Entanglement, Causality, and the Cohesion of Space-Time

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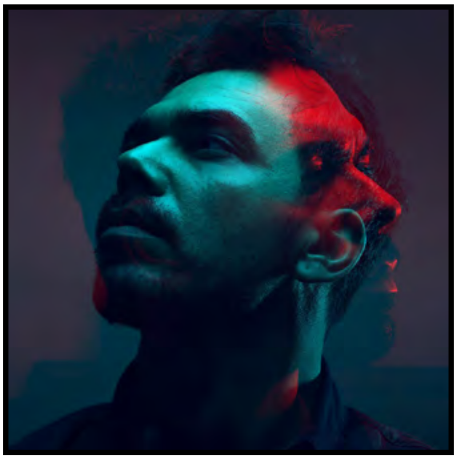
Entanglement is an extraordinary quantum mechanical property where two particles remain connected to one another, no matter how far apart they may be in the universe. Far from simply being a curiosity, entanglement may exist across time and provide not only cohesion to space-time, but also a primordial scaffold for causal links. This suggests the existence of symmetrical relations between events separated in time and raises the possibility that the future may influence the past.



I have previously argued for a worldview where time periods coexist and where the past is as indefinite as the future.[1] This implies that the laws of physics are not only invariant across space but also across time. Causality is the underlying principle that links causes and effects, the influence of one event upon another across time and space. Those considerations raise the question as to whether or not there may be some kind of elementary scaffold that would bring cohesion to space and time and allow such a thing as causality to occur. Entanglement is a quantum mechanical property, where two particles created together remain connected no matter how far apart they may be. This phenomenon of entanglement appears to create relations across space and time that could be the scaffold we have been searching for. The asymmetry between cause and effect would then be secondary to the perception of the arrow of time. The implications are that events occurring far apart in time may be related independently of causal chains and that the future may influence the past.

A Brief Review of Time

It is difficult to conceive of more than the three spatial dimensions that we routinely experience, and especially difficult to visualize how the world would look like if our senses could perceive across time. We call "Time" the background dimension against which we plot past, present, and future. But we also call "Time" the ever-ongoing flow of the present from the past into the future. "Time" therefore appears to be made of two distinct components, one being the background dimension and the other the constant movement of the present. For clarity, the word *Time* will be used for the background dimension and the words *Time flow* for the movement of the present.

We have seen that, if we pursue the implications of the modern theories of special relativity as well as quantum mechanics, we must come to the conclusion that time periods coexist and that the past is as variable and as indefinite as the future. This obviously raises the problem of time paradoxes and of why would our observations of the historical, archeological, and geological records suggest a frozen and stable past. It was argued that any change in the past cannot "instantly" affect the present, but must move towards our current epoch along the causal chains at the same rate as the time flow, therefore never catching up with the present.[2]

The Time Invariance of the Laws of Physics

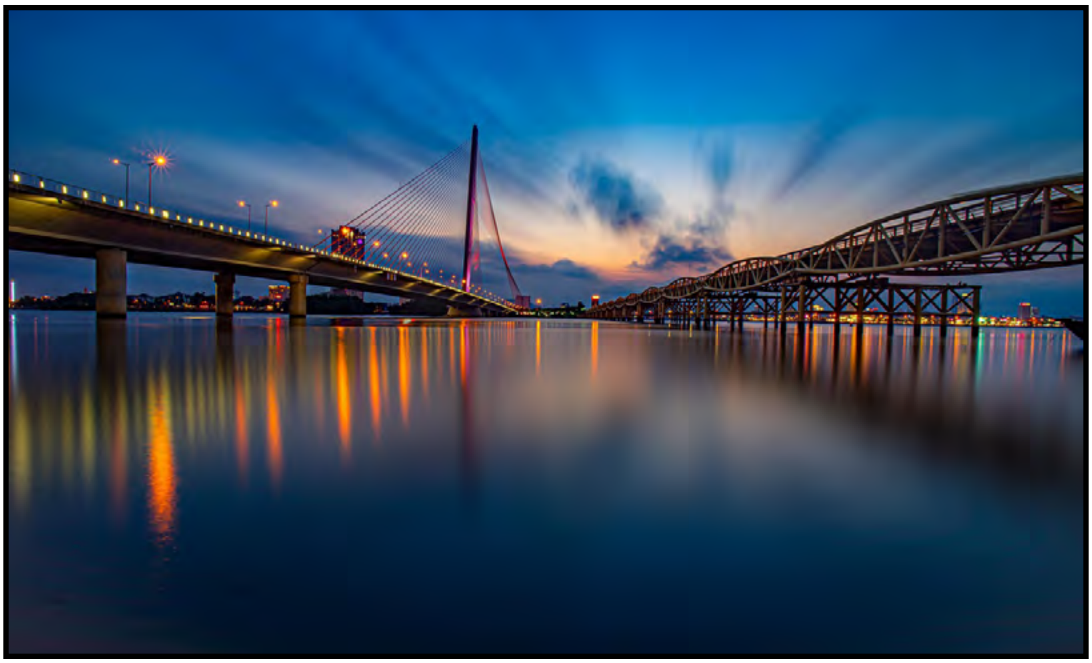
The laws of physics follow certain basic symmetries. The first, for example, is charge conjugation, where every particle is replaced by its antiparticle. A second is parity, which represents spatial reflection of a particle (in a mirror). A third is time reversal where an interaction is time invariant if it is unaltered when viewed moving forward or backward in time.[3] Another type of symmetry is that the laws of physics do not vary with their location, no matter where one is in the universe (translational and rotational symmetries).[4] Similarly, those laws should remain invariant with regard to time (except perhaps for the very special situation of the Big Bang, the initial explosion that is believed by scientists to have created our world). If those laws were different for the past, the present, and the future, it would not be feasible to make any prediction as to what the future might be or as to what the past might have been. We would then also have to explain what is so different about the present that the laws of physics suddenly change at this precise instant. Even if there are differences in some physical quantities across time (size of the universe, entropy, etc.), the workings of the laws themselves (i.e. their mathematical formulations) remain the same.

