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HOW MANY LIVES HAS SCHRÖDINGER'S CAT?[1] THE JACK SMART LECTURE, CANBERRA, 27 JUNE 2001

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I really pity
Schrödinger's kitty

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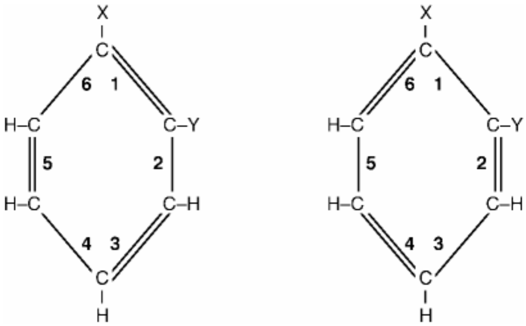

Figure 1

I. Quantum Mechanics: Superpositions

To reach the point I want to discuss, I must begin with a sketchy review of quantum mechanics. I apologise to those of you who know this material already, perhaps better than I do. But it will be an opinionated review: some of my opinions are eccentric. So there may be something in it even for those who are already expert.

Quantum mechanics is, in a nutshell, the theory of *superpositions*. To introduce this concept, I begin with the standard account of the benzene ring—an account so well entrenched in organic chemistry that it would probably survive even if its quantum-mechanical foundation crumbled away beneath it.

The benzene ring is a hexagon of carbon atoms, each with a hydrogen atom attached. Replace two adjacent hydrogens with two different substituents, so that we can unambiguously number the sides of the hexagon. Two structures conform to the rules of valence: one with double bonds on the odd-numbered sides, another with double bonds on the even-numbered sides (see Figure 1).

The molecule reacts sometimes as if it had one structure, sometimes as if it had the other. Yet we do not think that a population of molecules is a mixture of the two structures. Neither do we think that each molecule oscillates rapidly between one structure and the other. Neither do we think that the molecule has a betwixt-and-between structure—there is no such thing as a bond midway between double and single. Rather, we think that each molecule is in a superposition: a state objectively indeterminate between the two structures. Objective indeterminacy is multiplicity: a cloud of indeterminate extent, for instance, is really many clouds, almost but not quite identical to one another [Unger 1980; Lewis 1999b].[2] Likewise a molecule with an objectively indeterminate structure is really two coexisting molecules, one with one structure and one with the other. (Or at any rate, two things that are molecule-like except for from their coexistence with one another.)

[2] The thesis that indeterminacy in nature is multiplicity fits well with the thesis that indeterminacy in language is semantic indecision: there are many clouds, and we haven't decided just which one to call 'the cloud'. Nevertheless, the two are separable. Maybe instead 'the cloud' refers to the entire multiplicity; or maybe just one of the many—but it is a secret which one—is a mighty reference magnet, and so 'the cloud' refers to that one.

Picture the molecule as a double image, as if we drew the two structures on two transparencies and laid one over the other.

Some terminology. We call the resolutions of the indeterminacy—the superimposed images—*branches* of the superposition. And we call a state which is not a superposition (or is, if you prefer, a degenerate one-branch superposition) a *sharp* state.

We can say that each bond is in a superposition of double and single. But if we say just that, we lose information. The superpositions of the individual bonds are *entangled*. That means that a double bond on any odd side goes with double bonds on the other odd sides, and likewise a double bond on any even side goes with double bonds on the other even sides. Relative to a double bond on side 1, we have one structure for the whole molecule; relative to a single bond on side 1 we have another. No branch of the superposition for the whole molecule hybridizes the two structures, putting double bonds on sides 1, 3, and 4, say. Some superpositions are entangled with other superpositions distinct from themselves. Others are unentangled, though they may have parts which are entangled with one another.[3]

Another example. We aim a photon at a half-silvered mirror that lies diagonally across its path. A fully-silvered mirror would deflect the photon sideways. An unsilvered sheet of glass would let it go straight ahead. But a half-silvered mirror creates a superposition: one branch is the photon deflected, the other branch is the photon going straight ahead. Again we can picture it as a double image (see Figure 2A).

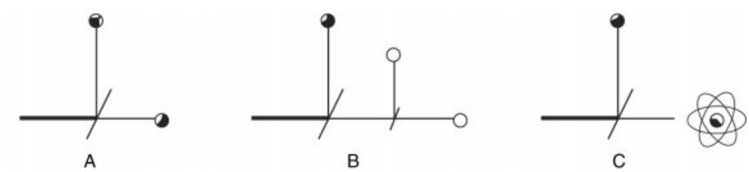

Figure 2

Now suppose we add a second half-silvered mirror. The same thing happens again. The straight-ahead branch of the previous superposition divides into a deflected branch and an undeflected branch, so we have three branches in all. However, these branches are not all on an equal footing. One of them, the one deflected at the first mirror, is more intensely present than the other two (see Figure 2B). In general, branches of superpositions have *intensities* (also known as squared amplitudes): the intensities are often unequal, and the intensities of all the branches add up to one. (Branches of unentangled superpositions are characterized also by another quantity, called *phase*, of which more will be said later.)

Suppose we add not a second mirror but rather a detector atom: an atom which, if struck by a photon, will absorb the photon and become excited. Now we get a superposition of deflected photon plus unexcited atom versus no deflected photon plus excited atom (see Figure 2C). This case teaches another new lesson: not only positions, but other

[3] Some would prefer to reserve the word 'superposition' for what I would call an unentangled superposition. When I speak of two entangled superpositions, they would prefer to speak of two mere parts of a bigger superposition. Others would say 'coherent superposition' for the unentangled superposition and 'incoherent superposition' for the entangled parts thereof.

magnitudes as well, can be in superpositions. For the difference between the excited and unexcited states of the detector atom is, in the first instance, a difference of energy. We need not assume (though it may be true) that this difference of energy rests on any difference in the positions of things. This difference in energy is entangled with the superposition of deflected versus undeflected photon.

A final example: quantum tunnelling. Confine a particle (or a system composed of several particles) behind some sort of barrier. It could be a force field; it could be a material obstacle. The particle (or system) goes into a superposition of positions. As time goes by, more and more of the total intensity goes to branches that lie beyond the barrier. The less permeable the barrier, the less total intensity goes to branches that lie beyond it, but the intensity never goes to zero. This time, we have not a finite number of branches but a continuous infinity of them. We can no longer picture the superposition as a multiple image: the multiple images blur together into a cloud, with different intensities in different parts of the cloud. That is what it means to picture the superposition as a wave.

