

MICHAEL BROWNNUTT**Response to Peter Clarke on
'Determinism, Brain Function and
Free Will'**

I enjoyed reading Peter Clarke's article on determinism, brain function and free will.¹ It clearly laid out the very serious problems in trying to hide the action of a soul behind the Heisenberg uncertainty principle. It is worth noting, however, that quantum mechanics has more tricks up its sleeve than Heisenbergian indeterminism. Some of these tricks increase the 'cloud cover' significantly and recent research has shown that quantum effects can indeed become significant in the biological realm.

Determinism and the Schrödinger equation

The well-known uncertainty principle follows as a natural and necessary consequence of classical wave mechanics combined with the superposition principle of quantum theory. With the uncertainty principle being a special case, the broader class of superposition states offers some interesting wiggle room for the soul. Critical to discussing such superpositions is a clear understanding of what is meant by the claim that 'the fundamental equation of quantum physics, the Schrödinger equation, is in itself fully deterministic'.² By 'deterministic' we mean that, for some given starting condition, the equation will, for some given later time, always give the same answer. It is important, however, to note what kind of answer it gives: it says (fully deterministically), 'If you were to make a measurement now, this is the probability that you would get the measurement result A.'

Imagine, for example, that I have an atom which is wont to decay. When I make a measurement, only certain answers are possible. If I make a measurement which asks 'Has this atom decayed?' the possible answers are 'Yes' and 'No'. The answer cannot be, and will never be, 'Sort of' or 'A bit' or 'Well, it's looking a bit wobbly'. Put more mathematically, the answer to the question 'How many undecayed atoms do I have?' will always be '1' or '0'. I can never have a half-decayed atom. It just doesn't happen. This 'quantisation' is what gives quantum mechanics its name.

In the Schrödinger equation, the solution to the equation will smoothly and deterministically evolve from '1', through '0.5' and on down to '0'. How

1 Clarke, P.G.H. 'Determinism, brain function and free will', *Science and Christian Belief* (2010) 22, 133-149.

2 *ibid.*, 142.

is this possible, given I cannot have a half-decayed atom? Simple: the Schrödinger equation does not answer the question ‘How many undecayed atoms do I have?’ but rather the question ‘If I were to make a measurement now, what is the probability I would measure that my atom has not decayed?’ It initially gives the reply ‘1’, which is to say ‘If you were to measure your atom now, then you would certainly see that it has not decayed.’ Some long time later it gives the result ‘0’ (If you were to measure your atom now, then you would certainly see it has decayed). In between, it gives the solution, say, ‘0.7’ (if you were to measure now, then there is a 70% chance you will find that the atom has not decayed).

This is all very well and good, but a major problem occurs when you chose to make a second measurement, on the same atom. Imagine that, at a time when the Schrödinger equation gives the answer ‘0.7’, you make a measurement and find (as you would expect to find 30% of the time) that the atom has, in fact, decayed. Now imagine you make another measurement straight away and (with 100% certainty) see that the atom has decayed. This should be no surprise, because you know it has decayed: you have already seen that it has decayed and the second measurement would almost seem redundant. Importantly, however, the Schroedinger equation just keeps on counting down smoothly: 65% probability, 60% probability, 55% probability... It is oblivious to the fact that I have measured already, that I know the answer, and that the probability of my atom being undecayed is now zero. We say that the wave function has ‘collapsed’; it does so non-deterministically, but according to the probabilities given by the Schrödinger equation. By contrast, the Schrödinger equation, which gives these probabilities, does evolve deterministically. This is why we know (or at least, why the vast majority of quantum physicists are pretty sure) that it is wrong. To get round this we just bolt on the axiom ‘When a measurement is made we interrupt the Schrödinger equation and start again with the updated initial conditions.’ This fudge (for it is a fudge, and every quantum mechanic knows it) means that indeterminism can work on enormous energy scales over enormous times.

Before turning to some concrete instances of such gross indeterminism, it is worth taking Einstein’s objection into account, which Clarke raised.³ Einstein – along with Schrödinger and a number of the other founders of quantum mechanics – spent the latter portion of their respective careers trying to unfound quantum mechanics. Schrödinger proposed his eponymous cat experiment to point out how silly quantum mechanics was.⁴ (He was, of course, totally unaware that sixty years later people would be mak-

³ *ibid.*, 142.

