**Article**

# The Universe - an Effect without Cause

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## Abstract

Through the history of science we have become accustomed to experiencing paradigm shifts in our fundamental understanding of the Universe. Previously-cherished principles have been abandoned by radical thinkers in order to free them of the constraints that were hindering progress. Copernicus ousted the geocentric worldview that had been the dogma for centuries and Einstein led us to abandon the absolutes of time and space introduced by Newton, then Heisenberg took away certainty leaving us to accept unavoidable unpredictability in the laws of nature. In each case the revolutionary move was met with strong resistance from the ruling guard of physicists, but eventually victory fell into the hands of a new generation of thinkers. Each of these revolutionary changes came as a surprise, but the next great shift in thinking will be different in that it has long been anticipated. Physicists already expect that some former assumptions will be tomorrow's sacrifices in the battle to understand the nature of reality. They know that everyday senses, intuition and philosophical prejudice cannot be trusted when exploring the fundamental laws that prevail in physical regimes that are not part of our ordinary experience. They have seen it all before and all agree that something important has to give before the next breakthrough can be struck. I think it is clear that space and time will be the first casualties of this revolution. They will become emergent properties of a deeper reality. That is the easier part but with them, locality and causality must also fail. Of these it is temporal causality – the principle that every effect has a preceding cause – that is the hardest for scientists to lose. In this essay I discuss why this must happen and what can take its place.

**Key Words:** Universe, effect, without cause, physical assumption, wrong, FQXi, essay contest.

### What assumptions must be dropped?

The need to progress with the foundations of physics today is driven by the requirement to combine general relativity and quantum field theory into a unified and consistent theory. Already general relativity on its own has its problems. It predicts the collapse of massive stars into black holes with singularities at their centre. Matter is compressed together so strongly that the curvature of space and time is forced to become infinite. Time itself ends at that point and the classical theory is incapable of explaining what really happens. The solution should take the form of a new theory of quantum gravity which would take over as matter is compressed to unimaginable density. It would provide a consistent explanation of how time ends at the singularity. But when gravity is combined with quantum mechanics the problem of infinities just gets worse. Fluctuations of space and time at the working scale of the theory become so wild that the very structure of space-time seems to break down.

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By this logic it seems natural that space and time must take a different form in the sought after theory. The smooth manifold of space-time used in general relativity must emerge from a deeper pregeometric concept. In 1995 I wrote a bibliographic review of all the literature I could find, written on the subject of what might replace smooth space-time [1]. It had 330 references. If I were to try and update the list today the task would never be finished. There would be thousands of papers I would have to include covering an incredibly diverse range of ideas, with more being added faster than I could take note of them. I think it can no longer be said that rethinking our concept of space-time is a paradigm shift for the future. Indeed it is the physicists who want to keep space or time intact who have become the radicals with a need to justify their point of view. There is no general consensus yet on *how* to replace space and time but there is a widespread view that the space-time manifold as we knew it in general relativity is no longer the accepted starting point. It is just an approximation to some other unknown mathematical structure.

## What about causality?

Space and time are inseparable, that is a lesson from relativity that must not be lost. If space is emergent then so must be time. What then of causality? The principle of cause and effect is regarded as fundamental to all of science. Cause must precede effect. How can this even make sense if we don’t hold on to the concept of time?

Causality is so central to the way we do science that it is hard to imagine giving it up. When you ask “why?”, I answer with “because”. The very idea of a cause for any effect is built into the language we use to answer questions. Can we explain anything without invoking temporal causality? Many physicists are reluctant to give up the notion of cause and effect. Here is a quote from Lee Smolin, an influential physicist working in the field of quantum gravity.