We saw that position superpositions can be entangled with superpositions of other magnitudes. (If so, we can say for short that the magnitudes themselves are entangled.) We can even have a superposition which is entirely a superposition of a magnitude other than position. A complete description of an unentangled position superposition, specified in terms of its branches and their intensities (and their phases), will in general be equivalent to a complete description of various unentangled superpositions of other magnitudes, though in general with different intensities (and phases). Indeed, a sharp state of one magnitude is equivalently specifiable as a spread-out superposition of some other, 'complementary' magnitude.[4] Here, however, we shall confine our attention to superpositions of position, involving other magnitudes only insofar as they have become entangled with position. I leave in abeyance the question how my story could be retold in terms of other magnitudes. The mathematics of quantum mechanics does not privilege position superpositions. I shall privilege them, for ease of exposition and because I doubt that anything much is lost. Whether there is any sense in which nature privileges them I do not venture to guess.

Superpositions evolve as time goes by, as we've seen. For the most part, at least, their evolution is continuous and deterministic. We call such evolution *Schrödinger evolution* because it is governed by a differential equation due to Erwin Schrödinger.

II. Quantum Mechanics: Collapse

But sometimes, so say almost all versions of quantum mechanics, Schrödinger evolution is interrupted by a very different process, *collapse*. Collapse is neither continuous nor deterministic. When a superposition collapses, it is instantaneously replaced by a sharp state corresponding to a single one of its branches.[5] Instead of the multiple coexisting actualities of

[4] This is the *Uncertainty Principle*. It is ill-named: when we know, say, that a particle has a sharp position, we are not at all ignorant or uncertain about the complementary magnitude. We know just what superposition the complementary magnitude is in, and that's all there is to know about it.

[5] A single branch; or, at least, a superposition in which all of the total intensity is concentrated upon branches that fall within a very small sphere. Such incompleteness of collapse matters little, provided that almost-collapsed superpositions and fully collapsed ones would act in much the

superposition, we end with one of several alternative possibilities. Which one is a matter of chance (also known as single-case objective probability). The chance of collapse to any given sharp state equals the intensity of the corresponding branch of the superposition. When a superposition collapses, so does any other superposition that is entangled with it.

Why should we believe in collapse? Recall our example of the photon, the half-silvered mirror, and the detector atom. When one branch but not the other of the superposition of undeflected photon versus deflected photon reached the detector atom, the atom in turn went into a superposition of excited versus unexcited. That is what Schrödinger evolution predicts. Now replace the detector atom by a macroscopic photon detector with a pointer that can point to 'yes' or to 'no'. This time, Schrödinger evolution predicts that the pointer will go into a superposition of pointing to 'yes' versus pointing to 'no'. Now, we never see atoms, so we're in no position to tell whether they're in sharp states or not. But we do see the pointer. When we do, we see that it's in a sharp state of pointing either to 'yes' or to 'no'. Or so it certainly appears. Unless this appearance is an illusion—but soon we shall consider hypotheses which say that it is exactly that—Schrödinger evolution must be interrupted at some point by collapse.

Similarly in quantum tunnelling, when some of the total intensity goes to branches of a superposition that lie beyond a barrier, collapse can result in the particle appearing at a sharp location beyond the barrier. That is what we think happens in radioactive decay, at least if the decay is observed by means of a Geiger counter.

When does collapse take place? There are many hypotheses on the market, and thus many versions of quantum mechanics. Unfortunately they are as near as makes no difference empirically equivalent. Our only hope of adjudicating between them is to judge them on their inherent plausibility. Most of these hypotheses fall on a spectrum, starting with those on which collapse takes place often and easily, and ending with those on which collapse takes place only under very special conditions.[6]

We begin, however, not with any of the hypotheses on our spectrum but with an empirically *in*adequate hypothesis. This hypothesis says that superpositions are born already collapsed, or at least that all of them collapse extremely quickly. Immediately, or extremely soon, what we have is not a superposition but a sharp state, and which sharp state we have is a matter of chance.

To see why this won't work, we need to say a little more about phase. Here is what we need to know. If two branches of an unentangled superposition diverge and then re-unite,

[5] *continued*
same way upon other things they encounter.

I distinguish such incomplete collapses from *localizations* (also known as collapses with tails). Localizations are chance redistributions of intensity in which not quite all the intensity, but only the lion's share of it, becomes concentrated within a very small sphere, and in which the intensity of a branch never falls quite to zero. Localizations, like collapses, are indeterministic interruptions of Schrödinger evolution; nevertheless, what I shall say later about the deterministic no-collapse hypothesis on which Schrödinger evolution is never interrupted will apply equally to localization hypotheses.

[6] The so-called 'Bohm interpretation of quantum mechanics' falls nowhere in this spectrum. Although built to be empirically equivalent to quantum mechanics, Bohmian mechanics is not a version of quantum mechanics at all. It is a rival theory, presenting a radically different account of the workings of nature. This account is weird, weirder than some of the versions of quantum mechanics we shall consider, less weird than others. But it is weird in totally different ways. See Albert [1992: 134 ff].

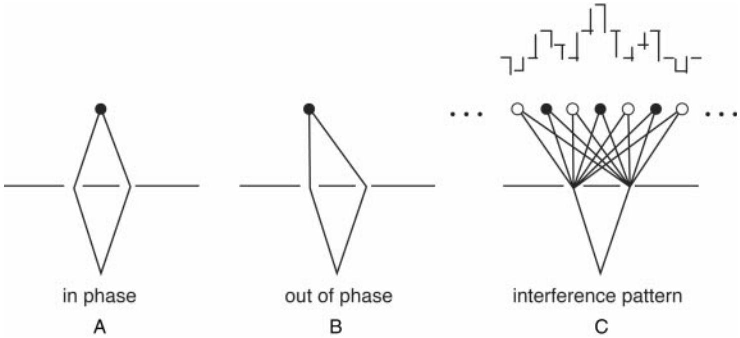

Figure 3

they may be matched or mismatched in phase. If exactly matched, their intensities add (see Figure 3A). To the extent that they are mismatched, they reinforce one another less or not at all (see Figure 3B). If they are exactly mismatched, and also equal in intensity, they cancel altogether. As a branch of a superposition goes forward from the point of divergence to the point of re-uniting, its phase on arrival depends cyclically on how far it has travelled. Consequently we get interference phenomena, like the pattern in the well-known two-slit experiment (see Figure 3C).[7] But if superpositions were born collapsed, or if they collapsed before they had gone very far, there would be no matches or mismatches of phase, so there would be no interference phenomena. And interference phenomena are in fact observed.

