Essay

Holographic Principle & Quantum Theory

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Abstract

In recent years, physicists have discovered the holographic principle of quantum gravity, but most physicists have not fully appreciated that the holographic principle is a radical transformation in our understanding of quantum theory. The key idea of the holographic principle is that everything in physical reality can be reduced to qubits of information encoded on a holographic screen, and that holographic screen can always be understood as an event horizon that arises in an observer's accelerated frame of reference. Most physicists have not fully appreciated that physical reality is an observable reality that must be observed by an observer to appear to come into existence. This lack of understanding reflects that physicists are ignoring the central role the observer must play in constructing its own observable physical reality.

Keywords: Holographic principle, observer, physical reality, quantum theory.

Both Ted Jacobson and Tom Banks have stressed the holographic principle of quantum gravity is a radical transformation of our understanding of quantum theory, which most physicists have not fully appreciated. Quantum theory in the conventional sense of particle physics really only applies in some bounded region of space. In the holographic principle, this conventional particle physics formulation of quantum theory can always be reduced to qubits of information encoded on a holographic screen that bounds that bounded region of space. The holographic screen is a bounding surface of space that in the sense of relativity theory can always be understood to arise as an event horizon in an observer's accelerated frame of reference. The holographic screen encodes qubits of information through some sort of geometric mechanism, like non-commutative geometry. The AdS/CFT correspondence gives an explicit example of how a holographic world is constructed. Quantum theory is inherently about measurement since the observer is observing events in its own holographic world as displayed on its own holographic screen that arises as an event horizon in its accelerated frame of reference. The holographic principle is inherently an observer-centric and observer-dependent description of observable reality. Physicists are ignoring the central role the observer must play in constructing that observable physical reality.

Jacobson has shown how Einstein's field equations for the space-time metric arise from the holographic principle as thermodynamic equations of state. Near thermal equilibrium, the laws of thermodynamics specify how change in energy is related to change in entropy and temperature as $\Delta E = T\Delta S$. Using the Unruh temperature of the Rindler event horizon observed by an accelerating observer, $kT = \hbar a / 2\pi c$, given in terms of an observer's acceleration, a, and the holographic entropy

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of the region of space bounded by that event horizon, $S=kA/4\ell^2$, given in terms of the surface area, A, of the event horizon and the Planck area, $\ell^2=\hbar G/c^3$, Jacobson was able to show how Einstein's field equations arise from this relation as thermodynamic equations of state.

Using non-commutative geometry, Banks and Fischler have shown that the holographic principle is automatically in effect for any space-time geometry, including de Sitter space, when that space is bounded by a holographic screen that encodes qubits of information. The holographic screen can always be understood as an event horizon that arises in an observer's accelerated frame of reference, like a Rindler horizon or a de Sitter horizon. The simplest case is for a spherically symmetric horizon, like that of a black hole. An SU(2) matrix gives a representation of rotational symmetry on the surface of a sphere, but its eigenvalues also encode information in a binary code, like a spin ½ variable that can only point up or down. On the surface of a sphere, the n eigenvalues of an nxn SU(2) matrix encode n qubits of information in a rotationally invariant way. The qubits of information are inherently entangled in the sense of quantum entanglement since they arise as the eigenvalues of a matrix.

Putting these findings of Jacobson and Banks and Fischler together, tells us that gravity is not really a classical theory. Like electromagnetism, gravity is a quantum theory in disguise, but that quantum theory can only be understood at the level of first quantization, and not at the level of second quantization. Recently, Maldacena and Susskind have stressed this point that classical gravity is really a quantum theory with their argument on ER=EPR that wormholes in classical gravity in the sense of an Einstein-Rosen bridge between two black holes gives an example of quantum entanglement in the sense of an entangled EPR pair.

Gravity is a quantum theory, but only at the level of first quantization, not at the level of second quantization. The space-time metric is the quantum wavefunction, and Einstein's field equations are the quantum wave equation. This is just like electromagnetism, where the electromagnetic field is the quantum wavefunction and Maxwell's equations are the quantum wave equation. Quantum entanglement is operative at even the level of first quantization since the quantum wavefunction gives the quantum probability that some property of the quantum particle, like its location in space and time or its spin state, can be measured. Entanglement is an inherent property of the quantum state formulated as a superposition of all possible measurable states of the quantum particle, with each possible measurable state weighted with a probability factor that is the essence of the quantum wavefunction. For example, for a spin ½ particle, the quantum state of the particle is a sum over the spin up and spin down states, with each spin state weighted with a probability factor that specifies the likelihood of measuring that particular spin state. Quantum entanglement is inherent in this superposition of measurable states, and the quantum wavefunction specifies the probabilities of measuring these properties of the quantum particle. All measurable states arise as eigenstate solutions of the quantum wave equation, and the most general wavefunction solution is a superposition of eigenstate solutions. The very idea of quantization, as in quantized energy levels, requires some sort of periodic boundary conditions that constrain these eigenstate solutions. For example, the quantized energy levels of the electron in the hydrogen atom require the periodic boundary conditions of periodic orbits, where in effect an integral number of wavelengths of the electron wavefunction must fit into an electron orbital. At the level of first quantization, the Schrodinger equation or the Dirac equation gives a perfectly good description of the electron as a quantum particle, and Maxwell's equations gives a perfectly good description of the photon as a quantum particle, but to fully characterize the quantized interactions of the electron with the photon requires a second quantization procedure.