*"It's easy to talk about space or space-time emerging from something more fundamental, but those who tried to develop the idea have found it difficult to realize in practice, Indeed, several early approaches failed. We now believe they failed because they ignored the role that causality plays in space-time. These days, many of us working on quantum gravity believe that causality itself is fundamental - and is thus meaningful even at a level where the notion of space has disappeared."* [2]

So Smolin wants to keep causality even if he ditches space and locality. This is at least partly for practical reasons. Approaches to quantum gravity that retain causality seem easier to make work, at least according to Smolin. Well-known examples of approaches to quantum gravity that give causality a fundamental role include Causal Sets, Causal Dynamical Triangulations or Quantum Causal Histories. In each of these ideas time is emergent but causality is built in at a fundamental level using relationships that encode the ordering of cause and effect. Even in theories of cosmology, models that preserve causality are now becoming prevalent. Eternal inflation, cosmic evolution, baby universes, colliding brane-worlds, a quantum fluctuation from nothing, Cycles of time. All these fanciful sounding ideas are constructed to avoid the initial event at the big bang where otherwise time seems to start from nothing. Cosmologists don’t want to accept a universe that begins with no cause.

So let me state my thesis. I don't think that science needs temporal causality at the most fundamental level. The universe does not need a cause at the beginning of time. If time is emergent causality can be emergent too. But if causality is lost, what must remain? What lies at the root of science? The answer in my opinion is just consistency.

## Philosophical debate

In 450BC the Greek philosopher Lefkipos was the earliest thinker to record his thoughts on causality, defining all phenomena as derived from pre-existing causes. I will spare you the long and confused history of the subject that followed in which each philosopher redefined causality and classified it into different sorts of causation. In past centuries the subject was heavily influenced by the intellectual study of theology with some philosophers using causality to prove the existence of God. It is no surprise then that eventually it took David Hume, an atheist, to question the validity of cause and effect in the 18th century [3]. It is ironic in the light of this history that some people now claim that a *lack* of causality would imply a universe ruled by magic and superstition.

Hume recognised that causation is deeply ingrained in our thinking and is an important aspect of the way we experience our world. He referred to causality as the cement of the universe. However, he made the deep observation that causality is never experienced directly. We may observe that two events are apparently related and that one precedes the other. Then we accept that there is a causal relation between them, but we can never prove it definitively.

In modern times we are used to reading reports in the tabloids where some survey purports to show a causal relation between two things of interest. For example I read recently that one such survey had shown that people who smoked are more likely to suffer from tooth decay. It is tempting to conclude that smoking causes the dental problems and that was clearly the implication that the journalist expected us to draw, but is that valid? All the survey really showed was that there is a statistical correlation between the frequency of smoking and the prevalence of fillings. There is no direct logical reason from this to conclude that the smoking caused the health problems. We can't even be sure that the smoking habit started before the tooth decay. How do we know that the tooth decay did not in some way cause the smoking? We only discount that option because it sounds less likely and does not fit with our prejudicial biases. The reality is more likely to be that both smoking and poor dental hygiene and linked to some other pre-existing factors such as poverty, inadequate education or a personality trait, so there may be social causes of both problems that lead to the correlation. In this case there may be no real causal link between smoking and bad teeth at all. The kind of illogical reasoning seen in newspapers has become so common that statisticians now have a well-known rebuke to counter it: *Correlation does not imply causation*.

Hume went further. It is not just that there could be other unseen causes. He questioned whether a definitive cause or set of causes needs to exist at all. Correlations may be all that there is. His reasoning was countered vigorously by his younger contemporary Immanuel Kant [4]. Kant credited Hume's scepticism with awakening him from his dogmatic slumber but rejected Hume's conclusions. Others accused Hume of heresy and even today it is common to read claims that

Hume has been debunked and shown to be guilty of flagrant circular reasoning. I do not agree. I find Hume's reasoning and conclusions to be perfectly sound. In normal circumstances causality is valid and important. Many areas of science use it faultlessly, but at a fundamental level there need not be a principle of causality. It could be a purely emergent concept from deeper principles. Correlations and consistency are all that can be counted on if we want to understand the foundations of physics.

