Topics in Quantum Theory

If we're willing to get down into the weeds of the mathematical formalism of quantum theory, it's possible to explain the holographic principle of quantum gravity in a fairly straightforward way. Ed Witten has recently pointed out that any possible quantum theory must be defined by a set of quantum operators, but not every quantum operator corresponds to an observable eigenstate of that quantum theory. The reason this fact is important is because it resolves all the apparent paradoxes of quantum theory. Those paradoxes only arise because we're confusing the quantum operators that define the quantum theory with the observable eigenstates of that quantum theory. Witten's lecture on *What Every Physicist Should Know About String Theory* can be found at:

https://www.youtube.com/watch?v=H0jLD0PphTY

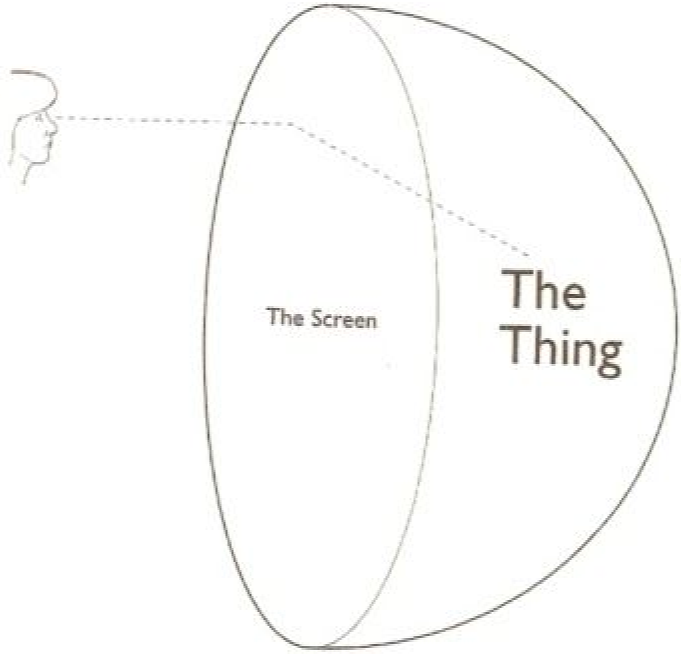
Witten shows how space-time geometry emerges from the information encoded in a conformal field theory in two dimensions, which is the essential nature of string theory. This is explicitly demonstrated by the AdS/CFT correspondence, where space-time geometry in a bounded three dimensional region of space emerges from the way information is encoded by a conformal field theory defined on the two dimensional bounding surface of that space. The essential nature of this emergence of space-time geometry in a bounded region of space is holographic projection.

Juan Maldacena has also given a recent lecture on *Quantum Mechanics and the Geometry of Space-time* where he discusses the AdS/CFT correspondence and its implications in detail. A word of advice is warranted: the reader should skip the 21 minute introduction to this lecture:

https://www.youtube.com/watch?v=1wKVbFM_UXk

Witten points out that a one dimensional quantum field theory results in the ordinary quantum mechanics of a particle in space. In the sense of relativity theory, the one dimension of the QFT is proper-time, where proper-time is defined along the particle's world-line. The space that the particle appears to be located in and move within, which appears to be a three dimensional space, is an emergent space that only defines particle coordinates within this emergent space. This emergent three dimensional space emerges through the holographic projection of forms of information encoded on a two dimensional holographic screen. Those forms are projected like images from the screen to the point of view of an observer that observes the particle in space.

Witten then points out that a two dimensional conformal field theory along the lines of string theory results in a theory of quantum gravity. The two dimensions of the CFT define the string's world-sheet, which is a generalization of proper-time. The nature of gravity as formulated by Einstein's field equations for the space-time metric is inherent in the information encoded in the two dimensional CFT even though the space of Einstein's field equations is an apparent three dimensional space. The answer again is that apparent three dimensional space is a result of holographic projection from a two dimensional holographic screen to the point of view of an observer. The three dimensional space emerges through holographic projection. The important point is neither a QFT of particles in space nor a field theory of dynamical space-time geometry along the lines of Einstein's field theory of gravity can be a fundamental theory. The fundamental theory is always defined on a bounding surface of space, since that is where all the fundamental bits of information are defined. This is fundamentally an observer-centric description since a bounding surface of space can only arise as an event horizon in the observer's accelerated frame of reference. The nature of the observation of anything in space is holographic projection of a form of information projected like an image from the observer's holographic screen to its central point of view. In a holographic world, everything observed is a projected form of information.

