# Parallel universes and the arrow of time

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In a previous post about quantum mechanics and parallel universes I ended with a puzzle:

> All measurements are in principle reversible. Imagine that we could actually carry out this program of undoing the myriad entanglements that constitute your making a particular observation. What would be the subjective sensation, i.e. what would it "feel like" if this were done to you?

If you haven't read the previous post, please do before you read the rest of this one, otherwise this won't make any sense. The point of this puzzle is not the answer, but the process by which one arrives at the answer. Knowing the answer and understanding *why* it is the right answer are not the same thing, and in this case the latter is much more important than the former.

The intuitive answer to the question is that it would feel something like having time run backwards, but this is wrong. The reason it is wrong goes to the very heart of the nature of reality. To prime your mind to accept that the answer I am going to give is in fact correct I'm going to start by giving you the answer to what seems like it should be a completely different problem but is in fact almost exactly the same problem. It is a classic problem first contemplated by Albert Einstein: what would it feel like to travel at the speed of light?

The intuitive answer to this question is that it would feel like a thrill ride, like zipping through the universe really, really fast. Pluto is about four light-hours away, so if you headed towards it at the speed of light you'd get there four hours later, right? How could it possibly be otherwise?

The unintuitive but undeniable fact of the matter is that the speed of light is the same in all reference frames. This was shown experimentally in 1887 by the Michelson-Morley experiment, but it was actually predicted by James Clerk Maxwell 23 years earlier, in 1864. Maxwell's equations for electromagnetic fields predicted the existence of electromagnetic waves that propagated at the (already well known) speed of light, but the equations made this prediction without any mention of a frame of reference. The significance of this was not understood except in retrospect: it was forty years before Einstein first took the mathematical prediction and the experimental verification seriously and derived the theory of relativity, which can be summed up in the following pithy slogan: the speed of light is the universal reference. Everything is always moving at the speed of light through space-time. When you move faster through space you move slower through time. When you move through space at the speed of light, time stops. So what it would "feel like" to travel to Pluto at the speed of light is not that it would take four hours, but that you would get there instantaneously. In other words, you would arrive at the same time that you left.

Now, an interesting thing happens if you arrive at the same time you left, and that is that you can no longer distinguish between leaving and arriving. A trip from earth to pluto at the speed of light is indistinguishable (to the traveller) from a trip from pluto to earth at the speed of light. Both consist simply of being at earth and pluto (and everywhere in between) at the same time (in the traveler's reference frame). How do we reconcile this with the fact that an observer back on earth can easily tell the difference between a beam of light traveling in one direction rather than the other?

Here's a clue: the solutions of Maxwell's equations that predict electromagnetic waves are time-symmetric, that is, they predict the existence not only of waves traveling at the speed of light c, but they also predict waves traveling at speed minus c, that is, waves that move backwards in time. These solutions are usually discarded out of hand as being "unphysical", but if Einstein teaches us anything it is that discarding mathematical results

just because they don't "feel right" can blind us to deep truths. (And indeed, if we take seriously the idea that there are electromagnetic waves moving backwards in time what we end up with is a completely self-consistent theory called the transactional interpretation of quantum mechanics.)

So what happens in QM if we really take the math seriously? Well, we end up with a deeply unintuitive but nonetheless self-consistent description of the universe (except near a black hole -- physics is still working on that). The math tells us that our classical reality is merely an approximation of the underlying metaphysical truth, just as Galilean relativity (where space and time are separate things) is. The reason we think particles exist is not because they really exist, but because when you slice-and-dice the wavefunction in a certain way you end up with something that acts like (but isn't really) a bunch of classical entities all of which agree on a set of measurements (i.e. are in classical correlation with each other).

But, like Maxwell's equations, the Schroedinger equation is time-symmetric. You can run it backwards as well as forwards. And if you throw relativity into the mix then space and time are equivalent, and you can't distinguish forwards versus backwards any more than you can left versus right or up versus down. In other words, the wave function is a *static* four-dimensional "thing" (for want of a more general noun) out of which space, time, and classical reality "emerge" when you slice it up in certain ways. But there is nothing in the math that says that the slice that we are living in (what we call classical reality) is in any way special. You can slice up the wave function in a different way and get a different universe. All of this seems to be very much at odds with the (apparently) undeniable truth that our universe is special (at least to us), and that time only moves in one direction.

But again we must be very careful about trusting our intuitions, which have been proven wrong time and time again (the pun being a quantum superposition of intended and not :-) The math says time doesn't "flow", just as it says particles aren't real. So why does it appear to flow?

Again, we will approach the issue of time obliquely by drawing an analogy with particles. Why do we think particles exist? Because we can measure them. But QM tells us that the results of our measurements indicate the presence of particles despite the fact that there are in fact no particles (or, if you're a multiple-worlder, that there must be other universes). Let us go through the exact same mental exercise with respect to time: why do we think that time moves in one direction? Because there is this manifest asymmetry: we can remember the past, but we can't remember the future. And it's not just us: the *universe* "remembers" the past but not the future, which is to say, the universe contains information about the past (in books, for example) but not about the future.

There is another way to describe this asymmetry: we can "travel" forwards through time but we can't travel backwards. Except that we actually *can* (in principle) "travel backwards in time" by "rewinding the universe" i.e. undoing all the entanglements that led to the present situation. So let us go back and consider the opening puzzle: what would it *feel like* to "travel backwards in time" this way, to have yourself "reversed"? Picture the scene: you would have to go into a sealed chamber of the sort that houses Shroedinger's cats. Once safely ensconced inside, you would make some kind of measurement. It doesn't really matter what kind, but let's suppose you made a quantum measurement just to keep things simple. So there is some particle in the box with you, and you arrange for that particle to become entangled with some measurement apparatus and thence with your brain. Your brain is now, by virtue of having become entangled with the particle in the having-observed-the-particle state. You can remember making the measurement. You know what the result of the measurement was. All of the atoms in your brain are now acting together to make you appear like a classical system in classical correlation with itself and the measuring device. This is what makes you think you know the state of the particle (even though in reality there is no particle).