The tenable hypotheses in our spectrum disagree about whether or when there are macroscopic superpositions: superpositions involving enough particles in entangled states to constitute some macroscopic object. We can observe the interference phenomena arising from microscopic superpositions. We cannot observe interference phenomena arising from macroscopic superpositions. The reason is that if the macroscopic superposition develops new entanglements in the course of the experiment, the interference phenomena vanish (because the branches of an entangled superposition have no phases); and we cannot in practice isolate a macroscopic thing from its environment well enough to prevent new entanglements [Albert 1992: 88ff]. That is why hypotheses that disagree only about macroscopic superpositions are, near enough, empirically equivalent.

Take our example of the photon, the half-silvered mirror, and the macroscopic detector with a pointer that points to 'yes' or 'no'. Suppose the photon has had time to reach the detector, but the pointer has not yet been observed. One hypothesis (one out of several) says that so far we have had nothing but Schrödinger evolution; the pointer is now in a macroscopic superposition of 'yes' and 'no', with equal intensities (but no phases, since the

7 Imagine a row of counters above the two slits, and each one counting the particles that reach it. The interference pattern shown at the top of Figure 3C is a pattern of counter readings. How do the intensities of the branches of the superposition translate into the pattern of counter readings?—A good question, but one that is differently answered by different ones of the hypotheses we shall consider.

pointer has become entangled with its environment); collapse will take place when someone observes the pointer, not before. Another hypothesis says that collapse has already taken place; the pointer is already pointing either to 'yes' or to 'no', but we do not yet know which. Both these hypotheses make the same probabilistic prediction about what will be seen when the pointer is observed: 'yes' or 'no' with equal probabilities. Both hypotheses invite the same mathematical representation of the pointer: a 'mixture' of 50% 'yes' and 50% 'no'. But that representation is ambiguous. On the first hypothesis, the weights in the mixture are intensities of coexisting actualities. On the second, they are probabilities of alternative possibilities. At this point, someone whose distaste for distinctions without any empirical difference outweighs his distaste for doublethink might insist that the two hypotheses are not just empirically equivalent; they are one and the same hypothesis. That would mean that collapse has somehow been conjured up out of Schrödinger evolution: what has happened so far is nothing but deterministic Schrödinger evolution and it is indeterministic collapse! This is empiricism gone mad. Set it aside. We should not conflate empirically equivalent hypotheses. Rather, we should be prepared to admit our ignorance [Bell 1990; Albert and Feinberg 1993: 81].

The first hypothesis on our spectrum says that there are no macroscopic superpositions. Any process that might have brought a macroscopic superposition into being brings about collapse instead. Macroscopic superpositions are born collapsed; microscopic superpositions, in accordance with our observations, are not.

We can object that being macroscopic is a matter of degree, collapse is all or nothing. There will have to be a law that collapse takes place when some arbitrary threshold is crossed. This is somewhat repugnant, though there are worse repugnancies to come.

Our next hypothesis says that not only is the outcome of a collapse a matter of chance, but whether collapse takes place at all is too; and that the chances of collapse at any given moment are such that the more macroscopic a superposition is, the less stable it is. Now we have matters of degree on both sides of the collapse law, so we need no arbitrary threshold. But if the chances are right, the upshot will be almost the same as that of the previous hypothesis: microscopic superpositions are stable enough to fit our evidence for their existence, whereas macroscopic superpositions will in all probability disappear very quickly.

The GRW hypothesis (in a simplified version) implements this idea as follows [Ghirardi, Rimini, and Weber 1986; Albert 1992: 92ff].[8] There is a constant but very low chance of any particle in a superposition taking a collapse-hit. When it does, its superposition collapses; and any further superposition entangled with it collapses too. So a superposition of two entangled particles has a double chance of taking a hit because either particle can take the hit. For a superposition of a million entangled particles, the chance of collapse is multiplied a million-fold. But a macroscopic superposition consists of vastly more than a million entangled particles. So the very low chance of collapse for an

[8] However the real GRW hypothesis, unlike the simplified version considered here, posits spontaneous localization rather than spontaneous collapse (see footnote 4). Turning GRW into a collapse hypothesis would require an additional revision of Schrödinger evolution, besides the hypothesis that it is sometimes interrupted by chance events. See Lewis [1995]; and Albert and Loewer [1995]. I take it that any other collapse hypothesis would require the same additional revision for the same reason.

individual particle translates into a very high chance of collapse for a macroscopic superposition. Unfortunately we have no very precise estimate of the chances of collapse if all we know is that they are not too low and not too high. That seems at worst a minor drawback.[9]

I much prefer this, or something like it, to all the other hypotheses we shall consider. It is a comfortable and plausible way for nature to work, though scarcely the pinnacle of mathematical or metaphysical elegance. (Or so it seems to me. Perhaps that is because my scientific background lies not in mathematical physics but in chemistry.) But our present topic lies at and beyond the far end of our spectrum, so let us push on.

The most popular hypothesis—the one you find in the textbooks—says that collapse is brought on by measurement. When we attempt to measure a magnitude that is in a superposition, the superposition collapses to give a sharp state of the measured magnitude. Usually, this 'Projection Postulate' is said to apply to all magnitudes indiscriminately; but we won't go far wrong if we confine our attention to measurements of positions or of magnitudes that have become entangled with positions. For real-life measurements are always mediated by the position of something: a pointer on an instrument, the top of a mercury column, a pattern on a photographic plate, a spot of light on a screen, a sound wave in the air, or what have you. We can think of the measurement as proceeding in two steps: first the quantity to be measured becomes entangled with the position of something, then the superposition collapses. And if instead the measurement and collapse happen all at once, that doesn't matter, provided the chances of various outcomes for the one-step process are the same as those for the two-step process would have been.

We can object that it is unclear when a measurement is complete. We usually think of a person, perhaps aided by a measuring instrument, gaining information about the magnitude measured. But what if something intervenes before the information reaches the person, if it ever does? Suppose the result of the measurement goes to a recording instrument. Or suppose the measurement is made by a crude robot; or suppose it is made by a sophisticated robot, functionally isomorphic to a person. Or suppose it is made by a trained chimp, capable of handing on the information gained to a person by sign language. Or suppose it is made by an almost-human prehistoric hominid who has somehow survived into our own time. Which of these, if any, are measurements within the meaning of the collapse law? Is the measurement complete, and does collapse take place, only when a person comes along and retrieves the information from the recorder or the robot or the chimp or the hominid? Again it seems that the collapse law will have to involve an arbitrary threshold.

