**Article**

# Measurement Problem & the True Nature of the Observer

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## Abstract

The measurement problem of quantum theory remains unresolved in terms of how the quantum state of the physical world can be reduced to an observed state of the world. In the conventional formulation of quantum theory, the quantum state of the physical world is understood as an unobserved state of potentiality or a quantum wavefunction that must collapse into an observed state of actuality for the physical world to actually be observed. The unresolved issue of the quantum measurement problem is about the true nature of the observer. This question about the true nature of the observer explodes when we understand the quantum state of the physical world in terms of the holographic principle of quantum gravity, which tells us the fundamental nature of the physical world is quantized bits of information, called qubits, encoded on a holographic screen. The holographic screen in turn can be understood as an event horizon that arises in an observer's accelerated frame of reference. This way of understanding the holographic principle can be understood in terms of matrix models that utilize non-commutative geometry. The holographic principle understood in the context of an observer in an accelerated frame of reference has something important to tell us about the true nature of the observer, which is that every observer is at the center of its own holographic screen that defines its own observable holographic world.

**Keywords**: Quantum theory, measurement problem, holographic principle, observer.

The unitary aspect of quantum theory in the sense of the wave equation for the quantum wavefunction demonstrates time translation invariance, but the measurement aspect of quantum theory does not. Measurement in the sense of a quantum state reduction or collapse of the wavefunction breaks time translation invariance. This is demonstrated on page 529 of the book "The Road to Reality" written by Roger Penrose where he interposes the processes of unitary evolution U with quantum state reduction R in the time evolution of the quantum state of a physical system. The physical universe is understood as a physical system, and so this analysis applies to the physical world. The process U respects time translation invariance, but the process R does not. The process of measurement or observation in the sense of the collapse of the wavefunction is not a time translation invariant process. In effect, a measurement resets the initial conditions for the unitary time evolution of the quantum system. Every measurement resets the initial conditions. That is exactly what a quantum state reduction does. Once the initial

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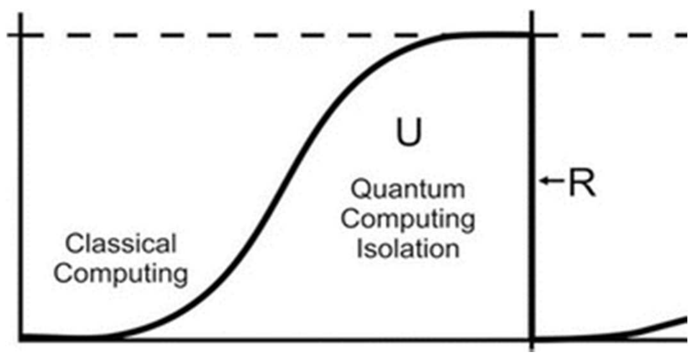
conditions of the system are reset by a measurement of the system, time translation invariance in the sense of the unitary time evolution of the system is broken.

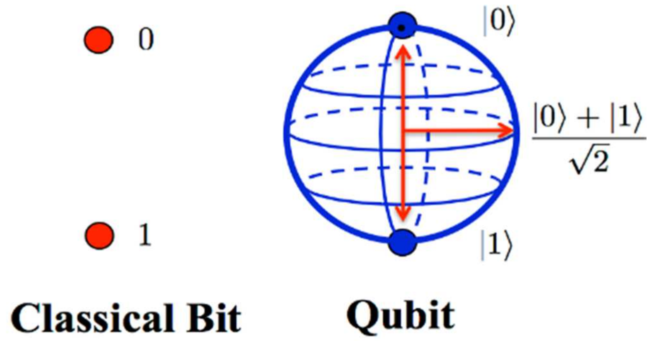
The reason this is so important is because this is what we are constantly doing as we observe the world. Every observation of the world is a measurement of the world, and by its very nature, every observation must break time translation invariance. We are constantly resetting the initial conditions of the world as we make observations of the world. Unitary time evolution of the world, as represented by the process U, only applies between our observations of the world, as represented by the process R.

