Help Wanted— Philosopher required to sort out Reality. Apply to any school of Physics.

by

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If you travelled to a different universe and found out that things were weird, well, that wouldn't be too surprising. Going, possibly via the back of a wardrobe, into a universe where magic worked, or where the animals could talk, or both at once, would undoubtedly require a bit of mental flexibility. But none of these begin to compare with the weirdness of what actually happens in laboratories studying light and electrons. The terrible truth is that the wildest imaginings of fantasy writers don't come within coo-ee of what actually happens in a physics lab.

Recently, some physicists have decided that the idea of a reality out there existing independent of us has to go. Some say that the consciousness of the observer is crucial to determining the results of measurements: that the coming to my consciousness of the outcome of a measurement determines the answer; if so, what if I am drunk and barely have any consciousness? This suggests an interesting experiment involving huge quantities of beer. Others have suggested that everything that might happen does happen, mostly in some other alternative universe, and infinitely many alternative universes are spawned all the time. The mystical view that the universe only exists because we are here to observe it, has been proposed with all seriousness. You can see that sharp minded and properly informed philosophers are badly needed, and indeed some exist, but more would be useful.

We now know heaps about the structure of matter and the universe and it turns out to be beyond our capacity to understand it. The actual observed phenomena of the world are mind boggling. We observe it, we can describe it, we can predict it to astonishing precision. What we can't do is get any picture of what is going on. And it is possible that our brains can never understand it because they work the wrong way, being evolved for a human scale where things happen very differently.

The scariest and most incomprehensible part of the whole business is a little, utterly trivial, mathematical result called Bell's inequality. I shall explain it shortly, to convince you that it is blindingly obvious and has to be true and is bound to work. Before that I shall describe a physical set up that violates it. This will show that the impossible happens, and indeed it happens all the time as a matter of routine.

Suppose we have some coloured balls but are all blind so can't see the colours. This is a fair description of the quantum world. What we have is some filters, three of them. One is called a Black-White filter, one a Red-Green filter and one a Blue-Orange filter. We don't know if this describes the balls in any way, because we don't know what colour is, but we do get consistent behaviour out: if a ball is dropped into the Black-White filter and comes out on the Black side, if we drop it back in, it still comes out the Black side. Likewise for the other two filters. Any ball, dropped in any filter, is bound to come out one side or the other.

The balls come in twinned pairs. If one of the pair is dropped into a filter and comes out the Red side, the twin *always* comes out the Green side, and similarly for both the other two filters. Any ball always comes out one side or the other of any filter, and the twin always comes out the other side if dropped in the same filter.

The filters might actually be measuring something quite different from colours, but the behaviour of the filters and their consistency makes it clear they are measuring *some* property of the balls. We could certainly picture a ball as having three colours on it, say Black, Green and Blue, whereupon its twin would have to have the colours White, Red and Orange. If we take a squillion balls and drop them in the Black-White filter, we find that half come out the Black side and the other half come out the White side. The same holds for the other two filters. This gives us some information about the numbers of balls of each type. There are eight possible combinations of colours, there are Black-Red-Blue balls and White-Red-Orange balls and so on for the other six possibilities. Any scientist worth his salt would like to know the relative frequencies of each colour combination, and it is easy to devise experiments to count them. This is where the trouble starts.

Now for some mild weirdness. You would expect the 'three-coloured balls' theory to give you the result that if a ball has just gone through a black filter and you just drop it in the filter again, it will come out the Black side again. This indeed happens. You would also expect that if it comes out the Black side of a Black-White filter and then you put it in the Blue-Orange filter and it comes out the Blue side, if you put it in the Black-White filter again, it will always come out the Black side.

Unfortunately, this is wrong. Only half of them do, and the other half come out on the White side. Time for a quick brood if you want to see if you have enough imagination to explain it.

Finished brooding? It is clear that if those labels stayed the same, and if the filter is reading them and making a deterministic choice based on the label, then this couldn't happen. If the filters just made random choices then we couldn't get the twin pairs always behaving as they do, so the filters *must* be making some kind of deterministic choice based on labels. The only conclusion left is that the filters must be changing the labels.