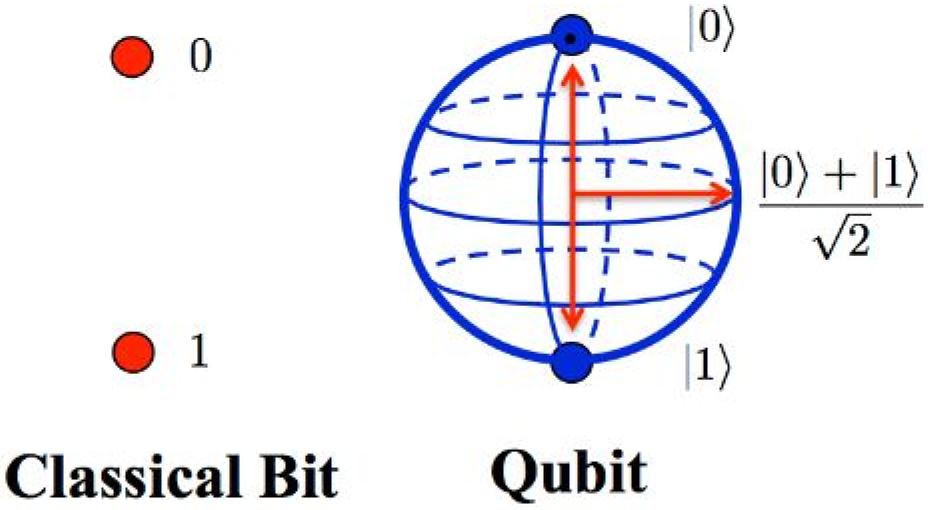


The Observer, the Screen and the Thing

This brings us back to the issue that the quantum operators that define a quantum theory do not necessarily correspond to the observable eigenstates of that quantum theory. The best way to explain this fact is with non-commutative geometry. There is consensus among theoretical physicists that string theory is a special case of non-commutative geometry. See the review article on *Non-Commutative Geometry for Pedestrians* for the details:

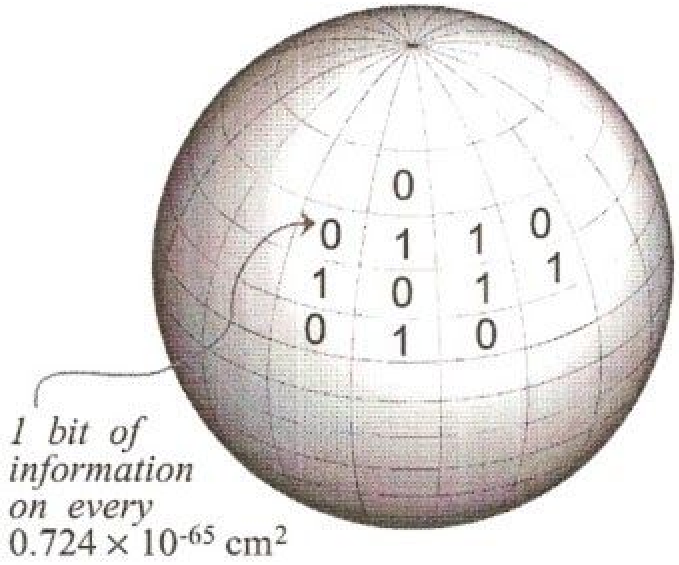
https://arxiv.org/pdf/gr-qc/9906059.pdf

In the mathematical formalism of non-commutative geometry, quantum gravity can be defined on a bounding surface of space by non-commuting variables, which are the quantum operators of quantum gravity. The non-commuting variables are the quantum operators that define quantized position coordinates on the bounding surface. In a heuristic sense, these quantized position coordinates are smeared out into area elements like pixels on the surface, and each pixel encodes a bit of information, not as a classical bit but as a qubit. When n non-commuting variables are defined on the bounding surface, n bits of information are defined as qubits, typically in terms of the n entangled eigenvalues of an n x n SU(2) matrix. The SU(2) matrix gives a representation of rotational symmetry on the surface of a sphere, and so these n qubits of information can be defined in a rotationally invariant way. Each qubit of information is like a spin ½ variable that can only point up or down, but due to rotational symmetry on the surface of the sphere, a qubit can always be expressed as a quantum superposition of the spin up and spin down states.



Qubit as the Information Encoded on a Planck-size Event Horizon

The n qubits defined on the surface of the sphere are inherently entangled due to the way these n bits of information are defined as the n eigenvalues of an n x n SU(2) matrix. In the holographic principle, the value of n is specified in terms of the surface area A of the sphere and the Planck area as $n=A/4\ell^2$, where the Planck area ℓ^2 is defined in terms of Planck's constant ħ, Newton's gravitational constant G, and the speed of light c, as $\ell^2=\hbar G/c^3$.



The Holographic Principle

The bounding surface of space is acting as a holographic screen. Quantum operators defined by non-commuting variables on the screen do not correspond to observable eigenstates of quantum gravity. The observable eigenstates of quantum gravity are defined in the sense of holographic projection in terms of forms of information projected like images from the screen to the point of view of an observer. This is inherently an observer-centric description of observable reality, since in the sense of the principle of equivalence, the bounding surface can only arise as an event horizon in the observer's accelerated frame of reference. The observer's event horizon is the bounding surface that limits the observer's observation of all observable things in space. An observable thing is a form of information encoded on the screen that is projected like an image to the observer's central point of view. That is the nature of the observable eigenstates in quantum gravity, which is to say the nature of observation in quantum gravity is holographic projection.

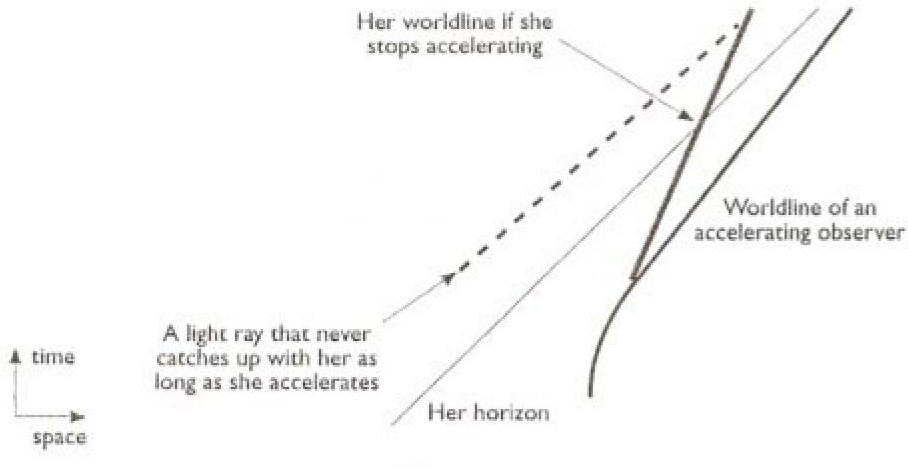
Since the bits of information encoded on the holographic screen are entangled, this is inherently a nonlocal description of whatever appears to happen in the bounded region of space, and so a local QFT description of particles in space cannot be a fundamental description. A holographic screen is inherently a nonlocal way to define how particles appear to be localized in space, but even that three dimensional space only emerges from the holographic screen through holographic projection of forms of information from the screen to the observer's point of view. The form of a particle in space is just another thing that emerges through holographic projection. Even the observed dynamical space-time geometry described by relativity theory, which is the nature of gravity, emerges through holographic projection from a holographic screen.

