Quantum Entanglement

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In 1972 Freeman and Clauser succeeded for the first time in preparing two particles which exhibited a strange condition, predicted by quantum theory, called 'entanglement'. The condition had been discussed theoretically by Einstein and co-workers in 1935, and at that time they argued that, because such a thing was obviously impossible, there must be something wrong with quantum theory. Freeman and Clauser's work, and subsequent more detailed experiments that fully confirmed the prediction of quantum theory, triggered a tide of speculation. There seemed no limit to the mysteries that might now be explained using this new phenomenon: telepathy, consciousness, healing … all were examined. Now that the production of entangled particles has become almost routine technology, it is perhaps a good time to take stock of what we have learnt. I shall indicate a range of possible positions, which I shall characterise as the sceptical, the liberal and the cosmological.

But first, what is entanglement? All the observations have been made on very simple microscopic particles, so I must ask the majority of readers, who are not normally interested in such things, to bear with me while I discuss these physics experiments. I will widen the discussion before long. Briefly, the essence of the idea is the production of pairs of particles which, though separated by a large distance, show correlations in their behaviour that are inexplicable on a basis of old (non-quantum) physics. To give more detail, let me describe a typical experiment, which uses the particles that make up light (particles called photons).

Entanglement experiments use a property of light called polarisation, to do with the direction in which the fields that constitute light are vibrating. (Polaroid sunglasses filter out light with a particular direction of polarisation.) It is possible, using a special optical material, to split a single photon into two so-called daughter photons. These two are allowed to travel apart (by more than 10km in some experiments) and then the directions of polarisation of the two photons are measured simultaneously. Two points emerge from analysing the results:

1. The direction of the polarisation of either particle is not fully determined before the measurement takes place; it must involve a partly random response of the particle to the measuring apparatus.
2. There is a correlation between the results of the measurements on the two particles. For example (and depending on the arrangement of the measuring apparatus) it might be that if particle A is measured to have its polarisation pointing vertically, it is then more likely that the same result will be obtained for particle B.

Could it be that the particles are, as it were, pre-programmed when they are split to respond in this way? (For example, it might be that the split always results either in both particles vibrating horizontally, or both vibrating vertically.) A detailed argument by the renowned theorist of foundational physics John Bell demonstrated that no 'pre-programming' could explain the observed results. In other words, the particles were responding spontaneously, but in an interconnected manner.

There is a huge literature expanding the sketch I have just given into detailed arguments: exploring possible loopholes, closing them, finding new ones … I will not go into these here. My concern is rather with the question, if the ideas just presented are taken at face value what are their implications? Quantum theory presents a very precise, and by now almost universally accepted, mathematical account of what is happening, in which entanglement corresponds to a particular mathematical form for the expression describing the pair of particles. What are the possible translations of this mathematics into words and pictures?

Let me describe some of the key assertions of the conventional verbal translation of the quantum mechanical account.

1. The properties of particles, properties which are the objects of experimental investigation, do not exist independently of the observation. Rather, they arise in the process of the interaction between the particle and the experimental apparatus. It is even misleading to think of them as 'properties of particles' at all: they are aspects of an event of measurement.

2. Spatial separation, and to some extent separation in time, are irrelevant to the correlations produced by entanglement. Spatial and temporal relations do not enter into the calculations at all; the particles could be anywhere.

3. Entanglement is the general rule; any interaction at any time in the past will entangle particles, so that very special conditions have to hold in order to produce particles that are not entangled. The achievement of Clauser and others actually lay not in the mere fact of producing entanglement, but in producing an entanglement that was of such a form that it could be examined experimentally. This point will be crucial below when I come to discuss the wider implications of this work.

