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Dead Cats: The Dark Secrets of Causality and Quantum Mechanics

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In the continually changing world of science, there emanates, for many, a constant sense of intimidation from the field of quantum mechanics. It is the subject that Einstein, perhaps the most revered scientist of all time, said was "spooky" and spent much of his life trying to disprove. It is the subject that lies in the roots of arguments that nothing is real, that new universes are being created every second, and that there is conclusive scientific proof there is a God. Its most famous metaphor involves dead cats, which are intimidating in themselves.

But for those among us who can overcome Schrodinger's morbid felines, there lies completely different problems that most of us would rather just see go away. The bizarre conclusions suggested by the EPR paradox and Bell's inequality challenge our most fundamental assumptions about nature, and pose staunch philosophical questions about the essence of the universe. The transfer of undetectable information at presumably superluminous velocities, the issues of causality and

determinism, the question of realism, and the burden of getting a superimposed cat through a Stern-Gerlach magnet detector are all issues arising from this quantum enigma, as we will soon see.

So let's begin. Before we get into the philosophical issues, it will be helpful to understand the events and theories leading up to them. A great place to start is to explain our modern mathematical interpretation of nature. Since the late 1920's, it has been known that several properties of particles on the atomic scale and below can be accurately described by what is called a "wave function". The wave function helps us determine the probability that a particle's property, such as position and momentum, will have a particular value at a given time *t*. The wave function can never say exactly what the value of the property will be, no matter how great the number of given experimental parameters. It can only suggest a *range* of possible values, and the statistical *probability* that the property will have one of those values when measured. Thus the wave function is kind of like a quantum bookie: it tells us the teams playing, i.e. the possible values, and odds of each team winning, i.e. the associated probability, but really has no idea which team, or value, is going to come out on top.

So unlike standard mechanics, we can not predict or solve for the property's value, and generally have no way of knowing it until we measure to see what it is. However, when we measure it once, we can measure it again and see that it still has the same value. We say the property is no longer indeterminate, and the wave function is said to have "collapsed" to suggest that the property will now only have the value we just measured. Since we don't know the value until we measure it, the wave function suggests a state of indeterminacy of these properties before hand. Now, it sure would be nice to know if this indeterminacy represents the actual state of the particle or just reflects an incomplete, or limited, quantum theory.

The most famous pursuit of this dilemma has stemmed from an experiment proposed by scientists Einstein, Podolsky and Rosen (EPR), and is described as follows. One of the properties of an electron that can be described by a wave function is called "spin". It is rather difficult to understand what it means to say that an electron has "spin", and it almost seems we could just as well say that the electron has "brown", "newspaper", or even that it has "gas". Well, it turns out that spin is a quantity that is conserved due to angular momentum, so, by pneumonic default, scientists embrace the word "spin" in an attempt to perpetuate the myth that it resembles something in real life. In any case, it is known

that a pi meson, with spin 0, decays into an electron and a positron, each with a spin possibility of +/- 1/2. If the spin of the electron is found to be +1/2, then the positron must have spin -1/2 (or vice-versa) because angular momentum must be conserved.

It is both intuitive and accurate to say that, upon the decay of a pi meson, there is a 50% chance the electron will have +1/2 spin and a 50% chance it will have a -1/2 spin, and the same goes for the positron. Since spin (or "gas" if you prefer) can be described by a quantum wave function, there is an allowed 50/50 probability for each spin value, it is mathematically indeterminable which value it will take on at the time of measurement. EPR (not to be confused with the "ELP" of Emerson, Lake, and Palmer) were convinced that the spin was actually determined at the moment the meson decayed. They believed the only reason it was mathematically "indeterminate" before measurement was because they perceived the quantum theory to be incomplete. They felt that a complete theory would be able to correctly predict the spin before measurement, much like all other mechanics up to that time could predict the outcome of events with some given parameters. This is known as the "local hidden variable theory", because it asserts that the electron has a definite spin who's value is "locally hidden" with the electron until it is measured.

