc., by the conventional plural interpretation of doppelgangers.

As we saw earlier, if the conventional plural interpretation is applied and the subjects in each world are assumed to be well-informed of the probabilities associated with a stochastic process then those subjects can speak truly about those probabilities. But for the unitary interpretation to work any apparent talk of probabilities by the likes of D_L and D_R must numerically tally with Una's talk of f-probabilities. *And this must be so whether the collection of doppelgangers is finite or infinite*. So the measure problem for the classical model evaporates if the unitary interpretation is adopted because that interpretation of an observer's predicament when spanning an infinite number of worlds supplies exactly the measure which is needed. Talk of a probability of value N for a given outcome by well-informed subjects on each planet according to the plural interpretation translates into talk of an f-probability of value N for the corresponding multi-outcome on the unitary interpretation.

5 Superslice me

We can now attempt to apply these ideas to a GMH ensemble of fine-grained histories where a fine-grained history is understood in terms of extended probabilities, always remembering that the picture relies on the acceptability of the choice of preferred variables. Return to the two-slit experiment and consider an electron's wavefront just prior to impinging on the detector screen. It somehow contains the characteristic interference pattern. And suppose that what Gell-Mann and Hartle take to be an imaginary ensemble of fine-grained histories is wholly real. From the point of view of one of the fine-grained histories there is a relevant electron somewhere, but for any given spatial region only an extended probability can be assigned to that electron's being there. Considered as a whole, the ensemble of fine-grained histories thus furnishes a multitude of relevant electrons, one in each history, which are following non-differentiable trajectories with associated extended probabilities.

Let's now apply the unitary interpretation of doppelgangers to this setup. The idea would be that in each fine-grained history there is a single doppelganger, like D_L and D_R in the earlier classical example. Certainly the fine-grained histories are not perfectly isomorphic. The dynamics in each fine-grained history in the ensemble is determined by mutual causal interaction which depends on anisomorphisms between those histories. But the histories in the ensemble are only anisomorphic at the *fine-grained* level. At a level of coarse-graining determined by decoherence the histories constituting the ensemble are isomorphic. What follows depends on the assumption that isomorphism at this level is all that is needed to apply the unitary interpretation of doppelgangers. That is, fine-grained anisomorphism between doppelgangers is not sufficient to determine qualitatively distinct mental lives for them. The intuitive support for this is that such subjects can only observe coarse-grained aspects of their environment.

Applying the unitary interpretation of doppelgangers, the setup for an electron passing through a two-slit apparatus is that the observer is a single subject spanning an ensemble of fine-grained histories and the single electron in the observer's environment is somehow constituted by a multitude of relevant electrons, one in each fine-grained history. What is the mode of constitution of the observer's single electron? Should we appeal to the Concrete Set rule and consider the single environmental electron to be a multipleton set? No, it turns out that in the quantum context that's not necessary.

In the classical model Concrete Sets excludes aggregates because in the classical setup we were considering worlds as Hubble spheres distributed in space. A *spatial* aggregate of apples weighs more than an apple. But within currently defensible metaphysics a type of aggregate can be described in which an apple is an aggregate of timeslices. According to the worldtube version of four-dimensionalist metaphysics, popularly known as worm theory, an apple is an aggregate of timeslices. And when an apple has a stable weight for a period, each timeslice of the apple over that period weighs what the apple does. In the quantum context might there be another type of aggregation available which is more akin to temporal aggregation than spatial aggregation?

It turns out that there is. It was first introduced, so far as I know, in Tappenden ([2000], pp. 105-8). When an object is in superposition, as is the single electron passing through the two-slit apparatus, the components of that superposition can be understood to be its 'superslices'[13]. When an object is an aggregate of superslices the whole has some definite property if and only if all the superslices share that property. This is similar to the idea that a temporally extended object only has a determinate mass if its mass does not change during the course of its existence. So, in the case of Schrödinger's famous cat, if its dead and live superslices each has a mass of two kilos the superposed cat-in-the-box has a mass of two kilos also.

The upshot is that in applying the unitary interpretation of doppelgangers to the quantum context we do not need to have recourse to set theory as was the case for the classical model. Mereology will do. Given the concept of superslices, coupled with the idea that the GMH ensemble of fine-grained histories is real, the

[13] The term 'superslice' was used because it names a component of a superposition which is analogous to a temporal part, ie. a timeslice. This of course presumes a 'preferred basis' for the decomposition of the superposition. But the assumption of a defensible basis is already required for Gell-Mann's and Hartle's analysis, as they acknowledge.

Concrete Set rule for the unitary interpretation of doppelgangers in classical contexts can be transformed for use in RSqm.

To see how this could work, keep in mind first of all than Gell-Mann's and Hartle's proposal is that our observed environment is constituted by a *single* fine-grained history. But the observable properties of our environment are not the fine-grained properties, they are emergent, coarse-grained, properities of the single history. And given the assumption that only a single fine-grained history exists the implication is that linear superpositions do not exist; they are notional in the sense that they are features of what Gell-Mann and Hartle take to be the *imaginary* ensemble.