## Quantum uncertainty

The first big challenge to causality from within physics came with the rise of quantum theory. According to the laws of quantum mechanics a nucleus of a radioactive isotope can decay at any moment in a fundamentally unpredictable fashion. It is as if nothing is causing the decay. It just happens. Einstein was particularly disturbed by this discovery because he thought it threatened the principle that every effect must have a cause. He felt that there must be some hidden cause that was not being observed. It could take the form of hidden variables that determined the moment of decay in a perfectly deterministic way. If only we could detect them, sanity would be restored.

To make matters worse he found than the entanglement of quantum states implied that the laws of quantum mechanics are non-local. In the theory of special relativity no causal effect is allowed to travel faster than light. If you are looking for the cause of something that happened at a space-time event $(x_0,y_0,z_0,t_0)$ then you must look in the backward light-cone where events $(x, y, z, t)$ are defined by the inequality $(x-x_0)^2 + (y-y_0)^2 +(z-z_0)^2 \leq c^2(t-t_0)^2$, $t < t_0$ . In quantum mechanics, this principle of locality is violated. Two particles such as photons can have entangled spin states. If they are sent apart in opposite directions to distant locations where two observers measure their spin, the outcome of one observation will affect the other even if they are outside each other's light-cones. Fortunately this happens in such a way that no information can pass from one observer to another faster than the speed of light. However it is not possible to describe the states of the system in such a way that the outcome of an event is determined by the state restricted to its past light-cone.

If we accept that space is emergent in our hoped-for theory of quantum gravity we may be willing to accept a breakdown of locality provided causality is preserved. Is this possible? If causality requires that every outcome is determined by preceding events we might still achieve this using a non-local hidden variable theory, but under assumptions much weaker than the locality principle it is still possible to prove that no such theory can exist. *See endnote on the Kochen-Specker Theorem.*

So does this mean that causality is already dead? In the end physicists avoided this tragedy with a simple trick. They redefined the meaning of causality so that it is now only necessary that the *probability* of any experimental outcome is dependent on prior events. They accept that the laws of physics can no longer be described as deterministic, but causality remains. In the language of quantum mechanics it is only required that the evolution of the state with time is given by a unitary operator. Causality has been replaced by unitarity in the quantum world. Locality is replaced by the principle that operators representing field variables that are outside each other's

light-cone must commute (or anti-commute). I think Hume might feel cheated by this redefinition of principles. In my opinion, it is just a trick to postpone the inevitable.
What now if time is emergent? What if quantum gravity leads to the breakdown of space-time at a singularity with no further effect beyond a black hole singularity and no earlier cause before the big bang?

## The wave-function of the universe

As a postgraduate of theoretical physics I cut my teeth with computational research in Lattice Gauge Theories. The field is not regarded as foundational, yet it taught me some useful foundational lessons. One of these is based on a trick called Wick rotation that makes lattice computations more tractable. See *endnote on the Wick Rotation.* Real time is replaced with imaginary time and the calculation becomes a statistical sum of 4 dimensional Euclidean lattices with no distinction between space and time. There is no sign of temporal causality yet the computation of the masses and decay rates of composite particles based on correlations over the lattice still works perfectly.

As we move from ordinary quantum field theory to quantum gravity the nature of the universe changes dramatically. We would like to preserve the idea that physics is described by a path integral over all ways of transforming from one classical state to another, but now the curvature of space-time must be included in the equation. The gravitational field variables are provided by the metric of space-time, so every kinematically possible evolution of the metric must be counted. This would naturally include changes to the metric that go beyond the limitation that its signature is Lorentzian. The geometry of the light-cone does not just fluctuate in the quantum world, it can collapse altogether. Placing constraints on the metric to ensure that only causal spacetimes were counted would be very unnatural. Causality has to be emergent.

We would not expect the quantum contribution from Euclidean metrics to have much effect near home on planet Earth, but in the extremes of matter density found as we approach the singularity of a black-hole the changes would become more significant. The causal structure of space-time would breakdown. The same principle applies to the initial singularity of the big-bang universe. This is the idea behind the Hawking-Hartle "no-boundary" understanding of the beginning of time in which space-time becomes like a four dimensional space and curves to round off the start of space-time [5]. In this picture saying that there is time before the big-bang is like saying that there is land beyond the North Pole. It is as if the Wick rotation takes over at the singularity and causality is replaced with just correlations.