The Arrow of Time

One of the problems of modern elementary particle physics is that the mathematical expressions of its laws do not make a distinction between past and future, in contradistinction to our common experience. A particle can (mathematically) as easily move toward the past or the future (time reversal symmetry). The reason for a direction (an arrow) to time has proven to be elusive.[5]

Several distinct processes have been described to contribute to the arrow of time:

1. Thermodynamics: The entropy (a measure of order, or lack thereof) of the universe has been constantly increasing (increased disorder).



2. Radiation of energy: An accelerated particle radiates energy while the reverse doesn't happen.
3. Cosmological: The universe is expanding.
4. State vector reduction: In quantum mechanics, particles occur in distinct alternative superimposed states (for example having opposite spins at the same time). A measurement (by an observer) or an interaction (with another particle) reduces all those states to only one, which is the reality we observe.[6]

From the above considerations, one can't help but have the feeling that there must be some kind of thread across the time dimension, some kind of cohesive fabric or scaffold that keeps it woven together and allows events to move smoothly from one moment to the next. John Wheeler, who was a prominent physicist, said that "time is nature's way of keeping everything from happening all at once."[7] The "one-way" direction of the arrow of time is an essential component of causal links.

Causality

The concept of causality has been debated for centuries.[8] Some philosophers believe that causality only represents our interpretation of a stable or constant connection between events. Others have argued that events occurring together or following one another are not necessarily always related in a causal way. They feel that there must be an influence from one event unto the other for a causal link to exist. This is the position of Mario Bunge[9] who defines the causal principle as follows (in formal logic formulation): "If C happens, then (and only then) E is always produced by it" (where C stands for Cause and E for Effect). For Bunge, there must therefore be a time correlation between events (they must both occur within a certain time frame), but there must also be an action (a production as he calls it) from one unto the other. Beyond the debate, Bunge's definition is the one that approaches most our common experience of causality, as we use it in our daily life.

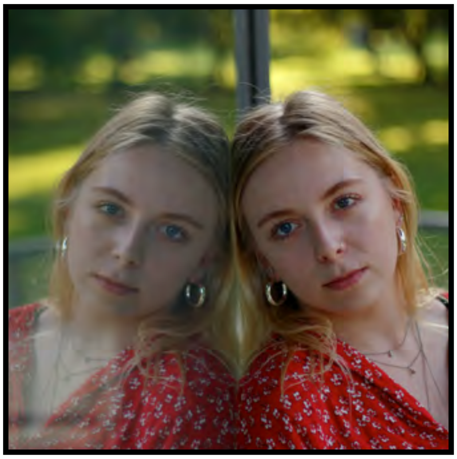
The question is: Is there an underlying principle in the modern laws of physics that would allow for such a thing as causality (as defined by Bunge) to occur? What is it that would allow for one event to influence another smoothly across time and/or space?

Entanglement

Entanglement is an extraordinary quantum mechanical property where two particles created together remain connected, no matter how far apart they may be in the universe. If a measurement is made on one of them (such as measuring its spin), the other instantly takes the opposite value.