A more serious objection is that measurements comprise an anthropocentric kind, not a physical kind. What's distinctive about them is not that they are unlike other physical processes but rather that they can serve the human purpose of gaining information. Therefore it is repugnant that the class of measurements should figure in the collapse law, which is after all meant to be a basic law of physics.

[9] We might narrow the bounds by looking for interference phenomena involving superpositions that are not quite microscopic but still far from macroscopic. If, before reaching the point where interference patterns disappear, we found attenuated interference patterns, that would not only give us a much better estimate of the chances of collapse but also would to some extent support the present hypothesis over the other collapse hypotheses in our spectrum, making these hypotheses not quite empirically equivalent after all. For a report on the study of superpositions that are more than microscopic but less than macroscopic, see Blatter [2000].

(That might seem not so bad to someone who thinks that the fundamental point of any scientific theory is not to describe the workings of nature but rather to predict our observations. Perhaps the popularity of the present hypothesis is due partly to an unholy alliance of anthropocentric physics with verificationist philosophy.)

Our next hypothesis defeats both these objections at the cost of a commitment to psychophysical dualism. Whether that makes it more or less repugnant than the previous hypothesis is a matter of taste. The hypothesis is due *inter alia* to Wigner [1961, 1964]. There are 'two kinds of reality': physical reality and Consciousness. (I spell it with a capital C to mark that it is not the mundane sort of consciousness that materialists believe in.) Consciousness never goes into superpositions. So when a superposition in physical reality acts upon Consciousness (via the pineal gland, perhaps?), Consciousness cannot in turn go into a superposition. Instead, the superposition collapses, and it is the result of that collapse that registers in Consciousness. There is no arbitrary threshold: collapse takes place exactly when the divide between superposed physical reality and Consciousness is crossed. There is no resort to merely anthropocentric kinds: the division between physical reality and Consciousness goes as deep as deep can be.

The last hypothesis in our spectrum is a solipsistic version of the previous one. Again it is due to Wigner; though in fairness it should be said that he sometimes defends only its empirical adequacy—at least for Wigner himself—and not its truth [Wigner 1961: 289f; 1964: 249, 256ff.]. On the solipsistic hypothesis, only Wigner partakes of Consciousness; the rest of us are part of physical reality, mere material minds. As before, superpositions collapse when physical reality acts upon Consciousness, but now it is only Wigner who has the power to bring on collapse. When a superposition acts upon a mere material mind, the mind does indeed go into a superposition.

This hypothesis retains the repugnancy of the previous one, and adds a further repugnancy. What's so special about Wigner? Why should he differ, in a metaphysically fundamental way, from all the rest of us?

Wigner imagines that he has a friend who makes a measurement and subsequently is debriefed by Wigner [1961: 289f, 292ff]. Collapse ensues only when the information reaches Wigner's Consciousness. Before that, the friend is in a superposition of states of seeming to have observed various different measurement results.

What is it like to be Wigner's friend? He is a mere material mind, but that is not to say that he is a zombie. *Ex hypothesi*, all of us with the sole exception of Wigner are material minds, yet we can scarcely deny that there is something it is like to be us! So material minds must be conscious in some sense, though not Conscious in the way Wigner is.[10]

Wigner's friend has gone into a macroscopic superposition. Superposition is multiplicity, so there are many of him. Each branch is a material mind (or just like one, except for coexisting with the others).[11] Each one thinks he's observed some sharp measurement

[10] By a zombie, I mean something that is not conscious in any acceptable sense whatever. I do not mean a Zombie, that being someone who is conscious in a materialistically acceptable 'psychological' sense, but is not conscious in some more exalted sense. There is something it is like to be a Zombie because a Zombie has experiences—again, in a 'psychological' sense. I take it that all of us, except *ex hypothesi* Wigner, are Zombies. On psychological senses, see Chalmers [1996: 11–30].

[11] If I am to adhere to a policy of confining my attention to position superpositions, I must assume that mind supervenes not just upon physical reality but upon the positions of things. That seems

outcome, but different ones of them think they've observed different sharp outcomes. None of them feels as if he's in an indeterminate state, because that would not correspond to any single branch of the superposition. There is no collapse until Wigner comes along, yet because different branches of the previous superposition have acted differently to bring about different branches of Wigner's friend, each branch of Wigner's friend is under the illusion of seeing a sharp state, and thus under an illusion of collapse.

The same thing happens again if Wigner's friend has a friend of his own, another material mind, and Wigner's friend tells his own friend what he has seen. Wigner's friend's friend in turn goes into a superposition. Each branch thinks he has been told something definite, but different branches think they've been told different things. The branches of Wigner's friend's friend in turn are under an illusion of sharpness and of collapse.

Wigner's friend branches, I said. Some philosophers reject the very idea that people, or anything else, can branch. For when one becomes two, it seems that one single thing is identical to two different things. I reply that there are two all along, though before the branching the two were temporarily identical in the sense that they shared an initial temporal segment. Temporary identity is not identity *simpliciter*, as witness the different futures of the two. But it does imply that before branching the two were exactly alike with respect to their present properties. In particular, they thought alike, since their shared segment did the thinking for both of them. They had exactly the same desires and expectations regarding their futures.[12]

The question what someone should expect if he anticipates branching is familiar even apart from quantum-mechanical branching. Suppose you are about to be beamed up, and you know that the signal will be received both on the starship *Enterprise* and on the starship *Potemkin*. Let's assume that beaming up works not by transmission of matter, but by transmission of structural information. That guarantees causal continuity in all bodily and mental respects. You will survive—twice over. (What does it matter that you will be made of different atoms afterward? Atoms are the ultimate interchangeable parts, and most of them will be replaced within a few years anyway.) Should you expect to find yourself aboard the *Enterprise* or aboard the *Potemkin*? Both. One of your future selves will be aboard one and another will be aboard the other. These two future selves are coexisting actualities, not alternative possibilities, and they are equally yours. So your two branches should contribute equally to your divided expectations about future experience. But none of your future selves will be aboard both starships at once, so you should not at all expect that.

When Wigner comes to debrief his friend, there is collapse. But what happens when Wigner is otherwise engaged? What went on in all the long years before Wigner's birth? What will happen forevermore now that Wigner is dead and gone? Without Wigner, there

11 *continued*
plausible enough. If mind supervenes upon the physical at all, wouldn't you expect it to supervene upon the positions of such things as electrical charges and currents in the brain, neural connections and synapses, and molecules of neurotransmitter?