Niels Bohr, however, felt quite differently about the whole matter, and decided it was imperative that he utter a famous quote, which we will print here for your reading enjoyment:

> "There is no quantum world...only an abstract quantum description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature."—a famous quote by Niels Bohr

Bohr's assertions were, and still are, perplexing and controversial. According to Peter Kosso, Bohr is making both a metaphysical claim about the way some aspect of nature is, namely that there is no quantum world, and an epistemological claim about our ability to know about some aspect of nature, namely that we can not know about the quantum world. Kosso says that Bohr likely means in the metaphysical part that, since indeterminate quantum properties (spin, position, momentum, etc.) are made determinate in the act of observation, their properties are not independent of the observers.

Thus "there is no quantum world" is probably misleading from

what he actually believed. He seems to be saying that measuring the property causes the wave function to collapse into a classical description of the property, and that, before we did this, the property was in a superposition state (or non-existent). More generally, he means that a quantum world does not exist in any classical sense. This raises the profound possibility that the world as we know it, that is, as one governed by classical physics, is a collapsed version of a quantum world that arises from us living and interacting in it. In any case, Bohr's quote seems to be unclear on whether he thought that the property existed in a superposition state (i.e. a real, physical wave function) before it was measured, or that it didn't exist at all, but we'll get back to the issue of causality and indeterminism a little later.

Bohr's epistemological assertion is also curious: how can one say that we can not know anything about the quantum world? Sure, we could say this if there was no quantum world to know about, but, according to Kosso, both Einstein and Bohr seem to think there is some type of quantum world. And if we thought that there was no quantum world, then we better make sure we are right.

So we have just encountered two philosophical positions, Einstein's "realist" position and Bohr's "anti-realist" position, regarding whether or not a property existed before it was measured. Notice we keep distinguishing between a particle and a particle's property. It seems that both Einstein, Bohr, and the theory of quantum mechanics give no reason to deny the particle some specific properties before detection. Sure, there are some properties whose values are indeterminate before detection, but there are others that are definite for a particle all of the time (in our electron example they include both a precise mass and electric charge). Since we can predict the exact value of these properties and we know that it will be the same every time measure it, it is hardly a stretch to say that the properties exist at all times, and therefore so does the particle. Thus, there is no reason to make sweeping claims that *nothing* is real: such unfounded claims seem to be produced by a metaphysical bias that lies far from the roots of formal science and philosophy.

Einstein and Bohr tossed intellectual mud at each other over this for years, and, unfortunately, Bohr died before a major breakthrough in the issue came in form of Bell's proof. In 1964 John Bell came up with an experiment to test the validity of the local hidden variable theory (see Rothman, Griffiths). Bell set up a relatively simple mathematical inequality describing the spin orientation of the electron/positron pair in

the decay of a pi meson. The ingenious part of this experiment was to set up the relationship so that the inequality *must* be true if the local hidden variable theory was valid. With the help of arbitrarily orientated Stern-Gerlach magnets to dectect the spin, Bell astonished the physics community when his experiment *completely violated* his inequality. This officially showed that the spin of the electron/positron pair was *not* determined at the time of decay, but rather was determined at the time of measurement. This implied that, of the electron/positron pair, the one that was measured first communicates with the other one, no matter how far away it is, letting it know what spin it should have so that the spin will stay conserved. This communication ensures the electron and positron will have equal and opposite spins, as is mandated by the most sacred laws of physics.

Scholars & noblemen have postulated many different interpretations of Bell's proof, so it is important to be precise about what it does and does not prove. First of all, it undoubtedly disproved the theory of local hidden variables, at least for the property of spin orientation. Unfortunately for Einstein, who detested the idea of this "spooky action at a distance", it leaves us no choice but to abandon the concept of any classical interpretation of the property of spin orientation before measurement. It is tempting for one to make the analogy that other indeterminate properties (those described by a wave function) also have no local variables. While this is certainly possible, and many would argue it is probable, this is not the subject of Bell's proof, and is not proved by Bell's experiment in any sense.

In the same way, we can also say that Bell's proof makes no mention of the possibility of multiple universes, extra dimensions, or the existence of God. While it does not disprove or contradict any of these ideas, it certainly does not show that they should or must be true. Bell' proof says that the electron/positron (or photon/photon) pair communicates information to each other in a means that is undetectable. Provided the information is traveling in our universe in dimensions that we know about, it is traveling faster than the speed of light.