This is characteristic of quantum effects, making a measurement changes the state of the system being measured. The state of the ball is specified by some label, and the measurement process of being dropped through a filter can alter it. The behaviour I have described works almost exactly this way when the balls are electrons or photons, and the filters are systems designed to measure a positive or negative component of the so called 'spin'. You don't have to know what this means to get the idea: there are binary filters and there are things that get through one side or the other of them, and physicists can find out which way they went and count them. And the filters behave as described.

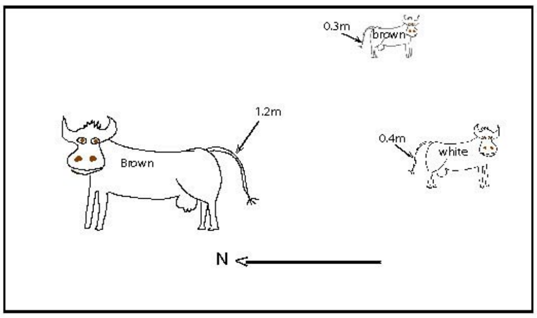
This is, so far, mildly weird but not *really* weird. You might even imagine doing a lot of experiments to work out something about the different labels and what the filter does when it comes across each type, bearing in mind that it can pass a ball either of two ways, and if it passes it then it may change the label in some way. It has to do this according to some definite rule, or again we could get non-opposite behaviour from the twin ball, and we don't ever see this. So by doing some careful counting of what happens as we try different sequences of putting balls and their twins through filters of different types, we should be able to work out something of what the labels are, and what is being done to them by the filters.

An even easier measurement would be to find the numbers of Black-and-Green balls, and likewise for all the other pairs. The Black-and-Green balls would include the Black-Green-Blue and the Black-Green-Orange and we wouldn't know how many of the Black-Green were also Blue, but we'd have *some* useful information.

This is where the *really* weird comes in. The counts we get are impossible. They can't happen.

But they do.

And so we come to Bell's Theorem. This is a simple result telling us that counts of things happening must satisfy a certain inequality. It works for finite sets of things, any things at all. And the fact that it is violated in the Quantum world has been called the most profound discovery in all Science. Which by some accounts would make it the most important discovery of the human race.



We think of finite sets. Well, those of an abstract cast of mind do, the rest of us think of a simple and clear example, say cows in a field. Some of the cows are brown and some are other colours. Some of the cows have tails longer than a metre and some don't. And some are facing towards the northern half of the field at some time, and others are not. Let the set of cows which are brown be called A, the set of cows with tails longer than a metre be called B and the set of cows facing in a generally northern direction be called C.

Now if ||A & ~B|| is the count of those cows in the set A but not in the set B, and ||B & ~C|| is the count of cows in the set B but not C, and ||A & ~C|| is the count of those cows in the set A and not C, Bell's inequality says:

$$\|A \,\&\, {\sim}B\| + \|B \,\&\, {\sim}C\| \geq \|A \,\&\, {\sim}C\|$$

where the ≥ sign means 'is greater than or equal to'. If your brain seizes up at the sight of mathematical symbols, beat it into submission by drawing a field and some cows, and label each of the cows for colour, tail length and facing northness. Then count the number of cows in your picture which are brown and have tails of length a metre or less, and write this number down. Now write just in front of it

'||A & ~B|| ='

because this is what you have found. Do the same for the other properties of the cows and verify that Bell's inequality holds. Now draw a different collection of cows in a different field and do the counting all over again. After you have repeated this about twenty times, your brain will start working again and you will suspect strongly that Bell's inequality will always hold.

The theorem indeed works for cows, and it also works for *any* collection of finite sets A, B and C. Some of the counts may be zero, but it still works. To prove it holds for everything, I need only two observations. The first is that if one set, U is a subset of another set, V, then U can't have more things in it than V. It's a bit hard to argue with this. The second is that if we have two sets which are disjoint, the number of things in the union of the sets is the sum of the things in each of the sets separately. If there are three cows in one half of a field and four cows in the other half of the same field then there are seven cows in the field. It is pretty hard to argue with this one as well. The only constraint is that the sets be finite so we can add up the numbers of things in them.