12 See Lewis [1983]. See also Martin [1958] and Robinson [1985], for a reminder that we'd better have some way to make sense of branching. Even if you dismiss branching people as a philosophers' and physicists' fantasy, branching amoebae are commonplace. The question 'what experience should you expect if you anticipate branching?' could be asked about a (non-quantum-mechanical) intelligent amoeba.

will be no collapse. The mere material minds will go into superpositions with ever more branches; and as they act upon other things, and act differently depending on what they think they've observed, other things will go into corresponding superpositions. More and more of the world will go into superpositions with more and more branches. Wigner is seldom around, not when we consider the entire history of the world, so this is an almost-no-collapse hypothesis.

III. Quantum Mechanics Without Collapse

It's a small matter to remove Wigner from the previous hypothesis, except as just another material mind. That leads to our final hypothesis: there are no collapses ever. This no-collapse hypothesis has been proposed by Everett [1973a, 1973b; Albert 1992: 171ff].

The no-collapse hypothesis lies beyond our spectrum. For the hypotheses in the spectrum differed only about the conditions which bring on collapse. None denied that collapses sometimes take place.

How does nature work on the no-collapse hypothesis? What we previously supposed to be the way it works in Wigner's absence is now the way it works always and everywhere. Things branch into ever more elaborate superpositions. Things go into superpositions *de novo*; and things go into superpositions when they encounter other things which are already in superpositions, and are acted upon differently by different branches of the superpositions they encounter. Superposition spreads outward into the world, like ripples on a pond.[13]

The no-collapse hypothesis was almost ignored for many years, but now it has suddenly come into favour. Many like it, of course, because a collapse law looks like a gratuitous blotch on an otherwise elegant theory. (We saw how repugnant some of the collapse hypotheses were that we considered. Others are worse. We did not even consider the hypothesis that collapse takes place just when a quantum system interacts with a classical system, that is, a system that cannot be thought of as quantum-mechanical; and that any system can be thought of as quantum-mechanical; and that collapse nevertheless does often take place.) Others like it because it lets us apply quantum mechanics to the entire cosmos, with no need for the hypothesis that some outside observer performs measurements on the cosmos and thereby brings on collapse. Still others like it because stable macroscopic superpositions could hold enormous amounts of information in readily accessible form, thereby delivering enhanced computing power.

We have an urgent problem: how does quantum mechanics now predict anything? And how can it be confirmed by the success of its predictions? Even if no-collapse quantum mechanics were the truth about nature, it's hard to see what reason we could have to believe it. For a hypothesis deserves our belief to the extent that it beats its rivals, not only

[13] This is not yet to say that whenever anything branches, the entire world branches. The extra hypothesis of worldwide branching, which seems to contravene Schrödinger evolution and serves no obvious purpose, was apparently supplied not by Everett (though his writings are so austerely mathematical that it is sometimes hard to tell what he means) but by Bryce DeWitt [1973a, 1973b]. Without this added extra, 'many-worlds interpretation' is no longer an apt name for the no-collapse hypothesis.

individually but collectively, with respect to two desiderata: inherent plausibility and predictive success. It deserves our disbelief, *ceteris paribus*, to the extent that when we rely on it to guide our expectations of experience, we find ourselves often surprised by unexpected experiences.[14] Under our previous hypotheses, the predictions of quantum mechanics were probabilistic predictions of the outcomes of collapses—but now we have taken away the last of the collapses. So we need some new way for no-collapse quantum mechanics to advise us what experiences to expect.

It needs to tell the minds located on the branches of elaborately proliferating superpositions what experiences to expect, since *ex hypothesi* those are the only minds there are. And if such a mind is about to go into a further superposition, with different experiences for different branches of that superposition, it needs to be told to proportion its expectations of experience to the intensities of the branches. Else the advice given will not match the successful predictions of collapse quantum mechanics. Call this the intensity rule.[15]

It's hard to see how to justify the intensity rule. How bad is that? It's also hard to justify the chance rule that governs our expectations in a chancy world: if you know the chances of alternative futures, expect each one to a degree equal to its known chance. Yet the chance rule is undoubtedly correct.[16]

Can we at least get by with one mystery instead of two? No; the intensity rule and the chance rule are not at all the same sort of thing. There is no hope of reducing the one to the other by invoking an a posteriori bridge law identifying intensities with chances. Chances pertain to alternative possibilities, whereas intensities pertain to coexisting actualities. Likewise, expectations divided between coexisting actual branches (unlike expectations divided between alternative outcomes of a chance process) are not subjective probabilities. Subjective probability measures uncertainty; but, given enough knowledge of initial conditions, there is no uncertainty about what your branching futures will bring. Nor is there any uncertainty about which branch is yours: all of them are.[17]

[14] I hope this statement strikes you as an innocent platitude. In fact it is an informal statement of Bayes theorem, the centrepiece of a somewhat controversial approach to confirmation.

[15] It may seem that there is another way to gain guidance about what to expect. We could invoke a theorem of Everett's which says that when a sequence of quantum mechanical experiments is performed, the frequencies of their outcomes will in almost all branches reflect the probabilities predicted by quantum mechanics with collapse. But 'almost all' means 'except on branches with a very low total share of intensity'. We need a prior appeal to the intensity rule to tell us to give these exceptional low-intensity branches negligible weight in governing our expectations. So the intensity rule has not been bypassed after all.

Note that something like Everett's theorem is needed to explain why Wigner's friend will almost certainly report to Wigner that he has observed the quantum-mechanically predicted frequencies in repeated experiments he has conducted. For instance, he will in all probability report that when he repeatedly fired particles at the two slits, the cumulative statistics of their impact points displayed an interference pattern.

[16] What's more, it is the key to understanding the conceptual role of objective chance. See. Mellor [1971], and Lewis [1986, 1999a]

The most promising approach I know to justifying the chance rule is found in recent unpublished work of Barry Loewer.

[17] There may well be uncertainty, and hence a subjective probability distribution, after a branching. A branch may not know which of all your branches it is—just as, when you are 'beamed up' to two different starships, each of your two arriving selves may at first be uncertain whether it is aboard the *Enterprise* or the *Potemkin*. This is uncertainty not about how the world is, but about who and when and where in the world one is. It is a probability distribution over alternative egocentric possibilities,

In fact, the intensity rule is even worse off than the chance rule. Not only have we no good way to justify the intensity rule; we have a plausible way to justify a conflicting rule. All your future selves, on all your branches, are equally real and equally yours. You will have the experiences of all of them. Do they not therefore deserve equal weight? Should they not figure equally in governing your divided expectations of experience, regardless of their intensities?