Ted Jacobson has shown that Einstein's field equations for the space-time metric, which is the nature of the gravitational field, emerge from the holographic principle as thermodynamic equations of state, which are only valid near thermal equilibrium, where the temperature T is constant. Einstein's field equations for the space-time metric are a consequence of the second law of thermodynamics when entropy is defined in terms of bits of information encoded on a bounding surface of space along the lines of the holographic principle. The reason is quite simple. As energy flows across a bounding surface of space and the total energy E of that bounded region of space changes by ΔE, the second law tells us the entropy S of that bounded region of space must change by $\Delta S=\Delta E/T$, but the holographic principle then tells us that the surface area A of the bounding surface must change, which implies a change in the geometry of the bounded space. Jacobson has shown that this change in the geometry of the bounded space is described by Einstein's field equations. In effect, Einstein's field equations for the space-time metric is a disguised form of the second law of thermodynamics interpreted in terms of the holographic principle. See the article on the *Thermodynamics of Space-time* for the details:

https://arxiv.org/pdf/gr-qc/9504004.pdf

Once we can explain Einstein's field equations for the space-time metric in terms of the holographic principle, the game is pretty much over. All the other quantum fields of the standard model of particle physics, like the electromagnetic field for the photon, the Dirac field for the electron, and all the nuclear force and matter fields, can be explained as arising from Einstein's field equations for the space-time metric through the usual unification mechanisms of the Kaluza-Klein mechanism of extra compactified dimensions of space and super-symmetry of space. All quantum fields for elementary particles arise as extra components of the space-time metric. The problem is none of these quantum field theories are really fundamental as they only have the validity of thermodynamic equations of state or an effective field theory only valid near thermal equilibrium. This is perfectly consistent with what the holographic principle is telling us that what appears to be an observed elementary particle in space is really only the holographic projection of a form of information from a holographic screen to the central point of view of an observer. The whole thing is observer-dependent since an observer's holographic screen can only arise as an observation limiting event horizon in the observer's accelerated frame of reference.

The Jacobson argument relies on the properties of a Rindler horizon, which is an event horizon that arises for any observer in an accelerated frame of reference. Every accelerating observer has an event horizon that acts as a holographic screen when the holographic principle is in effect. The holographic principle is automatically in effect whenever non-commuting variables are defined on the horizon in terms of non-commutative geometry. These non-commuting variables are the quantum operators of quantum gravity, but the observable eigenstates of quantum gravity are defined in terms of the holographic projection of forms of information from the observer's holographic screen to the observer's central point of view. This is inherently an observer-centric description of observable reality that is also observer-dependent, since the observer's holographic screen can only arise as an event horizon in the observer's accelerated frame of reference.

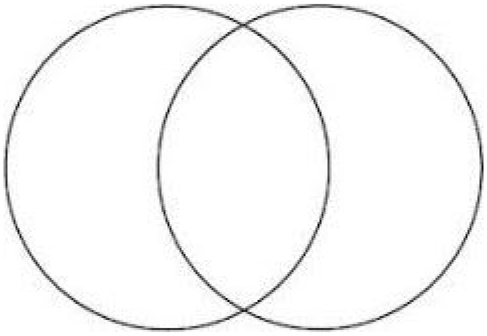


Rindler Horizon of an Accelerating Observer

Amanda Gefter has given the perfect scientific explanation in her essay on *Cosmic Solipsism* for why every observer is truly alone in its own world and only observes that world as images of that world are projected from its own holographic screen to its own central point of view. See:

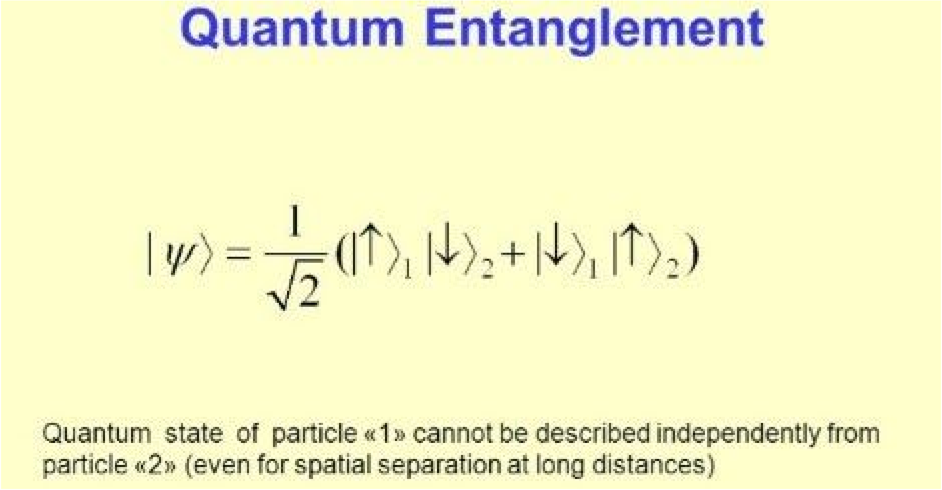
https://fqxi.org/data/essay-contest-files/Gefter_Gefter_Fqxi_essay.pdf

This scientific explanation resolves all the apparent paradoxes of quantum theory, like the Schrodinger cat paradox and the Wigner friend paradox, that arise when multiple observers are assumed to observe the same world and to observe the same quantum state of that world. The holographic principle tells us this assumption of multiple observers observing the same world is flat-out wrong, and so all the paradoxes that result from this assumption are incorrect. These apparent paradoxes arise from our incorrect understanding of the nature of a holographic world. A world defined on an observer-dependent holographic screen and observed by a single observer at the central point point of view of that world has no paradoxes. There is still the possibility that multiple observers, each located at their own point of view and each observing their own world on their own holographic screen, can share a consensual reality when those screens overlap and share information in the sense of a Venn diagram, like the kind of information sharing we see in a network of computer screen like the internet. In the sense of the holographic principle, these overlapping holographic screens are overlapping bounding surfaces of space.



Overlapping Bounding Surfaces of Space

The other apparent paradoxes of quantum theory are the paradoxes of quantum entanglement that Einstein called spooky action at a distance. When entangled objects, like particles that carry spin, become separated in the world, the observation of the spin state of one particle instantaneously determines the observed spin state of the other particle, no matter how far apart the particles are separated. The classic example is two particles that can only spin up or down, but have a total spin angular momentum of zero. If the first particle spins up, then the second must spin down, while if the first particle spins down, the second must spin up. The quantum state of the particles must sum over both possibilities, which is called an EPR pair after the three authors of the article that first described the effects of quantum entanglement.



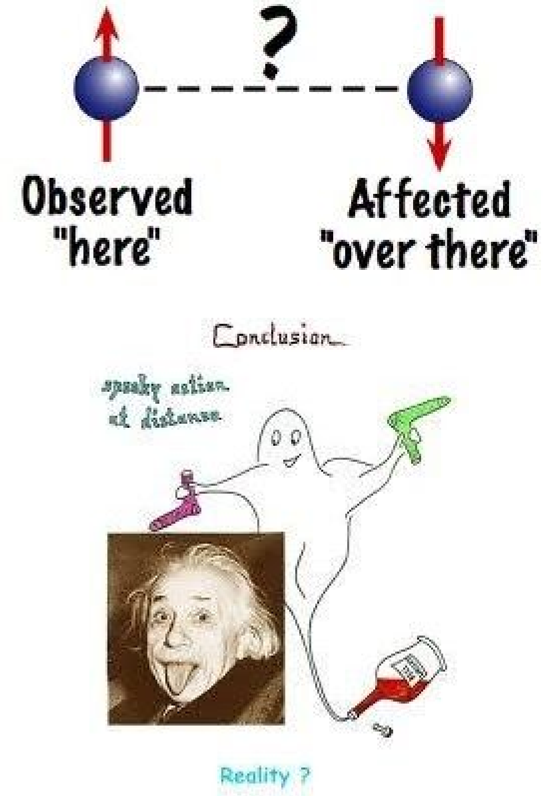
Quantum Entanglement

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1 |\downarrow\rangle_2 + |\downarrow\rangle_1 |\uparrow\rangle_2)$$