The nature of this information is unclear—David Griffiths suggests an "ethereal" kind that does not transmit energy or information could be responsible, since we know of things like shadows that can travel faster than the speed of light with no problem. For example, if a bug flies across the beam of a movie projector, the speed of its shadow on the screen depends on how far away it is from the screen. Since that distance can theoretically be as big as we would like, we could easily

create a situation in which the bug's shadow is travelling faster than the speed of light. Can something like the detection of a shadow be responsible for the particle communication in the pi meson decay?

That, of course, raises the question "Is energy absolutely necessary to transmit information?", a question whose answers that range from "yes" to "no" to "who knows?". Others believe that to think of the paradox in terms of information transfer is silly. They say that the problem is that we're viewing the pair as independent particles, when in fact they are never truly independent. The pair will always be correlated as a single particle; there is actually an uncircumventable wholism implied about the universe. While this is certainly possible, it is far from being understood in a scientific perspective. And the onslaught of philosophical and religious explanations of this particle correlation, although immensely popular, are generally circular or incomplete.

So far this might seem like a rather prissy list of conclusions. However, it is important to be precise about what we can and can not conclude from Bell's proof, especially since its results lend themselves to being easily misinterpreted. I believe that Kosso himself jumps to some unfounded conclusions. Because of the communication between distant particles that Bell's proof shows, we are forced to renounce the idea that the electron spin is determined before measurement. Kosso therefore states that Bell's proof shows that the property of electron spin must be in a superposition state of +1 and -1 before the spin is measured. I believe that Kosso is wrong, however, and that we can not conclude that there is any evidence of this being an accurate statement about nature.

This is a subtle difference, since the spin orientation is in fact accurately described by a probability before measurement. Kosso says "probability is a property of each particle", but it seems that this is only a construct, and we can not say that probability of spin orientation is an inherent property of the particle. In fact, there is no evidence that the electron has the property of spin in any state whatsoever prior to measurement, let alone that the property of spin orientation is inherent in a superposition (probabilistic) state. Kosso's own die analogy is a good example of this.

With each roll of the die, there is a probability that it will be a certain number. However, this probability is a property of each roll of the die, not of the die itself. The die at rest on a table has no probability prior to being rolled. Likewise, it is possible that the electron has no state of spin orientation attached to it before being measured, but rather spin orientation is a property of measurement. That is, the act of measuring

causes the particle to have a spin orientation property. This suggests that Kosso's claim, which asserts that measuring the property forces it from a real, physical wave function state to a definite spin value, is only a mathematical construct that is not a useful physical interpretation.

Kosso , however, does an excellent job fleshing out the relation between Bohr's famous quote and Bell's proof. It seems that Bohr's thoughts about the metaphysics were correct in the sense that there is no classical property concept that can be ascribed to quantum particles prior to measurement. However much it pains Einstein, we must abandon some of our classical notions at the quantum level. Since Bell's proof showed that classical property notions, i.e. the local hidden variable theory, do not hold at the quantum level, we did in fact learn something about particle behavior at the quantum level. Thus Bohr's epistemological claim that we can not know about the quantum world seems to be violated.

Personally, I have always been curious as to why the EPR paradox has never been related, at least philosophically, to the paradox of the big bang. In the big bang theory, which is accepted by a majority of scientists, there was nothing but a void of ...er, "nothing", and then, "poof!", there was something. This brings the fundamental tenets of causality into question, a paradox encountered with questions like "if there was absolutely nothing, than what caused the universe to be born in a big bang?", "if God made us, then who made God?", and "are these my pants?".