Intensity is, mathematically, a measure; and some measures do make intuitive sense as guides to the division of expectations. (I don't mean to suggest that any knock-down argument can be given in favour of following such guidance.) Unfortunately, there are very many different measures that can be imposed on the branches; and the one most favoured by intuition, the measure that treats all branches equally, was the one that gave the wrong answer. So there are two ways to go. We might hope that it's a basic principle of rationality that intensity guides divided expectations in the same way that chance guides subjective probability. But quantum-mechanical intensity, unlike chance, is a recently discovered and theory-laden magnitude, unknown to all rational thinkers of the recent past and many rational thinkers of the present. It's not at all plausible that it should figure in any basic principle of rationality. Or instead we might hope that some more familiar measure—I know not what—does make sense as an intuitive guide to divided expectation; and then we might propose a new law of nature, equating this more familiar magnitude to intensity, as a speculative ad hoc addition to no-collapse quantum mechanics. The second strategy seems more promising than the first, but its repugnant adhocery detracts greatly from the otherwise elegant simplicity of the no-collapse hypothesis![18]

IV. Life-and-Death Branching

Schrödinger's cat is the victim of an evil thought experiment. The evil experimenter puts the cat in a box. Along with the cat he puts a sealed bottle of some volatile poison. There is

[17] *continued*
not over possible worlds. But this genuine uncertainty comes after your branching, whereas your divided expectations for the future came before, when there was not yet anything for you to be uncertain about. Nevertheless, your divided expectations beforehand and your probability distribution afterward go together. A division of expectations before branching disposes you to have a corresponding probability distribution afterward. If beforehand you divided your expectations equally between the *Enterprise* and the *Potemkin*, then your branches afterward, until they gain new evidence, will distribute their probability equally. If for some reason you had divided your expectations unequally, your subsequent probability distribution would have been likewise unequal. Accordingly, any rational constraint on your subsequent probability distribution—for instance, a principle of indifference between egocentric possibilities located in the same possible world—translates into a constraint on the previous division of expectations.

[18] Here is one example of the second strategy—in fact, the only example I can think of. (It is by no means entirely satisfactory.) The more familiar measure that makes sense as an intuitive guide to divided expectation will be the principle that gives equal weight to all your future selves—the translation to expectations of a principle of indifference between alternative egocentric possibilities located in the same possible world. Isn't this the very principle that justified the incorrect rule that branches should have equal weight regardless of their intensity? Yes; but we can change that if we drop the assumption that your future selves come one to a branch. Let us speculate that there is a law of reduplication: it says that branches exist in multiple copies, with the number of multiple copies proportional to the intensity of the branch. (Perhaps the multiple copies are stacked up in

some sort of bottle-smashing device, and it is wired up to a photon detector. When all is ready a photon is fired toward the detector, but in its path is a diagonal half-silvered mirror. So if there are no collapses along the way, first the photon goes into a superposition of deflected versus undeflected. Then the detector goes into a superposition of untriggered versus triggered. Then the smasher goes into a superposition of idle versus operating. Then the poison bottle goes into a superposition of intact versus smashed. Finally the cat goes into a superposition of alive versus dead. After the first step, all these are macroscopic superpositions which may exist according to some hypotheses about collapse but not according to others.

What should the cat expect to experience, if it's a very smart cat and knows the set-up, and if it knows there are no collapses? The intensity rule says: expect branches according to their intensities. The intensities are equal. So the cat should equally expect to experience life and death.

[18] *continued*

some hitherto unsuspected dimension.) If the copies have equal weight in guiding expectations, then the branches have unequal weight, proportioned to their intensities—which is just what it takes to justify the intensity rule.

The big problem with this suggestion—besides its blatant adhocery—is that it only tells us what to expect when we have finitely many branches, and finitely many copies of each branch. Otherwise we're back to the problem that there are too many measures, and nothing to make any one of them stand out as an intuitively compelling guide to divided expectations. We get no guidance for the case of infinite branching. Even for the case of finite branching, we get at best an approximation to the intensity rule, hence at best an approximation to the advice of standard quantum mechanics. For if the intensities of two branches stand in an irrational ratio, we cannot proportion the finite numbers of multiple copies exactly to the intensities of the branches. We must round off. When the finite numbers are very big, the rounding error will be negligible. But as we consider branches with lower and lower intensities, the rounding error becomes more and more serious.

In fact, when we get to branches of low enough intensity, the number of copies will round off to zero; which is to say that the very-low-intensity branches simply vanish. Annihilation governed by a reduplication law differs both from Schrödinger evolution and from collapse. Unlike Schrödinger evolution, it annihilates branches; unlike collapse, it never annihilates any but the lowest-intensity branches, and it is deterministic. We shall soon see why we should fervently hope that very-low-intensity branches do indeed vanish entirely. Sad to say, hoping so doesn't make it so.

The present proposal could be called a 'many minds view'. However, it differs from the many minds view of Albert and Loewer [1988] in four respects. First, my many minds are material minds. Second, there are finitely rather than infinitely many of them associated with a single branch. Third, the minds associated with a single branch are duplicates. Fourth, their evolution is entirely deterministic. The present proposal differs also from the many minds view of Lockwood [1996], because Lockwood opts for infinite rather than finite reduplication [172–3], trading the problems of finitude for the problem of finding some intuitively salient measure.

On the present proposal, the standard quantum-mechanical advice about how to divide your expectations of experience has a triple source. It comes in part from the predicted intensities of the branches and in part from the reduplication law, and these are genuine hypotheses about how nature works. But also it comes partly from the rule that all your future selves should figure equally in your divided expectations. That rule is not a hypothesis about how nature works. It is a constraint on rational division of expectations, engendered by a corresponding constraint on your subsequent egocentric probability distributions. It's too bad that the advice does not come entirely from hypotheses about nature. But is collapse quantum mechanics really any better off? Again, its advice has a triple source. It comes in part from the predicted intensities of the branches and in part from the collapse law that equates those intensities to the chances of alternative outcomes, and these are genuine hypotheses about nature. But also it comes partly from the chance rule. That rule is not a hypothesis about how nature works, but rather a constraint on rational distributions of subjective probability.

But that's nonsense! There's nothing it's like to be dead. Death is oblivion. (Real death, I mean. Afterlife is life, not death.) The experience of being dead should never be expected to any degree at all, because there is no such experience. So it seems that the intensity rule does not work for the life-and-death branching that the cat undergoes.

The intensity rule does indeed govern the expectations of a bystander. What is life-and-death branching for the cat is life-and-life branching for the bystander, so we get the correct result: the bystander should divide his expectations equally between finding the cat alive and finding it dead.