⁴ Schrödinger, E. ‘Die gegenwärtige Situation in der Quantenmechanik’, *Naturwissenschaften* (1935) 23, 807-812; 823-828; 844-849. Trans. Trimmer, J.D. ‘The present situation in quantum mechanics’, *Proceedings of the American Philosophical Society* (1983) 124, 323- 338.

ing ‘Schrödinger-cat states’⁵ in his honour.) Einstein, for his part, helped formulate the ‘Einstein-Podolsky-Rosen (EPR) Paradox’ to demonstrate that quantum mechanics logically had to be wrong; either that or there one would have to invoke some inconceivable ‘spooky action at a distance’.⁶ He did not live to see the experiments which showed that quantum mechanics was right, Einstein was wrong, and spooky action at a distance really works.⁷ In short, despite the entirely reasonable misgivings of its founders, experiments have shown quantum theory to be strange, sometimes unreasonable, but always right. Importantly, the probabilities in quantum mechanics seem to be ontological, rather than epistemological. Time and again experiments support this view, and beat so-called hidden-variable theories into an ever tighter corner.⁸

Some concrete examples

Returning then to the claim of uncertainty on enormous energy scales over enormous times: how might this be possible? The standard quantum limit ($h/4\pi$), enshrined in Heisenberg’s uncertainty principle ($\Delta E \cdot \Delta t \geq h/4\pi$), sets only a lower bound on our ignorance. It says nothing about an upper bound on how ignorant we can be. Concretely, consider for example a particular electronic state of an atomic calcium ion⁹ which is well loved and studied by quantum researchers and is wont to decay. It has an energy of 2.7×10^{-19} J above the ground-state, and has a natural decay time (or half life) of about 1 s. Imagine, then, that an atom starts in this state and after waiting one second I ask the question ‘If I were to make a measurement, would I find that my atom had decayed?’ The Schrödinger equation deterministically answers ‘even odds’, which is equivalent to its holding up its hands and declaring ‘your guess is as good as mine!’ I do not know what my atom is doing, the Schrödinger equation does not know and, as far as we can tell, the universe itself has no idea. If we take this universal ignorance as constituting indeterminism (as many physicists do) then the level of uncertainty is $\Delta E \cdot \Delta t = 2.7 \times 10^{-19} \text{ Js} = 5 \times 10^{15} \times h/4\pi$. This is well above the standard quantum limit considered by Clarke and might possibly allow the soul some wiggle room.

While the uncertainty in Heisenberg-limited states is extremely robust

5 Monroe, C., Meekhof, D.M., King, B.E. & Wineland, D.J. ‘A “Schrödinger cat” superposition state of an atom’, *Science* (1996) 272, 1131-1136.

6 Einstein, A., Podolsky, B. & Rosen, N. ‘Can quantum-mechanical description of physical reality be considered complete?’, *Phys. Rev.* (1935) 47, 777-780.

7 Genovese, M. ‘Research on hidden variable theories: A review of recent progresses’, *Phys. Rep.* (2005) 413, 319–396.

8 *ibid.*

9 Kreuter, A., Becher, C., Lancaster, G.P.T., Mundt, A.B., Russo, C., Häffner, H., Roos, C., Hänsel, W., Schmidt-Kaler, F., Blatt, R. & Safronova, M.S. ‘New experimental and theoretical approach to the 3d ²D-level lifetimes of ⁴⁰Ca⁺’, *Phys. Rev. A* (2005) 71, 032504- 032515.

– you have to have it and cannot get round it – the uncertainty in much larger superposition states is incredibly fragile. Experiments with atomic ions must be performed in a very carefully controlled environment, in vacuum, in the dark, near temperatures of absolute zero. It might seem that we could reject out of hand any application to biological systems, which are necessarily hot and wet. Recently, though, both theory and experiment have changed this view and shown that biology can not only use such states, but can optimise the quantum nature to work best at room temperature.

It was realised that certain bacteria were very much more efficient at photosynthesis than would normally be expected.¹⁰ The energy was getting from the point where the photon was absorbed to the reaction centre where it could drive chemical reactions with almost 99% efficiency – an effectiveness that could not be explained by any classical transport mechanism. By contrast, quantum models in which the energy carriers did not go by a single route through the cell, but rather by a superposition of many routes through the cell, could explain the efficiency very well.¹¹ Most surprisingly, the quantum nature of the behaviour was not suppressed by the thermal environment in which the process took place. Indeed, when the efficiency of the quantum transport was modelled as a function of temperature, far from the effects being swamped by the thermal motion, the process was optimised at about 20° C!

Bacteria are not the only biological system in which quantum effects have been observed. It has been proposed that the ‘avian compass’ – the mechanism by which birds use their sensitivity to magnetic fields to help them navigate – is based on a quantum process. Very recent experiments on the European robin¹² support this view, and suggest that the quantum effects survive for around 100 μ s – comfortably beyond the 10 ps which Clarke postulates as being needed for synaptic functions.

What about the soul?

Where does this all leave us? It seems that quantum superpositions – and the indeterminacy which goes with them – can and do survive at biologically important energies and time scales. Should we then accept that ‘what everybody believed was random is in fact directed and meaning-

10 Lee, H., Cheng, Y.C. & Fleming, G.R. ‘Coherence dynamics in photosynthesis: protein protection of excitonic coherence’, *Science* (2007) 316, 1462-1465.

