

## Is it time to abandon free-will?

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For centuries man has been devoted to attaining the seemingly god like ability to predict and control everything, especially his own fate. This is perfectly exemplified by the manner in which classical physics has been formalised, with an emphasis and assumption of implicit control and predictability.

This was until the birth of Quantum Theory. Where the Danish physicist Niels Bohr claimed that the only way to interpret the theory (known as the Copenhagen interpretation) was to assume that nothing really existed distinctly until it was measured, where it would randomly (based on various probabilities) become definite. But even then as you could not possibly measure everything without affecting the values of other variables, which means that it is impossible to know everything for certain. Man's dream of god like knowledge seemed shattered, but with it came the liberating possibility of free-will.

Largely due to the phenomenal experimental success of the theory, the majority of the scientific community were willing to accept the uncertainty quantum theory brought and begin to take for granted the right that is free-will. This did not sit well with many physicists, such as Einstein (one of the founders of quantum mechanics), who very famously said "God does not play-dice".

Due to Einstein's distrust of quantum mechanics, he, along with Podolsky and Rosen<sup>[1]</sup> produced a paradox which was designed to show the possible inefficiencies or incompleteness of quantum mechanics based on a phenomena known as quantum entanglement. Based on this Bohm and Aharnov<sup>[2]</sup> created a thought experiment to illustrate the paradox, which is as follows.

Consider the decay of a particle at rest with zero spin, decaying into two spin-1/2 particles (such as two electrons). Where spin is a quantum property of all particles, which is always considered to be either 'up' or 'down' along whichever axis you choose to measure it.

Now, because the two particles were created together, they are in what is known as a 'singlet spin state' i.e. they are 'entangled'. This means, that if you were to measure the spin along say the x-axis of one of the particles and found it to be 'up', then according to quantum mechanics a similar measurement of the other particle along the same axis, would be found to be 'down' (and vice versa). This is easy to see, as the original particle had zero spin, and the decay did not effect the overall spin of the system, so the sum of the two spins of each electron must be zero (i.e. they would be found to be equal and opposite). Therefore by measuring the spin of one of the particles, you can know with certainty the spin of the other for that axis.

The problem occurs with quantum mechanics in the fact that the precise value of a variable does not exist until a measurement of that variable is made, where according to 'Copenhagen Interpretations' the wave-function of the particle said to 'collapse', so that any further measurements of that variable would be predictable. That is to say, until the spin is measured it is neither 'up' nor 'down' but in a superposition (mixture) of both, i.e. it has certain probabilities of being found up or down, but it does not actually know which it is until it is measured where it randomly falls into being, for certain, up or down.

This leaves the problem of what Einstein famously referred to as 'spooky action at a distance'. Where, if two experimenters were to measure the spins of the two electrons at precisely the same time along the same axis, the wave-functions of the two electrons would collapse at the same time and one would become up while the other down. However, the particles do not know which they will be until the point of that collapse, so if the measurements were taken at the same time, a faster than light (maybe even instantaneous) transfer of information would have to occur between the particles, seemingly violating special relativity and causality.

Nonetheless, most agree that this can generally be resolved by the fact that the information is not 'causal' and effectively useless to us. That's because it is impossible to predict or stimulate the spin into being found in any particular state, i.e. you cannot force the spin to be say up rather than down. Therefore, you cannot use entanglement to communicate useful information at faster than light speeds; you can merely verify that it occurs. The results still have to be transmitted between the experimenters using 'classical' means, so causality is preserved.

The quantum mechanical explanation of this 'action at a distance' would be that like the spins of the electrons, the experimenters and their results were in a quantum superposition (indefinite) state. Where it was not until each experimenter observed each others experimental results through classical (less than light speed) methods, would the results become definite and in agreeance with each other. This then avoids any breakages in special relativity, causality, or locality.

On the other hand, by using a quantum mechanical explanation to solve this problem, a second occurs. The variables of spin for each axis in a quantum mechanical system are known as being non-commutative. Which means, if the spin in one axis is known for certain then you cannot know for certain the spin of the other axes (similar to the more widely used example of position to momentum), under the predictions of the Hinesburg Uncertainty Principle.

Therefore an obvious loophole exists in this thought experiment. In that you can measure the spin of one particle and know its spin for say the x-axis, then if you were to measure the spin of the other particle along a different axis, you can know with certainty the spin of two axes of each particle.