The intensity rule also governs the very short-run expectations of the cat itself. In the very short run, the cat's branching is not yet life-and-death. For a little while the cat will be in a superposition of healthy life and life at death's door. It should divide its short-run expectations accordingly.[19]

When we have life-and-death branching, the intensity rule as so far stated does not apply. We must correct it: first discard all the death branches, because there are no minds and no experiences associated with death branches. Only then divide expectations of experience between the remaining branches in proportion to their intensities. (The problem of justifying the corrected intensity rule is exactly like the problem of justifying the original intensity rule in the case where there are no death branches, and we need not consider it again.) The cat should expect with certainty to find itself still alive after the evil experiment, since that is the guidance delivered by the corrected intensity rule.

The same goes for other examples of life-and-death branching. Suppose you're about to be beamed up, with the signal received both on the *Potemkin* and on the *Enterprise*. At the last moment you find out that the receiver on the *Enterprise* is malfunctioning: anyone transported there will be dead on arrival, or very soon after. What to expect?—No worries, you'll be safe and sound aboard the *Potemkin*. Your death branch should not figure in your expectations. In no way at all should it concern you, unless because you regret the distress to the crew of the *Enterprise* when your corpse arrives.

Suppose now that the evil experiment is repeated over and over, so long as the cat is still alive, or so long as any of its branches is alive—even if that is forever. What should the cat expect then? If there are collapses (unless they happen only when Wigner is around, and he is now dead and gone), then the cat will die sooner or later—probably sooner. Of course it will never find itself dead—death is oblivion—but it will no longer find itself alive.

Without collapses, however, the cat should expect to survive. It should expect to find itself alive after any number of repetitions of the evil experiment. For any initial segment of the sequence of repetitions is one big life-and-death branching, and there will be at least one branch that survives the whole initial segment. The cat's life branches will have ever-diminishing total intensity, to be sure, but that makes no difference. Under the corrected intensity rule, only the repeated-survival branches figure in governing the cat's expectations (long-run expectations, anyway) so the cat should expect with certainty to survive.

19 Something rather like the uncorrected intensity rule might indeed govern the expectations of the cat insofar as they are expectations not of experience but of what will happen whether experienced or not. But this is not really the intensity rule, which governed only expectations of experience. Nor can it share in any satisfactory justification of the intensity rule.

V. We Are All Schrödinger's Cats

Many things about the predicament of Schrödinger's cat, one-shot or repeated, are irrelevant window-dressing. It does not matter whether the situation is set up by an evil experimenter or whether it comes about some other way. It does not matter whether the victim is a cat or a person. It does not matter whether the total intensities of life branches and death branches are equal or unequal. It does not matter what the mechanism of death may be. However we change these features of the situation, our conclusion is unchanged. Given collapses, the victim may well die. Without collapses, the victim should expect with certainty to live, and should divide his expectations among the life branches in proportion to their intensities.

We are accustomed to thinking that death-mechanisms involving nuclear physics are quantum-mechanical processes. If you find yourself next to a critical mass of plutonium, there are branches on which it immediately undergoes a deadly chain reaction (and branches on which the chain reaction takes any of various courses). There are other branches on which the reaction fizzles more or less harmlessly. There are even branches on which nothing happens at all. Of course, the first sort of branches have the lion's share of the total intensity. If there is collapse, the chances are overwhelmingly in favour of the deadly chain reaction. Yet there are other branches too.

Chemical processes are no less quantum-mechanical. These include biochemical processes; and physiological processes generally work partly by biochemistry. So such death-mechanisms as poisoning, infection, auto-immune disease, ventricular fibrillation, or heart failure are also occasions for life-and-death branching. Chemical explosions fizzle in very low-intensity branches just as nuclear explosions do. The breaking of macroscopic things such as your bones works by the quantum-mechanical breaking of chemical bonds.

Even mechanical processes are quantum-mechanical, in view of the phenomenon of quantum tunnelling. If you stand in front of an oncoming bullet, there are branches (of stupendously low intensity, of course, and with negligible chances of being the outcome of a collapse) in which the bullet passes right through you, leaving you unscathed, or less than fatally scathed. If you stand in front of an oncoming tram, there are branches of still lower intensity in which you reappear on the other side of the tram, or in which not all of you, but enough of you to sustain life, reappears.

This list of sample cases persuades me that all death-mechanisms are quantum-mechanical. All of them are occasions for life-and-death branching. Given collapse, all of them pose at least some chance of life and at least some chance of death. Of course the comparative intensities of the life branches and the death branches, or the comparative chances of life and death, vary greatly from one case to another. But whenever we face the dangers of life—great or small, ordinary or extraordinary—we are in the predicament of Schrödinger's cat. And when we face dangers repeatedly, as we do, we are in the predicament of Schrödinger's cat with the evil experiment repeated.

Further, we are always facing at least some small danger. Life is never completely safe. For instance you could die because all the low-level radioactive atoms in the earth's crust around you decayed all at once, and all the decay particles were aimed at the same small part of you, and all of them were absorbed. Given collapse, there is a minute chance that this will happen to you. Without collapse, you have death branches in which it happens.

So my conclusion about Schrödinger's cat applies equally to every one of us. If there is no collapse, but not if there is, you should expect with certainty to go on forever surviving whatever dangers you may encounter.

VI. Evidence Against Collapse

We noted that our various versions of quantum mechanics with collapse were, near enough, empirically equivalent.[20] But this equivalence does not extend to the no-collapse hypothesis. If it is true, each of us will eventually gain evidence that supports it. When you find yourself still alive after facing repeated danger, and you have far outlived the people around you, that is just what you should have expected under no-collapse quantum mechanics, according to the corrected intensity rule. However it is an enormously improbable occurrence under quantum mechanics with collapse. Thus no-collapse quantum mechanics has enjoyed a predictive success which quantum mechanics with collapse fails to match. Thus you have gained evidence against collapse.

There is no other side to the coin. If some collapse hypothesis is true, you will not gain evidence of that. For its prediction is that in all probability you will soon die. So for its prediction to be borne out, you would have to find yourself dead. But you will never find yourself dead, because death is oblivion. When you are dead, it is too late to have evidence for anything. All that will happen is that you will no longer find yourself alive, and that is something that cannot be borne out by your experience.