Now I look at the sets A & ~B & ~C and A & B & ~C. The first contains those things in A & ~C which are not in B, and the second contains precisely those things in A & ~C which *are* in B. Since anything is either in B or not, we see that the union is A & ~C.

We write therefore:

$$\| A \,\&\, {\sim}B \,\&\, {\sim}C\| + \| A \,\&\, B \,\&\, {\sim}C\| = \| A \,\&\, {\sim}C\|$$

Translate this back into English or cow, and convince yourself that it is true whatever the sets A or B or C may be, so long as they are finite and have counts.

All we need to do now is to observe that A & ~B & ~C is a subset of A & ~B, so we must have || A & ~B|| ≥ || A & ~B & ~C||. Similarly, A & B & ~C is a subset of

B & ~C, so we must have || B & ~C|| ≥ || A & B & ~C||. Bell's inequality follows immediately. Don't take my word for it, try it with simple examples or check the logic carefully. Incidentally, Bell himself calls this the Wigner-D'Espagnat inequality.

It follows that in the case of the filters, if A is the set of balls which pass through the black filter, B is the set of balls which pass through the red filter, and C is the set of balls which pass through the blue filter, Bell's inequality must apply to the resulting counts. But we can make the measurements, and it doesn't.

What we do is to take a ball and see if it comes out on the right (black) side of a Black-White filter. Now we argue that had we put it in a Red-Green filter and it had emerged on the Red side, then the twin if put in the filter would certainly have come out of the Green side. Well we didn't put it in a Red-Green filter, we put it in the Black-White one. But we can put the *twin* in the Red-Green filter, and if it comes out of the Green side, then we know that the original ball would have come out the Red side. And if the twin does *not* come out of the green side of the Red-Green filter, then the original ball could not have been able to come out the Red side had we put it into the Red-Green filter instead of the Black-White one.

So we can take a squillion balls in twinned pairs, put one of the twins in the Black-White filter and the other in the Red-Green filter. Then we count the fraction where the first ball comes out of the Black side and its twin comes out of the Red side. This number we can call the 'Black and not Red' value. Which is the same as the Black and Green, and is consistently around seven percent of all the balls.

Similarly we can count the 'Red and not Blue' values, and the 'Black and not Blue' values for different collections of balls. Since there is nothing to distinguish any one squillion balls from another squillion, we assume that had we made the measurements in a different order it wouldn't affect the fractions more than a tiny bit due to random variation of the class of balls we have.

Now it is possible to set up three filters which work as described, although on electrons or photons instead of balls. We can do this in such a way that we find that about seven and a third percent of balls are in the 'Black and not Red' category. This fraction gets better and better determined the more balls we test. It can be calculated from Quantum theory as the number 0.073223… or one minus the square root of one half, divided by four. This is 7.3223… percent, as advertised. Testing lots of balls is possible and can be done quite quickly. The count of balls which are in the 'Red and not Blue' category are also roughly the same fraction of all balls presented, just over seven percent, and again the roughness decreases as the sample size goes up. And the count of balls in the Black and not Blue category is about one quarter; of all balls in a sample of a squillion, one quarter of a squillion will turn out to be Black and not Blue. And seven percent plus one seven percent is about fourteen percent which is ***not*** bigger than twenty-five percent. And Bell's inequality says these counts can't happen. But they do. The numbers do not add up.

Now the search for the fatal flaw in the argument has to start. Something is horribly wrong. The fact that Bell's inequality is so obviously forced by the simplest considerations (works for cows!) tells us that what has to be wrong is something deep. If Bell's inequality depended on a huge number of delicate assumptions and was hardly ever found to work in the real world, nobody would worry too much if it failed again. But it *always* works except at the quantum level, and we can see exactly why it *has* to work everywhere, because it is just a statement of the bleeding obvious. If we take some balls to have information on them saying `pass me through a black filter, a green filter and a blue filter' together with additional information saying how to change things if you are a particular kind of filter and I am passing through, we can ignore the second part altogether and just call this a black-green-blue ball. Then the black and not red is the black-green-blue plus the black-green-orange numbers, whatever they might be. Similarly for the other colours.. Try a few possibilities: guess that one eighth of all balls were black-red-blue, one eighth were white-red-orange and so on for all the other six combinations. Then the fraction of black and not red is just the black-green-blue plus the black-green-orange which is one quarter, a lot more than seven percent. OK, so try some other numbers for the fractions. The point is that no choice whatever will work. Any choice you make will have to satisfy Bell's inequality, but the actual counts do not.