The problem is, to fully treat the electromagnetic field as a quantum particle called the photon, and to fully characterize its quantized interactions with other quantum particles like the electron, we have to perform a second quantization procedure. This is only possible if the photon and electron propagate through some fixed background space-time geometry, like flat Minkowski space. Even this second quantization procedure has a limited range of validity since Maxwell's equations for the photon and the Dirac equation for the electron only have the validity of a thermodynamic equation of state. It's only valid to consider small quantum fluctuations around thermal equilibrium or the vacuum state. Even this second quantization procedure is not valid for gravity. The graviton cannot be understood as a quantum particle that propagates through some fixed background space-time geometry since gravity must inherently give a representation of the dynamical curvature of space-time geometry. It only makes sense to understand gravity at the level of first quantization, which essentially is a thermodynamic equation of state.

It's an interesting exercise to review how quantization occurs in conventional particle physics and how the holographic principle totally reverses this conventional quantization procedure. In conventional particle physics, we start with the idea of a point particle located at some position x at some time t in some fixed background space-time geometry and characterize the motion of that particle in terms of a particle trajectory through that space-time geometry as $x=x(t)$. In the sense of classical Newtonian physics, this particle motion is characterized by an action principle, where action is given in terms of kinetic and potential energy as $S=\int dt(KE-PE)$. The quantum state of the particle is then a sum over all possible paths through the space-time geometry, where each path or trajectory is weighted with the probability factor $P=\exp(iS/\hbar)$. This quantum state is equivalent to a quantum wavefunction that obeys a quantum wave equation. For classical Newtonian physics, this wave equation is the Schrodinger equation. The classical laws of motion are recovered in terms of the path of least action. This sum over all paths is the first quantization procedure. The second quantization procedure is to sum over all possible configurations of the wavefunction, $\psi(x,t)$, where each possible configuration of the wavefunction is weighted with the same kind of probability factor $P=\exp(iS/\hbar)$, but instead we use the action that corresponds to the wavefunction. The quantum wave equation arises from an action principle in the same way classical equations of motion arise from an action principle, by minimizing the action written in terms of the wavefunction. This sum over all configurations of the wavefunction is the second quantization procedure. Feynman diagrams arise from this sum in the sense of perturbation theory by expanding this sum in terms of some coupling constant, like the charge of the electron.

In quantum electrodynamics, the Schrodinger equation is replaced by the Dirac equation, which is the wave equation for the electron, and Maxwell's equations are used as the wave equation for the photon. The action for quantum electrodynamics is written in terms of the Dirac and Maxwell wavefunctions, and the second quantization procedure is to sum over all configurations of these wavefunctions. This sum generates the idea of the photon and electron as point particles that propagate through space-time and interact with each other through the electromagnetic force. The problem is, the gravitational force cannot be understood in the same way, since it makes no sense to think of the graviton as a point particle that propagates through some fixed background space-time geometry when gravity must give a representation of the dynamical curvature of space-time geometry. The holographic principle is the only known way to solve this problem.

The holographic principle totally reverses this idea of quantization. Instead, we start with the idea of qubits of information encoded on a holographic screen, which can always be understood as an event horizon that arises in an observer's accelerated frame of reference. The holographic principle demonstrates how Einstein's field equations for the space-time metric arise from the way qubits of information are encoded on that holographic screen as thermodynamic equations of state. The space-time metric is the wavefunction for gravity in the sense of first quantization and Einstein's field equations are the quantum wave equation, but it makes no sense to perform a second quantization procedure on the gravitational field. It does make sense to perform a second quantization procedure on the electromagnetic field that arises from the gravitational field with the usual unification mechanisms of super-symmetry and extra compactified dimensions of space, but only with a limited range of validity that is constrained in terms of how all quantum fields arise as thermodynamic equations of state. Second quantization is only valid for small quantum fluctuations around thermal equilibrium or the vacuum state.

All quantum fields can be understood to arise as extra components of the space-time metric with the usual unification mechanisms of super-symmetry and extra compactified dimensions of space, which M-theory explicitly demonstrates with its low energy limit of 11-dimensional super-gravity. The space-time metric is the quantum wavefunction that is the mother of all quantum fields, but even the space-time metric is not fundamental. The holographic principle demonstrates how the space-time metric arises from qubits of information encoded on a holographic screen as a thermodynamic equation of state. At the level of particle physics, all quantum fields only have the validity of thermodynamic equations of state. That holographic screen in turn must arise as an event horizon in an observer's accelerated frame of reference. It all has to begin with the observer. This radical transformation in our understanding of quantum theory that most physicists have not fully appreciated reflects that physicists are ignoring the central role the observer must play in constructing its own observable physical reality.

This radical transformation in our understanding of quantum theory that most physicists have not fully appreciated reflects that the laws of physics as represented by Einstein's field equations for the space-time metric and all quantum field theories that give a representation of particle physics are not really fundamental. At best, field theories can only give a thermal average description of what appears to happen in some bounded region of space. The more fundamental description of what appears to happen in that bounded region of space is given in terms of how qubits of information are encoded on the bounding surface of that space and the energy inherent in the observer's accelerated frame of reference that gives rise to that bounding surface as an event horizon. In some sense, what appears to happen in that bounded region of space over the course of time is like the animated images of a computer-generated virtual reality projected from a computer screen to the point of view of an observer, and the laws of physics that govern what appears to happen in that bounded region of space are like the operating system of the computer.

In some sense, the observable physical reality the observer observes is unreal, like the projected and animated images of a computer-generated virtual reality. The existence of the observer is more real than whatever appears to exist in the physical reality the observer observes. One of the reasons physicists have not fully appreciated what the holographic principle is telling us is due to their resistance to consider this interpretation of the holographic principle, but this interpretation is a perfectly sound and logically consistent interpretation. It may be the only logically consistent interpretation. This interpretation tells us that only the consciousness of the observer is really real, which may be why there is so much resistance to considering this interpretation of the holographic principle. Physicists seem to be unwilling to contemplate the possibility that the reality of their consciousness may be more real than the physical reality that they observe.

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