Your evidence against collapse, if you gain it, is a strangely private sort of evidence. You cannot share it with a bystander. For your life-and-death branchings are not the bystander's life-and-death branchings. What he should expect, whether by considering the chances under a collapse hypothesis or whether by applying the (uncorrected) intensity rule to branchings that are life-and-death branchings for you but not for him, is that you will soon be dead. His expectations are the same either way. And they will be borne out, either with overwhelming probability or in those of his branches that together have the lion's share of the total intensity, either way. If instead he sees you surviving a long sequence of dangers, of course he will be surprised. But his evidence is equally unexpected whether that is because it is a highly improbable chance outcome or whether that is because he gains it only in branches of low total intensity. So it does nothing to confirm or disconfirm the no-collapse hypothesis for him.

But as for you, remember my advice: if someday you find that you have survived a remarkably long sequence of dangers, the no-collapse hypothesis will then deserve your belief more than it did before.

If you'd rather not wait so long for evidence against collapse, you needn't. If no-collapse quantum mechanics is true, you can gain convincing evidence for it this very day. Suppose you're fairly sure that there are no collapses, and you're willing to run a risk in the service of truth. Go and wander about on a busy road, preferably a few minutes after closing time. When and if you find yourself still alive, you will have excellent evidence. If that's not yet enough to convince you, try the experiment a few more times.

[20] Except perhaps for the spontaneous collapse hypothesis (see footnote 8).

VII. Conclusion

My story so far, though not well known, has been told before, for instance by Huw Price [1996: 221–2; Lewis 2000] has been told as good news: the fortunate cat needn't fear death. The life to expect, if there are no collapses, is an endless sequence of lucky escapes. But are they all that lucky? Far from it! A terrifying corollary has gone unmentioned.

As well as life-and-death branchings, there may be life-and-life branchings such that you suffer harm on some branches and not on others. In some of these branchings, the harm branches get the lion's share of the total intensity. The intensity rule applies, so you should predominantly expect to find yourself harmed. As you survive deadly danger over and over again, you should also expect to suffer repeated harms. You should expect to lose your loved ones, your eyes and limbs, your mental powers, and your health.

To be sure, there are also life-and-life branchings such that on some branches your life is improved. Your previous losses are regained: your loved ones come back to life, or your eyes or your limbs grow back, or you regain your mental powers or your health. But in all such branchings, the improvement branches have a very low share of the total intensity. If there were collapses, the regaining of losses would be enormously improbable, and neither is it much to be expected under no-collapse quantum mechanics.

The general case is a branching which may have some death branches, may have some harm branches, may have some status quo life branches with neither harm nor improvement, and may have some improvement branches. (It might even be that all branchings have branches of all four kinds.) According to the intensity rule, you should first discard the death branches, if any, and then expect the remaining branches in proportion to their intensities. In the case of the worst dangers we face, the death branches have the most total intensity, the harm branches have the next most, the status quo life branches have much less, and the improvement branches have by far the least. Facing such a branching, you can expect to escape death, but by no means can you expect it to be a lucky escape.

We noted that if you stand in front of an oncoming tram, there are low-intensity branches in which you reappear on the other side of the tram by quantum tunnelling, or at least in which enough of you to sustain life does. The total intensity of these branches is low, but that doesn't matter. What does matter is that the overwhelming share of the total intensity goes to branches on which less than all of you, in fact a lot less than all of you, in fact only just barely enough of you to sustain life, reappears. You would probably miss the parts that had been left behind. Much the same goes for all the other deadly dangers that we face.

What you should predominantly expect, if the no-collapse hypothesis is true, is cumulative deterioration that stops just short of death. The fate that awaits all of us Schrödinger's cats is the fate of the Struldbruggs: victims of eternal life without eternal health, who had not only all the follies and infirmities of other old men, but many more which arose from the dreadful prospect of never dying.

> They were not only opinionative, peevish, covetous, morose, vain, talkative; but uncapable of Friendship, and dead to all natural Affection . . . they lose their Teeth and Hair; they have . . . no Distinction of Taste, but eat and drink whatever they can get, without Relish or Appetite. The Diseases they were subject to, still continue without encreasing or diminishing. In talking they forget the common Appellation of Things,

> and the Names of Persons, even of those who are their nearest Friends and Relations. For the same Reason they can never amuse themselves with reading, because their Memory will not serve to carry them from the Beginning of a Sentence to the End; and by this Defect they are deprived of the only Entertainment whereof they might otherwise be capable. ... Besides the usual Deformities in extreme old Age, they acquired an additional Ghastliness in Proportion to their Number of Years.
>
> [Swift 1965: 212–14]

(It seems that Gulliver met exceptionally fortunate struldbruggs. Why was their bodily decay limited to loss of hair, teeth, and sense of taste?) Eternal life on such terms amounts to a life of eternal torment.[21] It is not to be welcomed but feared. You should fervently hope that a collapse will cut it short.[22] You who bid good riddance to collapse laws, you quantum cosmologists, you enthusiasts of quantum computing, should shake in your shoes. Everett's idea is elegant, but heaven forfend it should be true! Sad to say, a reason to wish it false is no reason to believe it false.

So, how many lives has Schrödinger's cat?—If there are no collapses, life everlasting. But soon, life not at all worth living. That, and not the risk of sudden death, is the real reason to pity Schrödinger's kitty.

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[21] I thank Rae Langton for the comparison with the struldbruggs, and Sam Wheeler for the comparison with Hell. Another comparison is with the legendary Tithonous: in the words of Tennyson's poem 'Tithonous',
I asked thee, 'Give me immortality.'

> Then didst thou grant mine asking with a smile,
> Like wealthy men who care not how they give.
> But thy strong Hours indignant worked their wills,
> And beat me down and marr'd and wasted me,
> And tho' they could not end me, left me maim'd

For another comparison, see Williams [1973]. But if you become a quantum struldbrugg, tedium will be the least of your worries. Indeed, decay of memory is apt to forestall tedium altogether.

[22] Collapse could rescue you from eternal life. So too could the annihilation of very-low-intensity branches by rounding under the reduplication law (see footnote 17). Localization (see footnote 4 and Bell [1999] and Albert and Feinberg [1993: 81]) could not. It would sometimes reduce the intensities of your life branches by an enormous factor, but it could not cut them off altogether. You'd still have life branches, however low their intensity might be; your expectations would still be governed by the corrected intensity rule; so you'd be no better off than under the deterministic no-collapse hypothesis.

A localization hypothesis still requires a justification for the intensity rule, just as the deterministic no-collapse hypothesis does. And since both hypotheses alike advise you to expect eternal life, gaining evidence against collapse by finding that you have survived a long sequence of dangers does nothing to support one of these two hypotheses against the other.

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