Points 1 and 2 here carry an important philosophical message that challenges how we normally think about the universe, which is in terms of definite and separated things located in space. Point 1 undermines the definiteness of 'things'. It is not saying that physical entities are merely figments of our cultural assumptions (though this may indeed be the case): physicists behave as if they are dealing with what might in some sense be called 'reality'. But this inverted-commas-reality is what the philosopher of physics D'Espagnat called veiled. What we experience, either in the artificial setting of a laboratory or in normal moment-to-moment life, is quite distinct from what physicists regard as the foundation of the material universe, namely the abstract entities called particles and fields. And I should add that, while the connection between particles and experience is clear in the case of the laboratory, it remains in many respects obscure and controversial at the level of ordinary life.

It is point 3 that is vital for the wider implications of this subject. On the face of it, it would seem, for example, that we could use pairs of entangled particles for an instant communication system that operated independently of distance – something that would be highly reminiscent of telepathy. (Some authors have even written of one particle 'instantaneously changing its state' when the other is measured, for which there is no justification at all.) More generally, it suggests that the world, rather than being a collection of isolated particles pushing each other around, is more like an intricate web of subtle interconnections. But how far can we take this picture?

Physics is now pushing the idea of a web of quantum connections very far indeed. A significant new branch of what is sometimes called 'Quantum Information Theory' has emerged, covering the ways in which information can be transmitted through a mixture of entangled states and classical information transfer. The whole subject has moved out of the realm of speculation and is now supported by increasingly elaborate laboratory experiments using chains of entangled pairs of particles that verify the theory in great detail. One point that emerges from this work is that information cannot be transmitted by entangled states alone because the correlations that are observed are not ones that the user can control in order to insert information; rather, the spontaneity of the particles' responses is an essential part of the account. In other words, quantum communication always has to involve an ordinary communication channel (such as a telephone) and a quantum channel (such as entangled particles) working in tandem. So instantaneous communication (telepathy, in the sense in which it is usually conceptualised) is impossible by this means. On the other hand empathy, in the sense of remote beings producing synchronistically related behaviour, is a possibility.

When it comes, however, to the role of entanglement in ordinary life, outside the laboratory, the situation starts to look a lot less clear. Let me put the sceptical position first. If the entanglement that is present everywhere is actually to make a difference, then the systems and organisms of the natural world need to use it in some way. The discussions of quantum information theory assume that one can prepare a pair of entangled particles, put them in two boxes, and hand one to each of two observers who take them away for later communication. But what sort of 'box' does a natural organism have that can preserve a quantum state in pristine condition? The laboratory experiments using photons cannot be a precisely replica of what happens in a living organism: the only known way to 'store' a photon in a living system is to absorb it into the electromagnetic structure of a molecule, which is such a turbulent system that the details of the state would rapidly be lost. The only known 'box' is the microtubule, studied by Stuart Hameroff, that I will describe shortly.

To help us understand the problems that weigh against entanglement being effective in living organisms, I shall describe the way in which almost all particles are affected by a phenomenon, heavily researched over the last 20 years, called decoherence. This is concerned with a 'hidden property' of particles, namely phase. This is easy to understand in the case of a wave on water travelling past a buoy, when the buoy moves regularly up and down (with an additional regular oscillation in the direction of the wave). Here the phase of the wave at this place and at a given time is the point that the buoy is currently at in its cycle. All particles are thought of as associated with a similar wave-aspect and they carry a phase, but in general this is behind D'Espagnat's veil: there is no 'buoy' that can reveal it and it is deduced only indirectly, through phenomena (in particular, interference) that are analogous to those shown by waves.

Decoherence theory is about the way that the environment interacts with entangled particles so as to affect the relation of their phases. It turns out that the nature of the correlations between measurements on entangled particles is completely dependent on this phase relation. But the phases are exquisitely sensitive to perturbations by the environment, and so the influences of this can completely scramble the correlations produced by entanglement. All that is required for this to happen is that the particle states involved in the entanglement are sufficiently different for them to interact with a perturbation in different ways. If we are considering an entanglement involving the position of a large body or even a large molecule, then the slightest perturbing factor will produce enormous effects on the phase, leading to very rapid decoherence indeed.