Which make us wonder (well, me anyway): what's the deal with causality? Causality is an ancient philosophical idea that comes from the even more ancient Greeks (or at least it's safe to assume it came from the ancient Greeks, because we all know that the ancient Greeks enkindled the whole of human knowledge while eating olives and admiring each other's sandals). One of the basic principles of science is that if there is a cause there is an effect, and if we observe an effect there must be a cause. It sounds simple, but the ancient Greeks aren't the kind of people to bother with things that are simple. Aristotle said that we don't have to look for causes in things that are not changing. Something with no observable effect, he argued, implies that there must be some natural state in which there is no cause. He believed that the natural state of an object was at rest, a state in which nothing seemed to be changing. Then Galileo came along and said that the inertia principle defines an object's natural state, namely an object at rest wants to stay at rest and an object in motion wants to stay in motion. Newtown, realizing it was the

only principle that he didn't have at least one of, copied Galileo's inertia principle and called it his first law of motion.

This deliberation over the natural state of things is still a hotly pursued endeavor, as is seen in modern studies of gravitation and general relativity. Scientists have always thought that gravitation was a force produced by a mass that pulled other masses toward it, and the force between the two objects goes as 1/(r^2). When Einstein published his general relativity theory in 1916, he included several predictions that could be experimentally tested. In 1919 everyone went to an observatory during a total eclipse and said "yay! light is bent by the force of gravity! let's go home!". When they went home Einstein politely reminded them that he had not yet received a noble prize for telling them this would happen, so they had him send an SASE and the prize came shortly thereafter. While all marveled at this amazing occurance, no one even thought that it was not light being curved by gravity, but that space itself, the final frontier, was actually curved by a mass. In general relativity, the "force" of gravity can be described in two ways: as a particle being accelerated by a mass, or as a particle traveling through space curved by a mass.

And although this may sound strange, the explanation associated with it is actually quite nice. Fine folks like Heron and Fermat helped to form principles about what is the natural path for an object to travel that culminated in Lagrange's equations and the calculus of variations. Basically, the calculus of variations finds the path of least distance (or time or other stuff depending on what you're looking for) that a particle that a particle would take to travel between two points.

Fermat and others have long held a belief that particles in nature tend to intrinsically take the path that minimizes a function such as distance or time. If we described general relativity with curved space, then a photon (light) traveling through space would actually be taking a path of least distance through space that's curved. This would have potentially profound implications, including the possibility that there is actually an absolute space (or as Narendra Jaggi says, "Space" with a capital "S") that can be curved and manipulated. At the very least, it is concurrent with the notions of Heron and Fermat that nature follows the simplest path, and is far more elegant than a theory describing particles being accelerated in a gravitational field.

So what really "causes" the behavior of particles that we describe as gravitation? The issue is still hotly debated, but the theory of the gravitational force fails to describe the energy changes observed in photons in a gravitational field. These changes, however, are in complete

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agreement with general relativity, tending to suggest that space might be curved after all.

Another interesting thing about Einstein's work, as well as the better part of physics as a whole, is that all of the equations are completely time reversible. In all of Newtonian and Einsteinian mechanics, the descriptions with respect to time never indicate which way time flows. That is, the physics doesn't know that time flows forward. Time really is a variable with only 1/2 a dimension. That is, it is limited to one axis, like a variable with 1 dimension, but it is only allowed to move forward, and hence "1/2" a dimension.

Math is rather clumsy at handling variables in 1/2 a dimension, and thus it is much easier to consider a t variable of a full dimension and then eliminate the solutions the solutions in which time flows backwards. That is to say, we make it a condition that the cause must precede the effect. This seems like common sense, and I'm sure that Aristotle would say "this is obvious". However, there are cases in quantum mechanics in which scientists believe that assuming time flows forward is not a valid assumption (!). Griffiths notes there are events involving "advanced potentials" in which the possibility arises that electric and magnetic fields existing in the present are dependent on the changes in field sources at some time in the future. This means that the only way for the answer to make sense is if the effect precedes the cause, and time is reversed. Although advanced potentials are generally of purely theoretical interest, it is important to note that the reason these equations are time reversible is not necessarily due to a novelty of the mathematics. Consequently, the ancient assumption that nature limits time to only a 1/2 variable (flowing forward) may be wrong!

We've looked at several areas where science, philosophy, and reality all seem to butt heads. While some of the answers are a little more clear than others, rest assured the quest for truth will not be halted (only delayed until someone can get the dead cats out of the magnets).

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