There are alternative theories to help combat these problems, the major bulk known generally as Hidden Variable Theories, where one of the more famously proposed ones being by David Bohm<sup>[3]</sup> which he produced in conjunction with the above thought experiment. It suggests that quantum mechanics is a mere approximation to reality, and that there are quantum variables which are 'hidden' (not detectable or rather not observable) by us. These imply that the universe is principally deterministic, which means that the Uncertainty Principle would no longer apply and so the above non-commutative variable problem simply would not be an issue. Also as the particles would know what spin they were at the moment of separation (apposed to the moment of measurement), there would be no need for any communication between the particles and there would be no break in relativity.

Unfortunately the majority of these theories were halted by the Kochen-Specker theorem<sup>[4]</sup>. Which delicately proves given the two main assumptions of most hidden value theorems<sup>[5]</sup> which are firstly value-definiteness, "all observables defined for a quantum mechanical system have definite values at all times" and secondly non-contextuality, "if a quantum mechanical system possesses a property (value of an observable), then it does so independently of any measurement context," i.e. independently of how that value is eventually measured; are inherently contradictory.

Having said this, Gerard t' Hooft of the University of Netherlands has recently produced an alternative resolution<sup>[6]</sup>. His model outlines an alternative layer of reality at scales smaller than Planck's length, where there are no particles or waves, just highly deterministic energy states. This was only recently finalised on 3<sup>rd</sup> April 2006, following the resolution of eliminating the strange possibility that there could exist negative energy states. Then a week later on 11<sup>th</sup> April 2006, Simon Kochen (from the above theorem) and John Conway<sup>[7]</sup> of Princeton, mathematically proved that there is a disturbing relation between free-will, determinism and any sort of hidden variable theorem.

This relationship has deep implications to what is famously known as Bell's inequality. In 1964 John Bell<sup>[8]</sup> (at the time at CERN in Geneva) mathematically showed that if a set of certain basic assumptions (asserting to a deterministic universe) hold true then there would be a certain correlation between the spins found for each of the different axes. But, if quantum mechanics dictated the outcomes, then the correlation found should be measurably different. This means it is theoretically possible to experimentally verify whether quantum mechanics or determinism rules. This means if Bells Inequality holds, i.e. through experiment the certain correlation is found and the following assumptions hold (that the universe is found to be deterministic along with relativity being intact). However, if it is found to be violated then it can be assumed that either quantum mechanics is a more true description of reality or possibly relativity has broken down.

Although the assumptions vary slightly based on the context, they have been generalised by Angel G Valdenebro<sup>[9]</sup> as follows. Firstly, Realism is generally considered true, (1) "the outcome of a measurement is not created by the measurement, but corresponds to properties possessed by the measured system prior to the measurement" where (2) "each measurement has only one actual outcome." These two basically mean that some real and accountable variables exist at all times which dictates the behaviour of the particle, but with any 'many worlds' interpretations being rejected.

Secondly, there is a fair distribution of microstates, more specifically (3) "if detection efficiency is not perfect, i.e. if not all the intended measurements can be successfully completed, we must at least assume that the efficiency does not depend on the microstate system". Also under this 'fair distribution' assumption, is the no-conspiracy (or independence) assumption where (4) the "measurement settings are independent of the microstate of the system". These are assumed along with no backward-causation, (5) that an effect cannot precede its cause.

Then finally what is referred to as 'Bell-Locality', (6) "the separation of experiments must be enough to completely discard the exchange of subluminal signals during measurements" which is similar to basic locality (where two systems in different points in space are considered independent). This more explicitly says, like

(5), that transmission of information faster than light is not possible and relativistic locality must not be violated.

These can be summed up as, Generic Realism that if an object 'exists' then it has distinctive variables which accurately dictate the outcome of a measurements, and reflect some real and pre-existing property of the object (variable-definiteness). Bell-locality, which crudely means that no transmission of causal information can occur. Then finally the 'fair-distribution' assumptions, which is where the reliability of the inequality comes into serious debate.

Looking again at (4) the independence (or no-conspiracy) assumption, although the statement looks clear cut and on the whole innocuous, it might actually be impossible to achieve while the other assumptions hold true. Bell himself wrote about this in a later paper<sup>[10]</sup>, "even if we have arranged that a and b [the experimental setup, in this case the axes that spin is measured] are generated by apparently random radioactive devices, ... or by apparently free willed physicists, or by some combination of all of these, we cannot be sure that a and b are not significantly influenced by the same factors  $\lambda$  [some realist value such as hidden variables] that influence A and B [the measurement results]."