So, to summarise the sceptics case: if we consider two particles in different places then their states will in general be entangled. But, with the exception of the particular behaviour exemplified by the polarisation of photons in the laboratory, the way in which the particles are entangled, and hence the nature of any correlation between them, will be completely random, so that in practice their responses will be independent. If we consider, instead of single particles, larger systems of many particles, then the situation becomes even worse because of their greater interaction with the environment. Thus entanglement can have no effect outside the laboratory.

I now want to suggest that this argument, while defining important limits to what can happen, is not completely conclusive. Historically, we have constantly found nature to surpass our own ingenuity in evolving its own subtle ways of implementing effects which we have to implement by brute force. If, as I think, there is circumstantial evidence for entanglement playing a role in organisms, then there is a case for searching biological systems to discover how they might do it, even when we cannot imagine this in advance. So let us move on to discuss some areas where more solid evidence for the role of entanglement in living systems might be found, moving on from the sceptic's position to what might be called the liberal position.

This position proposes that entanglement – or at least something very like it – may play a role within an organism, as part of its internal communication and control system. In this context, Hameroff has drawn attention to the possible role of microtubules: tubes forming a 'microskeleton' inside each living cell, made of a regular arrangement of protein molecules. Because of their small size, and the way they are shielded by the structure of the surrounding water, these tubes could support internal vibrations whose states were well protected from decoherence by the environment. Microtubules might thus form a good 'box' for storing quantum states. For this to be effective, however, the microtubules need to communicate with each other by conventional means: both in order to set up a states with a known entanglement (recall the need for a classical communication system alongside the quantum one) and also to keep refreshing the entanglement as decoherence penetrates the tubules and randomises the correlations. Hameroff, in collaboration with Roger Penrose, achieves this classical communication through a novel scheme of physics in which an aspect of gravitation, yet to be worked out in full detail, intervenes so as to realise correlated manifestations at separated microtubules, in a process that is closely linked to consciousness, with co-ordination happening via 'gap junctions' in the microtubules. The many technical details of all this make it a very uncertain area: in 2001, for instance, Guldenagel and co-workers produced a mouse with no gap junctions but apparently normal behaviour; calculations of the length of time that the entanglement can survive decoherence are difficult and contested; Penrose's theory is still at a very speculative stage, and it is unclear how crucial it is to the co-ordination of the microtubules; and, at the end of all this, it is not all that clear just what the microtubules are supposed to do once they have got their act together. The liberal position leads to lots of interesting scientific research, but in terms of the big questions of life it is not in the top league.

So the sceptical and liberal positions lead to a rather provocative situation. On the one hand, entanglement seems to be consonant with some of our deepest experiences: of the connectivity of the world, of the reality of synchronicity. Yet on the other hand it is hard to see how entanglement can act so as actually to deliver the goods. Are we somehow looking at things in the wrong way?

Before trying to answer this question, let me link it with another issue in which quantum theory promises much but somehow fails to deliver, namely that of the nature of mind. Many writers – including, as I have mentioned, Penrose – have associated quantum processes with mind (sometimes using in addition the word 'consciousness'). Though we like to believe that our minds make decisions using some approximation to the formal structure of logic first described by Aristotle. But in reality, and fortunately, this is not so: the power of our thought actually lies in a process that goes significantly beyond that logic, namely our ability to hold many different conceptual frameworks conjecturally together until a creative resolution emerges. And this is essentially the definition of quantum logic (the logic governing quantum systems), rather than Aristotelian logic. Is it just a coincidence that minute particles and higher mammals (let us not be too anthropocentric) share the same perverse logic? Or could it be that, as Gregory Bateson argued – with a rather careful information-theoretic definition of 'mind' – all natural systems exhibit mind; and, moreover, the effect of mind is described by quantum logic?