Now we turn on the magic reverse-o-matic ray. One by one, all of the entanglements that led you to be in the having-observed-the-particle state are undone. This involves reversing the entanglements in your brain, the measuring device, and everything else inside the box (including the magic revers-o-matic ray, but since this is a thought experiment we can ignore the obvious difficulties that entails). When this process is over, what mental state are you in? Well, you are in exactly the same mental state that you were in before the whole process

began. You have no memory of having measured the particle. You would have no memory of having the reverse-o-matic ray turned on. And since completing the erasure involved undoing *all* of the entanglements in the box resulting from the initial measurement, you would not be able to find any evidence anywhere inside the box that any of this had happened.

In other words, the subjective sensation of undergoing a macroscopic quantum erasure is*exactly* the same as the subjective sensation of having *nothing happen to you at all*! In fact, the only evidence that you would have that you had in fact undergone a quantum erasure is that when you emerged from the box after the experiment, you would find that more time had elapsed there than could be accounted for by what you experienced. (Note the similarity to relativistic time-dilation. Exercise: what would happen if you took a clock inside the box with you?)

So this is an unsatisfying sort of time-travel because it is experimentally indistinguishable from the normal state of affairs. What we really mean when we fantasize about time travel is moving into the past with the information contained in our brains and bodies intact. In other words, we're thinking about transporting *information about the present into the past,* at which point it becomes information about the future. We think this might be possible because we think we're classical entities, coherent material things that move volitionally through space but are swept inexorably through time by some sort of "flow", and if we could just figure out how to "move through time" the way we move through space that we might be able to swim against the tide.

But we are not classical entities.

To understand the truth you need to adopt a completely different mindset about what *you* are. Again, I will approach this obliquely starting with a more familiar concept: you think you're a human being, a physical entity with some coherent *identity* that remains intact through changes like growing older and learning new things. (It is this abstract identity that we imagine moving into the past when we fantasize about time travel.) What does this identity consist of? It can't be the atoms in your body because those are constantly being swapped out for new atoms. Maybe it is the *arrangement* of those atoms, at least at some high level of abstraction. But the arrangement of your atoms today is radically different from what it was the day you were born. In what sense, then, are you the "same person"?

The reason we consider ourselves to be in some sense the "same person" throughout our lives is because there is a continuous sequence of "yous" that lead from cradle to grave. You today may be radically different from when you were born, but in between there is a smooth transition from one to the other. At any instant in time, the you of that instant is very similar to the you one second previously, and very *very* similar to the you one Planck time earlier.

Imagine for a moment that you could take a God's-eye view of the universe and see all four dimensions at once. Consider two different instances of "you" at two different times. Is there any way you could tell which is the "earlier" you and which is the "later" you? If the two times are far apart then you could look at which you appears older, but what if the times were just, say, a minute apart? Well, you could still tell (if you were God) by examining your mental state: the later you would contain information that the earlier you didn't, namely, memories of the events that transpired during the intervening minute. In fact, if you were presented with an unordered set of all the you's that have ever existed you could easily reassemble them in their proper order simply by looking at which ones contain information about which other ones. If You-A remembers You-B then You-A must come after You-B. It can never be the case that You-A remembers You-B and You-B remembers You-A because then one of those you's would be "remembering" the future, and that's not possible.

But the crucial point is not *that* it is impossible but *why* it is impossible. The reason it is impossible is *not* that time only "flows" one way (that explanation would beg the question). The reason it is impossible is that *memories are entanglements* just as measurements are. In fact, memories *are* measurements, because every memory is a memory *of something*. So it is not that a memory can't be reversed (it can), it is that in order to reverse a memory you have to reverse all the entanglements that comprise that memory.

Now, here's the killer question: given that the observable result of undergoing quantum erasure is

indistinguishable from having nothing in particular happen to you at all, how can you be sure that at some point in your life it hasn't happened to you?

The answer is: you *can't* be sure it hasn't happened to you! It is possible that you (and the rest of the universe) have undergone quantum erasure at some point. In fact, it's possible that it happens regularly, that the entire universe is constantly being rolled back and replayed from different points in "time". In fact, the universe is chock-full of little quantum "isolation boxes" where this happens constantly! These are called "vacuum fluctuations" or "spontaneous pair generation", where a particle and an anti-particle just materialize out of nothing and almost immediately annihilate each other. The members of a spontaneously generated pair are entangled. The annihilation process "undoes" the entanglement and returns the universe to its previous state.

The punch line is this: the statement that we can't time-travel into the past is *exactly the same* as the statement that we can only remember the past. It is not the case that one *causes* the other, it is that the two things are *logically equivalent*. Your perception of "traveling through time" *emerges from your mental states and not the other way around.* You feel like you are "traveling forward through time" *because* your mental states have this natural order to them. You can remember the past and not the future *because* whatever you remember *is* your past. The laws of quantum mechanics (and entanglement in particular) insure that what any given instance of you remembers appears to be a continuous and coherent sequence that behaves according to regularities that we call the laws of physics. But in fact you do not travel through time, because at root there is no you, and there is no time. There is only the wavefunction, from which you emerge as an approximation.