Quantum mechanics has been one of the most successful theories of modern physics. One of its quintessential components is the uncertainty principle of Heisenberg.[10] This principle states that not all values of a particle (such as spin, velocity, or position) can be known at any given time. The principle also implies that all quantities concerning particles constantly vary.

Einstein and two colleagues, Podolsky and Rosen, attempted to refute the principle of quantum uncertainty in an article now known as the EPR paper.[11] Einstein and his co-authors didn't like the idea that science, physics, and the world was suffused with indeterminacy and wanted to demonstrate that quantum mechanics was an incomplete description of reality. Using the example of two particles created simultaneously by the same process (such as two photons created by a two-levels drop in the energy of an atom's electron), the authors argued that those particles always had to have a definite velocity and position. This was due to features not allowed by the uncertainty principle and now called "hidden variables" as they came to be known.



More recently, John Bell showed that those concepts could be tested using the property of spin rather than position and velocity.[12] The experiment was conducted by Alain Aspect, in Paris, France, using photon polarizations.[13] This actually disproved the EPR hypothesis. It showed that, in this specific situation, there was no hidden variable (although they might exist under other circumstances), and also showed that an instantaneous connection existed between the two particles. It is this instantaneous connection across space that is called "entanglement." For the interested reader, I refer to the excellent discussion of this topic in Brian Greene's *The Fabric of the Cosmos*, in the chapter "Entangling Space."[14]

Amir Aczel, in his book *Entanglement*, states: "Entangled entities (particles or photons) are linked together because they remain intertwined forever. Once one is changed, its twin—wherever it may be in the universe—will change instantaneously."[15] Multiple experiments have now confirmed the initial findings of Alain Aspect.

Entanglement is an established fact of science and is currently routinely being used to encrypt messages.

We therefore have a situation where particles may remain connected no matter how far apart they are in the universe. So far, the applications have been for cryptography, as mentioned, and for the strange phenomenon of quantum teleportation, whereas a particle (or rather, its properties) can be teleported from one location to another (there are major challenges in teleporting larger objects and it is unclear if large object teleportation will ever be feasible).[16] Such an incredible property as entanglement must play some more fundamental role in our world than simply being a curiosity. How can this fit in our view of the world?

The question comes to as whether or not entanglement is only an experimental curiosity? There are many situations in nature where particles are created together and could therefore be entangled. Some types of particle interactions (such as collisions) could also cause the effect to occur. Entanglement might be much

more prevalent in nature than thought. For example, the strange properties of a salt (lithium holmium fluoride) can only be attributed to its constituents being entangled.[17]

Entanglement Across Space

Imagine a long rectangular piece of paper with vertical lines through it at regular intervals, for example lines A, B, C, etc. If entangled particles are produced at B, with each member of the pair going in opposite directions such as one goes toward A and the other toward C, they might interact with other particles at those locations. The properties of entangled particles are always opposite (for example, they will have opposite spins).

Therefore, if a particle interacts at A, its twin will immediately take the opposite value at C, where it might be also interacting with another particle. The results of those interactions will therefore be different (possibly opposite) but related through entanglement. If one considers that multiple particles might be created and interacting, one gets a relation between what is happening at A and what is happening at C. With entangled particles being created at each line, going in different directions and interacting with other particles, it can be appreciated how related effects can occur along the paper sheet.

Similarly, entangled particles naturally created in three-dimensional space would interact with other distant particles and therefore create relationships between events in the different regions of space. Those relationships would actually create some sort of cohesion between those regions. It would be expected that most of the interactions would be in the immediate surroundings and taper off with distance.

This also suggests a relation with what we understand of causality: Going back to our paper sheet, an event at A compels the twin particle to take an opposite value at C, with a resulting separate event, which, nevertheless, is connected to A. We could therefore state: "If A happens, then, and only then, C happens," fulfilling the criteria set forth by Bunge. Note that in this example, there is an "action" or "production," as the event at A compels the type of event occurring at C. However, note that there is also a symmetry, which is not supposed to exist in causal links: We could be talking as well of the events at C compelling the events at A.