The difficulty with linking quantum theory with these very suggestive correspondences lies in finding a way in which quantum effects can move from the microscopic, where we know they reign supreme, to the larger scale of living organisms. But could it be that this 'bottom-up' approach (building the large out of smaller sub-units) inevitably leaves something out? Moreover, when we examine the sceptical and liberal approaches just outlined, it looks very much as though we are trying to extend quantum theory to the large-scale realm, while at the same time working within metaphysical assumptions about space, time and reality that automatically exclude quantum theory from that that realm. Are there alternatives to this approach?

This brings me to what I call the cosmological position, which I support myself. The idea is that we regard the whole universe as a quantum system, and allow top-down influences (from the large to the small) as well as bottom-up influences. I was led to this by having devoted most of my work in physics to the large-scale structure of the universe, so that a cosmological perspective always comes naturally to me. Such a perspective radically alters one's view of quantum theory: decoherence is the losing of quantum information to the environment; but the universe as a whole has no environment. Cosmologically, information is never lost (even, if we are to believe Hawking's recent claims, in the presence of black holes). This suggests (and there are loopholes!) that the universe remains coherent: it was, is and always will be a pure quantum system. The non-coherence of medium scale physics – non-coherence 'for all practical purposes', as John Bell used to say – is only an approximate consequence of our worm's-eye view.

When we take this viewpoint (following lines that have been explored, more conservatively, by Chris Isham and others) we find that there is whole layer of physics revealed that is taken for granted as part of the metaphysics of laboratory physics, a layer that appears formally as the interplay of different logical structures associated with different organisms, but which we might identify subjectively as an interplay of different structures of meaning experienced by these organisms. This layer is independent of the dynamical layer investigated by laboratory physics, in the sense that, once a structure of logic/meaning emerges, then the dynamics of quantum theory operates within it without constraint, so that laboratory physics is not affected. Conversely, the outcome of this dynamics can help to shape the possible structure of logic/meaning, but it does not determine it. There is a freedom present at this level which points to a whole noetic dynamics of the universe.

This leads to the picture that I presented in Living in Connection, in which the world is a nested lattice of quantum organisms. We can see this at work in our own being. My ego (the subjective 'I') is a subsystem of my whole body-mind, and I can thereby sense both my relationships with the vaster patterns of meaning of the planet and beyond, which go into constituting 'me', and also the well-being of my body which in turn gives direction and meaning to the smaller scale processes that support it. It is this that could solve the problems of decoherence, though here I am speculating beyond what has actually been demonstrated. Certainly there is a constant interplay between the coherence which each system receives from the greater ones in which it is contained, and the processes of decoherence which make it behave, in relation to its environment, as if it were a classical system. Thus entanglement within a specific quantum state, having a function in the organism and in the greater whole, could be maintained by a top-down influence.

In this nesting of systems, the buck stops with the cosmos as a whole, which shares some of the properties of what many call 'the mind of God', though I always use the g-word with trepidation. If I accuse Penrose and Hameroff of being short on details, then I am much more guilty of that myself. But the more I live with this picture, the more I think it makes sense both of physics and of human experience, including the experience of the mystics. Entanglement may be an explanation of the major paranormal experiences that many of us have encountered, but we will only arrive at a justification of this by a theoretical and experiential investigation of the cosmological level.

Further reading

Clarke, Chris, 'Quantum Mechanics, Consciousness and the Self', in Science, Consciousness and Ultimate Reality, ed. David Lorimer (Imprint Academic, 2004) An extended account of the view given here.
Clarke, Chris, Living in Connection (Creation Spirituality Books, Warminster, 2002) An exploration of the spiritual principles linked with this position.
Omnès, Roland, Quantum Philosophy: Understanding and Interpreting Contemporary Science. Trans Arturo Sangalli (Princeton University Press, Princeton NJ, 1999) An alternative view of the same area.
http://www.imaph.tu-bs.de/qi/concepts.html A useful introduction to quantum information theory, including many further references.

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