At this point a pause for thought, and maybe refreshment, is in order. If you have followed the argument closely, you may be in need of a stiff drink. Conversely if you are not severely gob-smacked, it is because you have missed the point. The fact that the experiments merely count things is part of the awfulness of the result. Mostly, counting things *works*.

Of course, you can solve the problem of Bell's Inequality by not thinking about it, just as you can solve all the problems of life by being dead. The violation of Bell's inequality won't strike you as the least bit scary in either case. But if you *do* think about it, it gives you a strong sense of total insecurity about everything, and you have to face up to the fact that the universe just doesn't work the way you thought it did. It is weirder than you can imagine.

Does it have anything to do with the fact that making a measurement changes the state? No, because we only make one measurement on a ball and one on its twin. It wouldn't be surprising if measuring which balls go through a black filter and *subsequently* fail to go through a red filter gave us weird answers, but we aren't doing that.

Could we get these answers because the filters are sending messages to each other saying what has happened to the latest ball and changing the rules for the other filters? Or could a filter looking at one ball broadcast to change other balls? You could, maybe, devise a protocol for filters to communicate with each other, but you can do your filtering experiments a long way away from each other and in sealed lead-lined rooms. The sealed lead-lined rooms will rule out any conventional signal, but so will being far apart, and the latter is cheaper. We still get these results even when the places doing the counting get the answers long before a light speed message between them can mess things up. That anybody would even consider the possibility of the filters (or the balls) sending out broadcasts about the results of putting one in the other, tells you how desperate things are. Similarly, the twin balls can be far apart when we make the measurements on the pair of filters we drop them in. Measurements have been made that show the results happen faster than any information travelling at light speed could get from one to the other. This is the 'spooky action at a distance' which upset Einstein so much and made him believe Quantum Mechanics was fundamentally flawed. He was right to be unhappy. You should be feeling pretty unhappy too.

If common sense and counting screw up so badly, what does the theory of Quantum Mechanics have to say? At least it gives the observed answers. Unfortunately for your peace of mind, the theory asserts that there is a fundamental randomness about the results of measurement. It also asserts that which way a ball will go through a filter is not determined until it actually happens. Believing that the electrons or photons are not really making random choices, but are following some complicated but definite rules we don't know about, is not how Quantum Mechanics works, and (given Bell's inequality) is not an option. Not unless you believe that information can be sent faster than light either from twin to twin or from filter to filter. And while the result of whether a ball will go through the Black side or the White side is not, in Quantum Theory, predictable in advance, being intrinsically random, the twin always does the opposite. Even if it is the other side of the Universe at the time.

We have no coherent picture of what is going on here. We have a theory which we cannot understand. We can do the sums and we get the right answers, but what we cannot do is form a picture of what is happening. This is, nearly everyone agrees, absolutely maddening. Sane people like a picture of what is happening and use it when doing the sums; the algebra should describe the picture. In classical mechanics it does. In relativity it does too, although the pictures are more complicated. But in quantum mechanics, the pictures evaporate. You are not allowed to say that an electron or photon in motion has a trajectory, it has an infinite number of them, all at once. Unless you measure it, when it has one. It is hard to visualise this.

The Quantum Theory explanation is as incomprehensible as the things it tries to explain. In fact it isn't so much an explanation as a compact summary of what will happen if you make certain measurements, and the standard Copenhagen interpretation of the theory tells you that if you expect more, tough luck you ain't going to get it.

This is the bad news. The good news is that as a consequence of the laws of Quantum physics we can, in principle build quantum computers which can do a huge number of computations simultaneously. A small one has already been built. And it is just possible we might get some sort of understanding of quantum theory out from them after all. But that is another story.