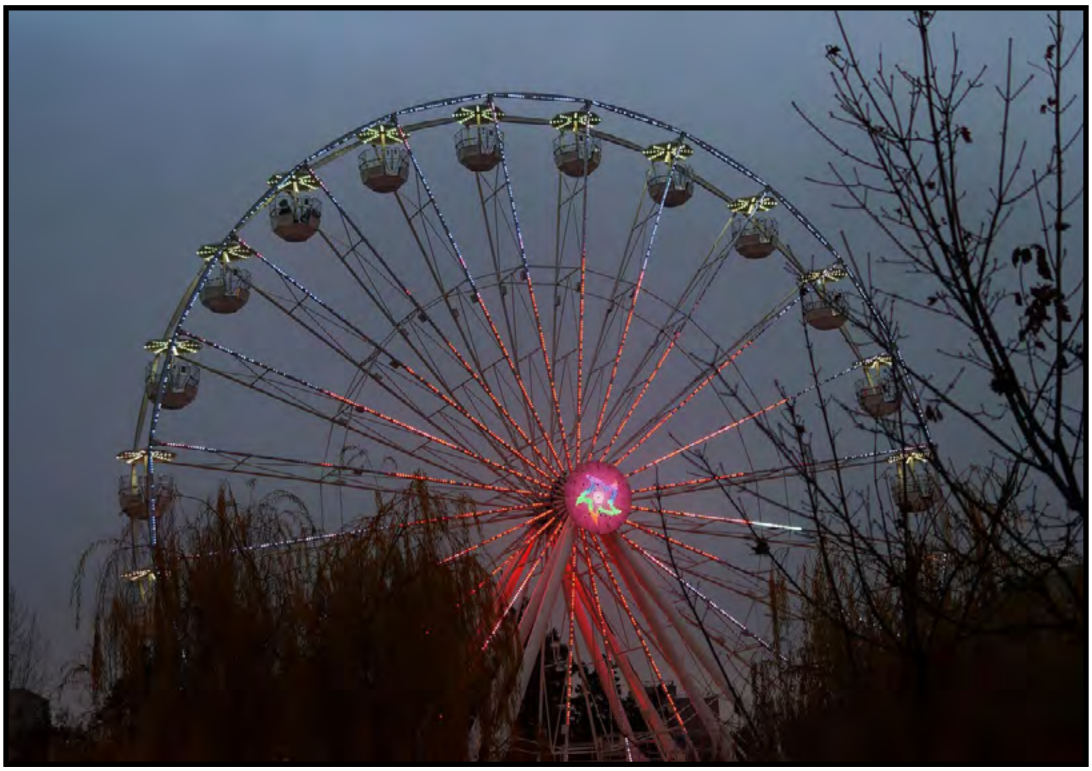
It would be easy to draw a time axis along the length of the paper. The above-mentioned events would then occur along the time dimension and their relation to the principle of causality would be even stronger. Can there be entanglement across time?

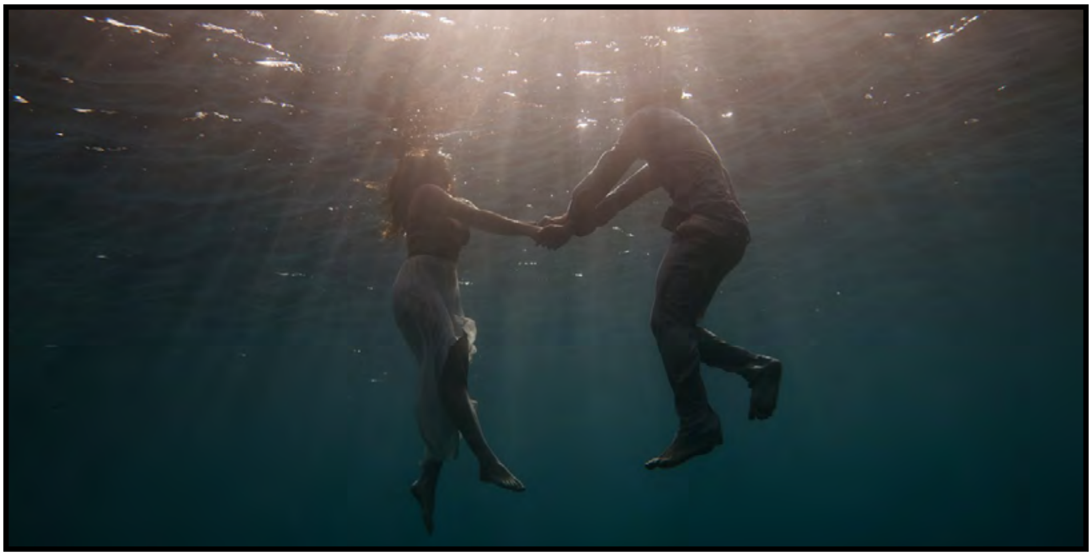
Entanglement Across Time

Entanglement has only been studied across space. Indeed, the definition is of an instantaneous effect at a distance. When doing his experiment, Alain Aspect placed his detectors about 10 feet (3 meters) from the source on either side. If one imagines that Aspect's laboratory is actually in a spaceship and that the spaceship is moving relative to a stationary observer, then the detectors will trigger simultaneously for Aspect, in the spaceship, but the events will not appear simultaneous to the stationary observer according to the rules of special relativity.[18]