However, this approach to quantum gravity is incomplete. It does not treat the infinities that plague a direct approach to quantisation of general relativity and can only work as a semi-classical approximation. A more successful formulation will probably require that the matric of space-time and even space-time itself is replaced by something more fundamental. Does the lesson about causality still hold? In my opinion it does. What then must causality be replaced with and how does our classical notion of causality emerge? If the universe is described by an acausal sum over all possible block universes, why does cause and effect seem to run only in one direction from past to future and not also from future to past?

## Causality gives way to consistency.

If causality is not the basic principle of science then what is? The answer has to be purely consistency. Consider as a topical example the Higgs boson. It is remarkable that several groups of theorists predicted its existence and properties nearly 50 years before the technology became available to detect it. Naturally physicists are called upon by journalists to explain what it is all about. What answer do they give? The usual response is that the Higgs boson has a special status in physics because it gives mass through symmetry breaking. Physicists such as Higgs recognised this need and found the idea of a boson to do it, they say. The explanation is essentially causal. The Higgs boson is the cause of mass so it was obviously required. No wonder the public embraced the nickname “God particle” for the Higgs boson. As the particle required to give mass and therefore substance and life in the universe it certainly appears to have almost God-like properties.

The real story of how the Higgs boson was predicted is about consistency. Quantum Electro Dynamics is consistent in that all of its interactions are renormalisable. In this theory particles can have mass because the mass terms are gauge invariant and renormalisable. There is no need for a Higgs boson or symmetry breaking. Physicists knew that there should be an equally consistent theory for the other forces including the weak and strong nuclear forces and wanted to find it. When they checked the mathematics of renormalisation they realised that only a very limited list of possibilities was consistent without the need for coincidental cancellations. Spin one bosons could only be described as gauge theories that generalised QED along the lines of Yangs-Mills theory. Spin half fermions could interact with the gauge field through gauge invariant interaction but could not have any self-couplings. Any spin zero particles could also form gauge invariant couplings to the gauge fields and could interact with fermions through Yukawa terms but they could also have self-couplings up to fourth order terms in the Lagrangian. This was the complete list of ingredients they had to play with. Forget about elegance and unity. These possibilities were forced on the theorists by the requirement of consistency.

The main problem they faced was that the gauge theories did not allow for massive spin one bosons, yet both the strong and weak nuclear forces are short range and need to be mediated by massive bosons. In the case of the weak force a similar problem arose for fermions. The weak force violates parity conservation leading to a chiral form of gauge theory that does not allow fermionic mass terms. In the final model there were two different solutions to providing mass in a consistent way. For the strong force it turned out that the hadrons were composite with an underlying gauge theory of Quantum Chromo Dynamics in which the gauge bosons were massless, Then the observed massive mesons that mediated the strong force between nucleons are themselves composite. In the case of the weak force the full gamut of possible particles had to be introduced including a Higgs scalar to break the symmetry with quartic self-interactions and Yukawa couplings. The result was the standard model which succeeded in describing all the observed features of particle physics in a consistent remormalisable way.

The central message of this story is that the theorists who built the standard model were not looking for simple causal explanations of where mass comes from. Neither were they seduced by the beauty of the symmetries that might explain the origins of the forces. All that mattered was consistency; consistency with experimental observations and self-consistency of the mathematical theory. There was no great philosophically driven search for the cause of mass. Nothing but consistency was required.

## Arrow of Time

It is all very well to say that causality can be replaced by consistency but to justify it there needs to be some explanation for the way in which temporal causality emerges from an underlying acausal model. Such an explanation does not yet exist but the on-going search for consistency could be leading physicists to the solution.

The illusion of causality is linked to the arrow of time. There is a big difference between the past and the future without which it would make no sense to say that cause always precedes effect. We know more about the past then we do about the future because some past events have left a record that we can read. This feature of our experiences can be linked to the second law of thermodynamics that says that disorder (or more precisely entropy) always increases.