11 Mohseni, M., Rebentrost, R., Lloyd, S. & Aspuru-Guzik, A. ‘Environment-assisted quantum walks in photosynthetic energy transfer’, *J. Chem. Phys.* (2008) 129, 174106-174114.

12 Gauger, E.M., Rieper, E., Morton, J.J.L., Benjamin, S.C. & Vedral, V. ‘Sustained quantum coherence and entanglement in the avian compass’, *Phys. Rev. Lett.* (2011) 106, 040503-040506.

ful"?¹³ Right now this is clearly a step too far and the experiments do not yet support this. But so far they have also not been able to contradict it. We are, however, approaching the level where such a notion may be seriously tested. All experiments to date (carried out on atoms or photons) seem to indicate that the results of quantum processes are random. Still, we might safely assume a photon has no soul. What if one could probe the quantum processes in the brain of a person who *does* have a soul? Would we see apparently random results which were secretly directed by a soul hiding behind the scenes? Maybe. Alternatively we may see a very non-random process, lived large by a soul who did not want or need to hide? Why not? After all, a person and a rock behave very differently. Does a soul which animates a person make that person sit very still, lest someone notice that there is a difference in behaviour between an animate person and an inanimate rock? Not at all! Should we expect a soul which influences quantum processes in a person make those quantum processes appear random, lest someone notice that there is a difference in behaviour between a soulish person and a soulless photon? Maybe, maybe not. Until the experiment has been done, the matter is by no means decided.

In conclusion, while Peter Clarke argues very convincingly that free will cannot hide behind the Heisenberg uncertainty principle, Heisenbergian libertarianism is by no means synonymous with quantum libertarianism. Given the possibility of superpositions well above the level of Heisenbergian uncertainty it is not necessarily true that quantum indeterminism is excluded as the 'cloud cover' for free will, if indeed cloud cover is needed at all. Recent experiments in quantum biology have shown that quantum effects may well yet have a role to play.

Michael Brownutt is an experimental quantum mechanic working at the Institute for Experimental Physics, University of Innsbruck, Austria.

13 Clarke *op. cit.*, (1), 147.

PETER G.H. CLARKE

Indeterminism Beyond Heisenberg

Michael Brownutt's interesting response to my article argues that non-Heisenbergian quantum effects may provide indeterminism at levels much greater than Heisenbergian uncertainty, and might thereby rescue quantum indeterminism from my criticisms.

He first shows that uncertainty from larger superposition states could in principle be almost 10^{16} greater than Heisenbergian uncertainty. This would indeed be large enough to be relevant to brain function, but, as

Michael points out, it is too fragile to apply in biology.

He therefore gives two examples showing that non-Heisenbergian quantum effects can nevertheless be relevant to biology. Since the submission of his letter, a semi-popular review was published in *Nature*¹ explaining this new area of 'quantum biology' to non-specialists (like myself). The review cites a few more examples, but the best demonstrated remain those that Michael mentioned, photosynthesis and magnetic field sensitivity, both involving the phenomenon of *quantum coherence*, which refers to situations where the wavelike properties of all the elements of a system are in phase. This is thought to be rare in biology, or exceedingly brief, because molecular noise in living cells tends to destroy the coherence. It is therefore remarkable that the paper on avian magnetic field sensitivity claims coherence lasting for almost 100 μ s.

I think we should be cautious about extending these new quantum phenomena to brain function, for at least two reasons. First, the new phenomena need to be confirmed. Second, the best-supported cases concern the special biochemical phenomena of photosynthesis and magnetic field sensitivity; they have never been shown in neuron-to-neuron communication or brain function. The hypothesis of quantum coherence in the brain has in fact been debated intensely for more than twenty years following the proposal by Roger Penrose that human conscious thought requires the brain to work like a quantum computer,² and the proposal of Hameroff's group that quantum coherence could occur in brain microtubules,³ but the weight of scholarly opinion seems currently to be quite strongly against the microtubule hypothesis.⁴ Thus, if quantum phenomena can be shown in brain neurons, this could have far-reaching implications for our understanding of brain determinism and of conscious thought more generally. But, as Michael Brownnutt points out, this has not yet been shown.

1 Ball, P. 'The dawn of quantum biology', *Nature* (2011) 474, 272-274.

2 Penrose, R. *The Emperor's New Mind*, Oxford: Oxford University Press (1989).

3 Lahoz-Beltra, R., Hameroff, S.R., & Dayhoff, J.E. 'Cytoskeletal logic: a model for molecular computation via Boolean operations in microtubules and microtubule-associated proteins', *Biosystems* (1993) 29, 1-23.

4 McKemmish, L.K., Reimers, J.R., McKenzie, R.H., Mark, A.E. & Hush, N.S. 'Penrose-Hameroff orchestrated objective-reduction proposal for human consciousness is not biologically feasible', *Phys. Rev. E*. (2009) 80, 021912.