Daily life occurrences also have relativistic effects: For example, an observer simply walking toward or away from an apparatus located only 0 feet away, will cause simultaneous events to stand across the present by about 10^{-31} seconds (that is 1 divided by a 10 followed by 31 zeros, an incredibly small number). This could not be detected by our best clocks (a cesium atomic clock can only measure down to about 10^{-18} seconds)[19] but it is still orders of magnitudes above what is considered the smallest meaningful amount of time, called Planck time and equal to 10^{-43} seconds.[20] Even trivial motion relative to simultaneous events would make them lose their simultaneity.

Besides relativistic motion, there are other ways by which particles might be able to travel in time: A particle could fall in certain types of rotating black holes or follow certain trajectories around very heavy objects such as primordial cosmic strings, which exist, according to some theories. Most entangled particles would probably hover near the present, with a decreasing density as we progress further toward the past or the future. Some authors, such as Brian Greene suggest that entanglement across time might happen. [21] Roger Penrose quotes the term "quanglement" for entangled quantum information (about the status of spin and





other parameters of the particle) and states "... quanglement links have the novel feature that they can zig-zag backwards and forwards in time." [22]

Entangled particles on either side of the present would relate past and future events in the manner previously described in the sheet of paper example. If event C (past) happens, then (and only then) E (future) is always produced by it. The symmetry encountered on the paper example would not be perceivable because of the arrow of time and of the time flow.

As with the example across space, entanglement across time appears to provide cohesion between events by relating them to one another. Therefore, the phenomenon of entanglement appears to provide a cohesion factor, a fabric, from region to region and from time period to time period. It also appears to provide a scaffold for causal links, at least at the level of elementary particles.

Can the Future Influence the Past?

This question would have seemed ridiculous not too long ago. However, if we consider a universe where time periods coexist and if entangled particles can find themselves on either side of the present, it is certainly possible to imagine a mechanism by which events in the future may influence events in the past: If the twin of an entangled pair, located in the future, is subject to a measurement or an interaction, this would force its partner located in the past to take an opposite configuration, and therefore influence events there.

There may be other ways for the future to influence the past. Let's look at the two-slits light experiment: Photons from a light source pass through two parallel slits causing an interference pattern to occur on a screen beyond the slits. This experiment illustrates the wave properties of light and was carried out by Thomas Young 200 years ago. However, if you shoot photons one at a time and an observer finds out through which slit each individual photon goes through, the interference pattern is lost. The loss of the interference pattern appears to only relate to the knowledge of the whereabouts of the photons and nothing else. This was shown in a experiment called "the delayed choice quantum eraser" initially suggested by Marlan Scully and Kai Drühl.[23]

One version of the experiment uses a device that makes the initial traveling photon create another particle on its way to the screen.[24] This new particle is detected separately through a different detector. Again, if an observer checks whether or not the second particle has been detected (therefore gaining knowledge of the whereabouts of the photon) the interference pattern is lost. The interesting (still hypothetical) question comes when the detection of the second particle is delayed—let's say for a few years—by using some storage device. What happens then? Does the fact that one does or doesn't detect the second particle in the future influence the current results in the present? The answer would be yes. The decision, in the future, whether or not to verify if the second particle is detectable does influence the result of the experiment in the present.[25]

Conclusion

If it was possible for the senses to see across time and if the whole history of the world was laid before a privileged observer, they might see causality in a different light. When considering two entangled particles, it is impossible to state with certainty which one influences the other as they set their properties outside of time and space.

Such an observer would therefore have a difficult time determining whether it is the particle in the past that influences the one in the future or if the opposite is taking place. Our perceived asymmetry stems from the arrow of time. Connections between events along the time dimension therefore appear to gain their causal properties because of our concomitant perception of the arrow of time and of the time flow that orders them in a certain way. With the time dimension unfolded, what seems to be really happening is a system of reciprocal influences. Entanglement appears to provide the necessary elementary cohesive scaffold for space-time and for causal links. It may relate events across time that may not otherwise be connected by traditional causal chains. One implication is that the future may, at least in some circumstances, influence the past.

Endnotes

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