Entropy is a macroscopic statistical quantity that is not reflected in the underlying physics. In fact, the underlying laws are reversible. If we started a simulated physical system with an imposed initial low entropy condition and allowed it to evolve forward in time, then entropy would be observed to increase, just as in real life. We can understand from the theoretical work of Boltzmann why that is. However, if we evolved the same system backwards in time from the same initial conditions we would find that entropy also increased going backwards in time, very unlike the real world.

To reconcile this with nature we can draw only one conclusion. The entropy of the universe must have been constrained to be low in the distant past and had naturally been increasing ever since. For some reason the big bang itself must have been a low entropy starting point for the observable universe.

If we accepted a world ruled by temporal causality this would not be such an issue. We can imagine that some cause just set the universe going at the big bang with low entropy, but in our acausal worldview we need to see the universe as just one big path integral summed over all possible classical universes. How then is the symmetry between past and future broken?

## Complete Symmetry

If ordinary particle forces were all that counted, any universal path integral would be dominated by the highest entropy worlds, simply because there are more of them. Entropy is maximised when energy is smoothed out on macroscopic scales. There could be no interesting features in such a universe and no low entropy past.

Luckily, gravity is different. Gravitationally bound objects get hotter as they collapse. This means they have a negative specific heat and that entropy is maximised when the world is lumpy. It follows that a path integral over curved space-times will be dominated by worlds which are uneven. In fact black-holes maximise entropy so the universe should be full of black-holes of varying sizes. How could this lead to a universe like our own? The full explanation must lie at the singularities which are ruled by effects of the yet unknown theory of quantum gravity. One possibility is that a very large symmetry is restored at high densities of matter. This could be a *complete* symmetry, so large that every degree of freedom corresponds to a parameter of the symmetry. Symmetry implies redundancy so for each parameter of symmetry a degree of freedom can be removed from the local information content of the theory. With complete symmetry restored there would be no information left. Entropy is simply a measure of information content so the conclusion is that singularities force low entropy. This is just what is required to explain that the big bang has low entropy because of its past singularity, but it also implies that black holes with future singularities would constrain entropy to be low. Does this mean that the arrow of time would reverse as you fell into a black hole? This is not the case as we shall see. Size is also a factor and black holes are not big enough to control the arrow of time.

## Holographic principle

We have seen how the constraints of consistency have empowered theorists to make predictions such as the existence of the Higgs boson well ahead of experimental results. Another dramatic example pushes so far ahead of empirical science that some steps may never be directly verified, yet its ultimate predications could lead us to understand the nature of quantum gravity and hence the ultimate foundations of existence. This is the holographic principle of Susskind and ‘t Hooft [6].

Understanding of this deep idea came in a number of steps each of which sought consistency through hypothetical thought experiments. It is a long story but here in brief is an outline of the reasoning:

**Step 1**: Black holes have entropy given by the area of their event horizons. This was determined by Bekenstein who considered how a black hole grows as information is dropped into a black-hole one particle at a time.

**Step 2:** Black holes radiate at a temperature consistent with Bekenstein entropy. In classical physics black-holes cannot radiate but Hawking showed that if you take into account quantum effects using semi-classical quantum gravity you find that black-holes have a temperature dependent on their size that agrees with the area law for entropy.

**Step 3:** The information loss paradox must be resolved. Black holes radiate away mass as energy at a rate that increases as they shrink. If they are isolated they will eventually disappear in a final blast of radiation. Any information thrown into the black hole before this time would be lost in violation of unitarity, unless it is limited to the amount of information that can be recorded on the event horizon where it can be encoded into the radiation as the black hole evaporates.

**Step 4:** The holographic principle limits information content. If information sent into a black holes is limited by the area of its event horizon then the amount of information in any region of space must be limited by the area of a boundary surrounding it, otherwise a black hole could be formed by compressing a large shell of matter around the volume of space, trapping more information than the black hole can hold.