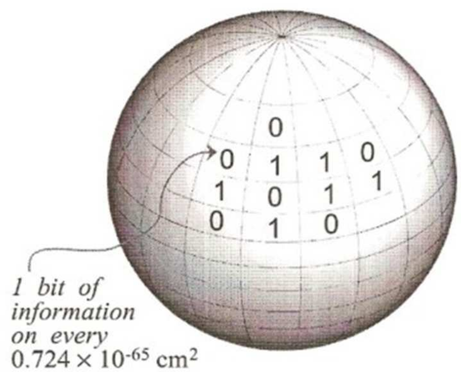



Unitary Evolution U as Pre-conscious Processing and Measurement R as Conscious Experience

The measurement problem is the most important and pressing problem we have in terms of understanding what modern physics is telling us about the nature of the physical universe. Until we get the measurement problem resolved in a satisfactory way, we will never be able to make any real progress in terms of our ultimate understanding of the nature of physical reality. We need to understand the connection between our observations of physical reality and the physical reality we observe, which inherently is an observable reality. At a fundamental level, this is the connection between our own observing consciousness and the physical reality that we observe. This question is all about the true nature of the observer.

There are two hints in the structure of modern theoretical physics that allow us to move forward. The first is the second law of thermodynamics, which basically says the arrow of time is directed in terms of increasing entropy, which is the same as heat flowing from hotter to colder objects. The second hint is the holographic principle of quantum gravity, which ties into the second law as it explains where all the fundamental qubits of information that constitute the dynamical degrees of freedom for the world are encoded. These qubits of information are the fundamental nature of entropy. The holographic principle fundamentally tells us that the qubits of information are encoded on a two dimensional bounding surface of space that bounds a three dimensional region of space, like the observable physical universe.




Holographic Principle

That two dimensional bounding surface of space can always be understood as an event horizon that arises in an observer's accelerated frame of reference. An accelerating observer's event horizon limits its observations of things in space. Every accelerating observer's observations of things in space are limited in space by an event horizon. The observer's event horizon naturally turns into a holographic screen when the screen encodes qubits of information for everything the observer can observe in its own observable holographic world.

Unitary time evolution of the quantum wavefunction is explicitly demonstrated in terms of the time dependence of the wavefunction solution of the quantum wave equation:

$$i\hbar \frac{\partial}{\partial t}\left|\Psi(t)\right\rangle = \hat{H}\left|\Psi(t)\right\rangle$$

$$|\Psi(t)\rangle = e^{-i\hat{H}t}\,|\Psi(0)\rangle$$

Time Dependent Wavefunction Solution of the Quantum Wave Equation

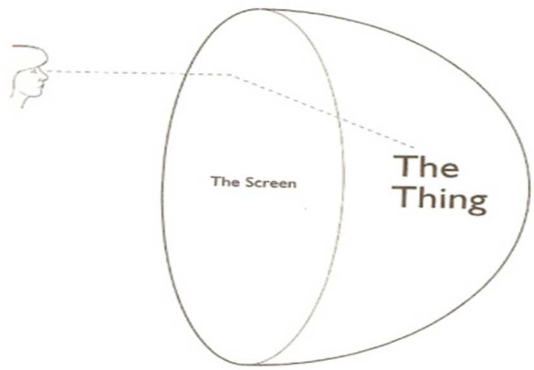
The unitary time evolution operator $U(t)=\exp(-iHt/\hbar)$ conserves quantum probability, which is explicitly demonstrated by the unitary nature of the exponential function $U(t)U(-t)=1$.

The most general way to formulate quantum theory is in terms of a sum over all possible paths in some configuration space. The quantum state of potentiality allows for all possible outcomes, not just the classical outcome. The way quantum theory expresses this potentiality is in terms of a quantum state that can always be formulated as a sum over all possible paths that connect a point of initial conditions to a point of final conditions in some information configuration space.

The laws of physics only enter into the quantum state as an action principle, which determines quantum probability. Quantum probability is determined by the quantum wavefunction, which in turn is determined by an action principle. All the laws of physics can be expressed as an action principle. Action is like a measure of distance along some path between two points in some information configuration space. The most likely outcome in terms of quantum probability is the path of least action, which is like the shortest possible distance between those two points in the information configuration space. That's why events seem to obey classical laws of physics, but there is an important caveat. The path of least action only arises from the quantum state as the most likely path in the sense of quantum probability when things are chosen from the quantum state of potentiality in an unbiased or random way. If there is bias in the way choices are made, then the laws of physics lose their classical predictability. In the sense of Einstein's metaphor of throwing dice, if the dice are loaded, then the game is rigged and all bets are off.