Schrödinger's cat will do perfectly well to illustrate the point despite practical difficulties. For Gell-Mann and Hartle the inside of the box is constituted by part of a single fine-grained history. Coarse-graining of that history at a given moment yields a probability that there is a live cat present and a probability that there's a dead cat. It's one or the other but we don't know which. The single history is perfectly definite, so it's relevant coarse-grained feature must either be a live or a dead cat. But if, as I'm suggesting, the GMH ensemble is taken as not being notional but as actually existing, then the live and dead cats are both present. And that can be made intelligible if a single subject is taken to span an ensemble of fine-grained histories so that the box in the observer's environment contains a cat which has a live superslice and a dead superslice, analogous to Una's concrete set cat which has white and black cats as subsets.

Minimal superslices of an environmental object are analogous to traditional instantaneous timeslices. They are the finest parts into which an environmental object can be superpositionally decomposed and each of those parts resides in a distinct fine-grained history, where a history is understood as a temporally extended object. An aggregate of minimal superslices may also be a superslice of an object, just as an aggregate of minimal timeslices of a temporally extended object may also be a temporal part of that object. The specification of 'observable' properties is inherited from the Concrete Set rule of the classical model because there is no reason to suppose that the number of fine-grained histories spanned by a given macroscopic environment at a time is observable. As we have already seen, and are about to see again, it is a measure of *relative* numbers of worlds spanned by a subject at earlier and later times which connects with observable f-probabilities. To sum up, we can now replace Concrete Sets with:

Superslices

> Any environmental object Q is an aggregate of minimal superslices which are fine-grained history counterparts and Q possesses some coarse-grained property P if and only if all the superslices of Q possess P.

6 A Constitution for Wavefunction

Equipped with Superslices we can now apply the unitary interpretation of doppelgangers to the idea of an extant GMH ensemble to provide an account of the two-slit experiment for RSqm. A single electron passing through the two-slit apparatus is an aggregate of superslices. The minimal superslices of the electron are the relevant counterparts in each of the fine-grained histories which the observer spans, in the sense that the observer has a component doppelganger in each of the fine-grained histories. Those histories are isomorphic at the coarse-grained level which constitutes the decohered environment which the observer inhabits, including the two-slit apparatus, flashes of lightning outside the laboratory window, and so on.

Relative to the single observer yielded by the unitary interpretation of doppelgangers, one electron superslice has passed through the left slit and one has passed through the right slit (for the sake of simplicity I ignore marginal pathways such as those passing outside of or tunneling through the barrier in which the slits are made). Each of those electron superslices is composed of minimal fine-grained superslices, each in a single fine-grained history. For each of those minimal fine-grained superslices only an extended probability can be assigned to its passing either through the left slit or the right slit. This is analogous to a football match having two timeslices, one before half-time and one after half-time. Each of those timeslices is composed of a multitude of minimal timeslices. The temporal decomposition of the first and second halves of the match is usually thought of as continuously infinite, going down to instantaneous timeslices, though a more realistic analysis may involve a finite decomposition down to timeslices of Planck duration.

For the electron wavefront about to impinge on the array of electron detectors which constitutes the screen there is a distribution of those fine-grained electron superslices, each with an associated extended probability in relation to being at a particular finite volume of location. As decoherence takes place with the interaction between the observer's single environmental electron and the screen, the ensemble of fine-grained histories branches into many coarse-grained histories, in each one of which a different detector in the array fires. Each of those coarse-grained histories is shared by a multitude of fine-grained histories which are anisomorphic. The image is of a bundle of fibres being separated into sub-bundles, like hair being divided in into tresses.

For each of the coarse-grained histories corresponding to the firing of a particular detector the squared modulus of amplitude yields an f-probability associated with the electron being detected by that particular detector. And those f-probabilities will have a distribution corresponding to the familiar interference pattern, manifest over time as the number of hits is recorded for each detector when the screen is exposed to a stream of electrons.

Given that for a single fine-grained history coarse-graining yields values of probabilities by the Born rule, it must follow that for the unitary interpretation of a GMH ensemble the corresponding values of f-probabilities are likewise determined. That follows from an argument parallel to the one by which the unitary interpretation of a classical multiverse resolves the cosmological measure problem.

As the observer's single superposed environmental electron interacts with the screen the observer fissions into multiple observers, each seeing an electron activate a different detector in the array which makes up the screen. The single electron in each of the downstream observers' environments is a superslice of the object which was the single electron in the upstream observer's environment[14]. And the single electron in each of the downstream observers' environments has a host of minimal electron superslices as parts. Each downstream observer spans a multitude of fine-grained histories which is a part of the original ensemble.