The holographic principle has a profound effect on the distribution of entropy and matter in the universe. It is not possible to have a smooth and even distribution of entropy Otherwise the entropy content would go up in proportion to the volume of space and would exceed the holographic bound at some sufficiently large scale. Instead entropy must have a fractal like structure with different scales of lumpiness so that the density of entropy decreases on larger and larger scales. This is consistent with the matter distribution in cosmology. However, it means that the universe can start out smooth on quite large scales provided the entropy density is initially very low. Luckily this is consistent with both observation and the theoretical bounds from holography.

## Higher spin symmetry

It remains to be understood how the holographic principle can actually be realised in nature. Physical theories are described in terms of field theories with degrees of freedom distributed evenly over space. Quantum gravity limits length scales on which measurements can be made but still we would expect information content to increase with volume roughly in units of the Planck volume. This can only be avoided if some field variables are redundant and that is what happens when there is gauge symmetry. Each dimension of the symmetry corresponds to a redundant field variable that can be removed from the system of equations.

To achieve holography almost all degrees of freedom must be redundant in this way so that information only remains in global structures that can be moved to the boundary. Again this implies a complete symmetry with one degree of symmetry for each field variable. We have seen already that complete symmetry might explain the low entropy of the big bang. The same conclusion is now found as a consequence of the holographic principle. This implies a huge amount of symmetry that is not realised in ordinary gauge theories or even in supergravity but it must happen if the holographic principle holds.

Complete symmetry means that the gauge group must match the spin structure of the field variables with supersymmetry to match the fermions. In ordinary supergravity there are generators of supersymmetry described by spin half and spin one fields, but the matter and gravity fields themselves have spins ranging from zero to two. In superstring theory the situation is even worse with particles of unlimited spin from higher vibration modes. The solution may be a new kind of invariance called Vasiliev higher spin symmetry. Originating from work of Fradkin and Vasiliev back in the 1980s, higher spin theories of gravity have generators of symmetry corresponding to all levels of spin [7]. Work on this area is heading new progress in the understanding of string theory and the holographic principle. It may be exactly what is required to explain how causality can emerge when space-time breaks down at a singularity such as at the big bang and why causality emerges.

## A Glimpse of The Final Theory

What then will the final theory look like? Let me finish by giving you my vision based on the reasoning I have outlined in this essay.

It will be an acausal universe in which space and time are emergent. With them will come locality and causality, also both emergent features of the theory. The emphasis on symmetry suggests an algebraic description of nature. Complete symmetry will be an important element. The creation algebra of fundamental objects in the theory is also the Lie algebra of its symmetries so that almost all degrees of freedom are redundant in the broken phase. The diffeomorphism invariance will emerge through a process of geometrogenesis from an event symmetric underlying model in which permutation symmetry embedded in the continuous symmetries is broken to leave the symmetries of space time that permute spacetime events in a continuous fashion. The matter fields will form spin structures with hidden symmetries for each field so that a holographic principle is formed.

In the 1990s I devised a prototype symmetry algebra for such a theory using necklace algabras and a process of multiple quantisation to build up a rich symmetry structure from simple principles [8]. The difficulty is to show that such structures can underlie string theory. I think that recent work on the holographic principle and higher spin symmetries indicates that this may be possible.

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## Note on the Wick Rotation

The objective of Lattice Gauge Theories is to calculate phenomenological quantities such as masses of composite particles, decay rates and phase transition temperatures. If we accept the principle of causality we would expect the dynamical processes of evolution and temporal causality to play an unavoidable role in such calculations. Surely we must simulate the way the systems can change with time to calculate a decay rate.