Quantum state of particle «1» cannot be described independently from particle «2» (even for spatial separation at long distances)

Quantum Entanglement of an EPR Pair

When the particles are entangled, measurement of the spin state of one particle instantaneously determines the measured spin state of the other particle no matter how far apart the two particles appear to separate from each other, hence Einstein's objection of spooky action at a distance. The holographic principle resolves this apparent paradox since all the bits of information for both particles are encoded on a holographic screen, and all those bits of information are naturally entangled in the sense of entangled qubits. The observer at the central point of view of its own holographic screen observes the spin states of both particles no matter how far apart the particles appear to separate in space. The observation of the particles is like a screen output from a computer screen to the observer's point of view. An observed particle is only a form of information encoded on the holographic screen and projected like an image to the observer's central point of view, and so the observation of a particle is only the result of holographic projection, which is analogous to a screen output. All the bits of information for both particles are encoded on the holographic screen and are naturally entangled as qubits. There is only a holographic illusion that the two particles are separating in space due to the nature of holographic projection. Spooky action at a distance is an illusion of holographic projection.



Quantum Entanglement and Spooky Action at a Distance

The holographic principle is a duality that relates what appears to happen in some bounded three dimensional region of space to the bits of information encoded on the two dimensional bounding surface of that space. This is inherently an observer-centric description of what appears to happen in a three dimensional bounded region of space as observed by the observer at the central point of view of that space. The nature of observation is holographic projection, as forms of information are projected from the bounding surface like images to the observer's point of view.

Holographic projection isn't just observer-centric, but is also observer-dependent. The observer's holographic screen can only arise as an observer-dependent event horizon in the observer's accelerated frame of reference. This is an essential property of the principle of equivalence that tells us there is no such thing as a preferred frame of reference. All frames of reference are equally valid. When the observer's acceleration comes to an end and the observer enters into a freely-falling frame of reference, the observer no longer has an event horizon, and therefore no longer has a holographic screen. When the observer no longer has an event horizon, the observer's observations are no longer limited in space, but when the observer no longer has a holographic screen, there is also nothing to observe. Everything the observer can observe in its observable world as defined on its holographic screen is a form of information projected like an image from its holographic screen to its central point of view. The holographic principle is telling us that when an observer enters into an ultimate freely-falling frame of reference, the observer observes nothing, but paradoxically, this ultimate observation of nothing is unlimited.

The AdS/CFT correspondence is an explicit demonstration of the holographic principle that was discovered based on the mathematics of string theory. The AdS/CFT correspondence is a quite general duality that is valid for all dimensionalities. AdS in three dimensional space has a corresponding dual description defined in terms of a CFT on the two dimensional bounding surface of that space, we just don't know how to mathematically define that two dimensional CFT. For AdS in four dimensional space, we do know how to define a dual CFT on the three dimensional surface of that space as a super-symmetric Yang-Mills field theory with N colors in the large N limit. A Yang-Mills field theory in the large N limit is equivalent to a string theory since the point-like particles of the theory, called gluons, are binding together into linear closed structures called glue-balls that act like strings. The AdS/CFT correspondence is just the most important of the dualities that have been discovered in the last 25 years thanks to string theory, which is probably not a fundamental theory, but has been a very helpful stepping-stone in terms of discovering these dualities. These dualities are inherent in any two dimensional CFT. The basic nature of string theory is a CFT defined on a two dimensional world-sheet. Conformal symmetry, also called Weyl invariance, is a symmetry of the changing size of objects. Weyl invariance of the space-time metric that measures the changing size of objects is an essential symmetry of quantum gravity. Weyl invariance is found in fractals that appear self-similar at all distance scales, and is the symmetry that allows for a holographic duality as bits of information encoded on a two dimensional bounding surface give rise to the appearance of forms of objects that appear in a three dimensional bounded space. The third dimension arises from conformal symmetry. The basic limitation of string theory is it cannot be generalized from AdS to de Sitter space, which is the kind of space that describes the observable universe, but string theory is a special case of generic non-commutative geometry, which can be generalized to de Sitter space.