This provides an account of branching for RSqm which puts flesh on wavefunction. In general, any object in an observer's environment, such as a table, can be understood to be *constituted* by wavefunction in the sense that the wavefunction of the table is the manifestation of an ensemble of temporal segments of fine-grained histories which the observer spans as a single subject. The observer's body and brain spans the same ensemble of fine-grained histories as are spanned by the observed table at the time it is observed, that table being understood to be composed of many superpositional parts at the fine-grained level, many superslices.

7 Varieties of Divergence

A few loose ends need tying up. Firstly, the whole proposal depends on taking the unitary interpretation of doppelgangers seriously. The perspective which yields objects in our environment as constituted by wavefunction is that which supposes us to be observers who span a host of 'parallel universes'. But the idea of a single subject spanning a multitude of worlds in that way usually strikes people as surreal on first acquaintance. Nowhere in modern philosophy of mind has this idea been mentioned outside the single recent paper to which I've referred. It is only reasonable to expect readers to be sceptical about such a novel idea which has not yet been subjected to substantive exposure in the philosophy of mind community. However, for the moment it does seem that there is no good reason to reject this idea beyond a gut sense of hilarity.

What I have said falls within the tradition of thinking about RSqm which Hilary Greaves once dubbed the fission programme. There is an alternative programme which has gained much force recently thanks to the work of Simon

[14] This way of speaking assumes Ted Sider's analysis of transtemporal identity. See Tappenden ([2011a], pp. 115-6) for details and references.

Saunders and Alastair Wilson. It's what might be called the divergence programme. It will be useful to say something about the relation between the ideas presented here and current discussion of that alternative.

There seem to be two independent strands to the divergence programme. One was introduced by David Deutsch ([1985], p.20). He has subsequently radically altered that original idea ([1997], pp. 43-5), ([2002]), ([2011], pp. 258 - 303) but has retained the concept of divergent parallel universes. The other strand was effectively first fielded by Saunders and Wallace ([2008a], [2008b]). The aim has been to provide a straightforward solution to the problem of making sense of probabililty in RSqm. According to the fission programme, a subject about to conduct a quantum measurement with multiple outcomes cannot assign a genuine probability to observing any of those outcomes, other than the probability of 1 of observing each of them simultaneously. Within the fission programme this problem is arguably met by positing what I've called f-probabilities and maintaining that f-probabilities can take on the same role as probabilities in guiding behaviours such as the paradigm betting against given odds. But the approach has some controversial consequences, as I mentioned earlier.

The divergence programme is much simpler in this respect. Where a quantum measurement has outcomes A, B, C… the divergence view posits parallel universes which are isomorphic up to the time of measurement and then diverge, result A occurring in one set of worlds, result B in another set and so on. The idea is then that probability arises out of self-location. Prior to the measurement a subject can assign genuine ignorance probabilities to inhabiting a world which is one of a set where A will occur, or one of a set where B will occur and so on. It is argued that the probabilities so assigned should be exactly those entailed by the Born rule.

Wereas Deutsch originally introduced the multiplicity of parallel worlds as a posit, what he called Axiom 8, Saunders has recently argued that the picture is already implicit in the formalism of quantum mechanics ([2010]). And Wilson ([2011], [2012]) has built on Saunders' idea to construct a divergence view of RSqm which takes its inspiration from David Lewis's 'modal realism' ([1986]).

If the unitary interpretation of doppelgangers were applied to any of these ideas the result would be that from a subject's point of view the divergence would induce personal fission. For the quantum measurement of A, B, C… there would be a single subject spanning a host of parallel universes and that subject would undergo fission into a subject spanning the universes with the A result, a subject spanning the universes with the B result and so on.

In that case the unitary interpretation of doppelgangers would only seem to bring trouble. The simple probabilities of divergence would have to be replaced by the f-probabilities of fission. And an extant GMH ensemble can provide a causal explanation of divergence, as we've seen. Deutsch's, Saunders' and Wilson's parallel universes would be branching bundles of interfering GMH histories, isomorphic at the coarse-grained, quasi-classical level but anisomorphic microscopically. And the classical cosmological measure problem wouldn't arise for this sort of divergence since the Born measure applies in the quantum domain.

A perceived virtue of divergence is that it has none of the bizarre consequences which are arguably entailed by fission when it comes to quantum Russian roulette and suchlike. On the other hand, the unitary interpretation of doppelgangers should be welcome in the analysis of cosmological multiverses since it provides a long sought-after resolution of the measure problem without the requirement of a finite limit on the number of constituent universes. Cognitive science may benefit too, from a rigorous challenge to contemporary semantic externalism, ushering the mind back into the body[15]. And it does seem that the unitary interpretation of an extant GMH ensemble allows us to understand how objects in our macroscopic environment may be constituted by the quantum-mechanical wavefunction.[16]

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[15] Detailed discussion can be found in Tappenden, ([2011b]).

[16] My thanks to David Deutsch, Simon Saunders and Alastair Wilson for useful comments. And particularly to an anonymous referee for a very detailed critique of the previous version posted on PhilSci Archive.

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