In the path integral formulation of quantum field theory the complex amplitude of the evolution from one classical state $\varphi_0$ at time $t$=0 to a possible future states $\varphi_T$ is governed by a sum over all possible classical evolutions dependent of the Langrangian of the system $L(\varphi_t)$.

$$\mathrm{A}(\varphi_0 \to \varphi_T) = \int D\varphi \, e^{i\int_0^T L(\varphi_t)dt}$$

These amplitudes can simply be normalised to give the unitary S-matrix describing the causal evolution of the system. Particle masses and decay rates can be read from the way the S-matrix elements change with time. According to the idea of Wick, this matrix is analytic as a function of time so you can replace time *t* with a complex variable by a 90 degree rotation in the complex plane. The analytic functions of *t* just become the equivalent functions of *it* and the setup still works. The relativistic Lorentz metric becomes a Euclidean metric in 4 dimensions.

In lattice gauge theories we use this trick so that the space and time directions on the lattice have the same characteristics. Calculations can be done by replacing the path integral by a statistical ensemble of configuration. Particle masses and decay rates can then be found just by looking at the behaviour of correlation functions on the lattice. If this works (and it does) what happened to the principle of causality? The light-cones are no longer present since the metric is Euclidean and all 4 directions on the lattice are the same. There is no role for cause and effect. Only correlations are involved in the calculation, and yet the derivation of masses and decay rates is perfectly alright. To my mind this is an indication that temporal causality is not a fundamental prerequisite of physics.

## Note on the Kochen-Specker Theorem

Even non-local hidden variable are not possible. One elegant demonstration goes as follows. Suppose you have a four state system such as an entanglement of two electron spin states. Consider the following 18 quantum states [9].

| | | | | | |
|---|---|---|---|---|---|
| 1 | (0,2,0,0) | 2 | (0,0,2,0) | 3 | (0,0,0,2) |
| 4 | (1,1,-1,-1) | 5 | (1,-1,1,-1) | 6 | (1,-1,-1,1) |
| 7 | (1,-1,1,1) | 8 | (1,1,-1,1) | 9 | (1,1,1,-1) |
| 10 | (1,1,0,0) | 11 | (1,-1,0,0) | 12 | (0,0,1,1) |
| 13 | (0,1,0,1) | 14 | (1,0,1,0) | 15 | (1,0,-1,0) |
| 16 | (1,0,0,-1) | 17 | (1,0,0,1) | 18 | (0,1,1,0) |

You could build an experimental apparatus that could prepare the 4-state system in any of these states. For each state there is a corresponding projection operator given by $P_i = |\psi_i><\psi_i|$ (where the $\psi_i$ are the states in the above table normalised) You could add measuring systems based on magnetic separation that could make observations corresponding to these operators as observables. Imagine that the apparatus has 18 buttons and when you press one it indicates a binary 0 or 1 result corresponding to the eigenvalues of the projection operators. Using this we can perform experiments to confirm that the outcomes are as predicted probabilistically by the laws of quantum mechanics, but how would we be sure that there are not some hidden variables that are determining the outcome in a predictable fashion if only we knew how to read them?

To answer this, consider the following 9 sets of 4 observables:

{P1, P3, P14, P15}     {P7, P8, P16, P18}     {P5, P6, P10, P12}
{P1, P2, P16, P17}     {P4, P6, P13, P14}     {P8, P9, P11, P12}
{P4, P5, P17, P18}     {P2, P3, P10, P11}     {P7, P9, P13, P15}

It is easy to check that the observables in each set form a complete commuting set of operators because the corresponding states are mutually orthogonal. If there are hidden variables that determine the outcome of pressing any button then each operator must have a predetermined outcome of 0 or 1 dependent in some way on those variables. According to the outcome given by the rules of quantum mechanics that we assume to have been checked experimentally, in each set of four operators there can only be one whose value is 1 while the other three are 0 because this corresponds to the eigenvalues of the projection operators. Is such a combination possible? You may try to assign the values of 0 and 1 to the operators according to these rules but you will never succeed. You can do it for 8 of the 9 sets but not all of them. To see this just notice that the sets of operators have been cleverly chosen so that each operator appears in exactly two states. Each set must contain exactly one operator whose outcome is 1 but there are nine sets. Whichever combination you select there will always be an even number of entries in the sets whose value is 1, but nine is not even. This means that no hidden-variable theory consistent with the observations of quantum mechanics is possible for such a system.