This can be thought of using Reichenbach's (1956) Principle of the Common Cause, where if the light-cones of the particles and experimenters coexist at some point in the past (have the same causal past), then they can 'conspire' to force the experimenters to set the trial in a biased way (or equally, produce a biased outcome based upon the experimenters decision). So by taking a rather extreme (but highly plausible) deterministic example of Big Bang creation, it is highly possible that every particle (or wave, or energy state) having all interacted at some point in the past, knows exactly what each and every other particle is going to do. Leading to a totally fatalist interpretation of the universe and strips us completely of any free will. This is not to mention, if assumption (5) of backward causation was not to hold, then not only would the systems have to be independent in the past, but also the future.

This is completely complimentary to the Conway, Kochen paper mentioned before<sup>[7]</sup>. Where they proved "if indeed there exist any experimenters with a modicum of free will, then elementary particles must have their own share of this valuable commodity". This would therefore seem to suggest that Kochen has again (as with the hidden variable theory) shown that two of the assumptions are incompatible. That is, if you take 'apparently free-willed physicists' (as Bell suggested) and try to make them take measurements on apparently variable-definite particles, you cannot. As free-willed particles cannot be variable-definite. So this suggests that the inequality should always be found to be violated.

However, Kochen only proved this for 'free' particles, not necessarily 'random' ones; the difference lying in the ability of free events to be twinned or recreated. This distinction and the various degrees of freedom which the experimenter can have is a very delicately debated topic<sup>[11]</sup>, but the distinction is clear and quantifiable. So suppose you got rid of the free-willed experimenters and used (as Bell also suggested) a random radioactive device or maybe the Swiss national lottery machine, which although in a deterministic universe are not theoretically totally random, the inequality would not be broken. This is because under assumption (4) the experimental settings merely have to be independent of the entangled system. This would also satisfy (6) where locality must not be breached (it was originally intended for the two parts of the singlet system not to be able to communicate with each other at faster than light speeds, but this implication should also be placed on experimenters to particles). So this means that the only possible way for the inequality not to be broken, is to abandon free-will, any notion of a singular casual past and accept the local-realist view of variable definiteness.

This means it is not surprising that the experiments designed to test Bells Inequality usually find it breached. Take Nicolas Gisin and colleagues from University of Geneva<sup>[12]</sup>, the experiment is much the same as that of the EPR thought experiment, except they are firing entangled photons down a 25 kilometre length of fibre-optic cable, and instead of measuring the spin, they see if the photon is 'early' or 'late'. Similarly Paul Kwiat and Aaron VanDevender from University of Illinois at Urbana-Champaign who using 'partial polarization' to perform a filtering process on the photon pairs<sup>[13]</sup> to maximize the entanglement, have found violations of Bells Inequality of more than 1000 standard deviations<sup>[14]</sup>.

This is very compelling evidence in favour of quantum mechanics being true (along with our and particle free-will), or at least the existence of a 'hidden' non-locality (where two points in space are not necessarily considered to be independent so relativity can therefore be broken). However, we have not taken assumption (3) into account which is often referred to as Bell's 'loophole'. If the detection equipment is not perfect (against the assumption), then it is possible that the detections might be biased in a way that only those particles that fit or do not fit the certain correlation are detected. Such as in Gisin's experiment in Geneva, only about 1 percent of both photon pairs were detected, which could easily mean there is an unfair representation of the

whole system and excessive correlations in that small detected percent could easily be biasing the results. However, how or why these alternative correlations would not be detected is not known, and given the evidence from Kwiat who hopes to achieve a much higher efficiency with his next experiment nearing more like 90 percent detections, it is hard under such strong evidence to deny that determinism and/or relativistic locality has not be broken.

So maybe it is not time to give up on free-will just yet. However, until a truly conclusive experiment is undertaken we should not be so critical and dismissive of any of the suggested deeper theories (such as 't Hooft's energy states or any of the other incredibly successful theories, such as Superstring Theory). It seems that many physicists, because of philosophical or psychological reasons, are too unwilling to relinquish their god given freedom. This is unfortunate, as like with the first showing of a movie, despite the ending having already been scripted out, you still do not know what is going to happen and as physicists we should be concerned with finding the absolute truth, totally void of any of our sentimental biases. It is more than wholly feasible that given the various paradox's and oddities, quantum mechanics may well be a truly fantastic and accurate description of our reality but it may still be a mere approximation. If there was an underlying system dictating the behaviour of quantum mechanics then this too would be at least as incredible and accurate. So with this said, until some truly brilliant experimental proof comes along telling us how nature really is, we should put our apparent freedom to good use, keep an open mind and not be so quick to assume how our universe should turn out.

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