This choice that chooses something from the quantum state of potentiality is called the collapse of the wavefunction or a quantum state reduction. Quantum theory tells us every measurement of something is a choice in the sense of collapsing the quantum wavefunction or reducing the quantum state. The quantum state of potentiality includes all possible outcomes. To actually measure some specific outcome, a choice must be made. Quantum theory says the choices are made randomly, but why can't choices be made in a biased way? Who would make that choice? The obvious answer is that the observer of the actual outcome of the measurement is making that choice. In the sense of perceiving consciousness, the observer is choosing what to observe in its own observable world. That world only exists in an unobserved state of potentiality until it is observed by the observer and appears to come into an actual state of existence. This raises an even bigger question. What is the true nature of the observer?

In the sense of relativity theory, the observer is nothing more than a point of view at the origin of its own coordinate system. That's what a frame of reference means in relativity theory. From the point of view of other observers, the observer is following a world-line through their space-time geometry, but from the observer's own point of view, the observer is at the center of its own space-time geometry. Quantum theory is telling us with the concept that the measurement of something can only arise as the quantum state of potentiality is reduced to an actual observable state that every point on the observer's world-line is a decision point about what to observe in its world and which path to follow through that world. Only the observer can make that choice. The big question is about the true nature of the observer's consciousness in relation to whatever the observer happens to observe in its world. This question explodes when that observable world is understood to be a holographic world. A holographic world is no more real than images depicted on a holographic screen. The images can always be reduced to qubits of information encoded on a holographic screen. Who is really observing those images? Can an image observe itself? The holographic principle gives the only logically possible answer. The observer is nothing more than a point of perceiving consciousness that arises in relation to its own holographic screen.




The Observer's Holographic Screen

The easiest way to understand how qubits of information are encoded on the observer's event horizon, which turns the horizon into a holographic screen, is with non-commutative geometry, which explains how space-time geometry is quantized. Each quantized position coordinate on the observer's event horizon is smeared out into an area element like a pixel that encodes a quantized bit of information or qubit. In quantum gravity, the pixel size is called the Planck area. This gives the observer's event horizon an entropy as $S=kn$, where n is the number of qubits encoded on the event horizon, which is proportional to the surface area A of the horizon as $n=A/4\ell^2$, where $\ell^2=\hbar G/c^3$ is the Planck area. Each Planck area on the horizon acts like a pixel that encodes a qubit of information. Non-commutative geometry fundamentally explains how the qubits are encoded on a holographic screen in terms of quantizing position coordinates on the screen, which smears out each quantized position coordinate into an area element like a pixel that encodes a qubit of information. This value for entropy of the observer's event horizon given in terms of the number of qubits encoded on the horizon is called the holographic principle.

The energy that flows through the observer's holographic world also arises in the observer's accelerated frame of reference. This energy is given in terms of the Unruh temperature as $E=kT$, which is proportional to the observer's acceleration, a, as $kT=\hbar a/2\pi c$. The Unruh temperature arises as the temperature of thermal radiation the accelerating observer observes emitted from its event horizon. This thermal radiation arises from separation of virtual particle-antiparticle pairs at the event horizon as observed by the observer in its accelerated frame of reference. This thermal radiation is also called Hawking radiation. Hawking radiation is confusing since it mixes up concepts of the holographic principle with the quantum field theory formulation of point particles. In quantum field theory, uncertainty in energy allows virtual particle-antiparticle pairs to become created within the vacuum state for a short period of time. The virtual pairs are created out of nothing and then normally annihilate back into nothing, but from the point of view of an accelerated observer, something weird appears to happen. The accelerated observer's observations of things in space are limited by its event horizon. At the observer's event horizon, the virtual particle-antiparticle pairs can appear to separate. One member of the pair can disappear behind the event horizon while the other member of the pair can appear to be radiated away from the event horizon toward the observer. The observer observes this radiated particle as a particle of thermal radiation, which gives its event horizon an apparent temperature. The observer's event horizon is acting as a holographic screen that encodes qubits of information for all the point particles that can appear in the observer's world, but the separation of virtual particle-antiparticle pairs at an event horizon gives the event horizon an apparent temperature proportional to the observer's acceleration. In quantum field theory, virtual particle-antiparticle pairs are entangled. This implies the entropy of the observer's event horizon is an entanglement entropy. This is consistent with the holographic principle as understood with non-commutative geometry since all qubits of information encoded on the observer's event horizon are entangled.

The idea of quantum entanglement is inherent in the holographic principle as understood with non-commutative geometry. All the quantized bits of information or qubit encoded on an event horizon that acts as a holographic screen are inherently entangled, which is understood in terms of matrices. Quantum entanglement allows qubits to be defined in a rotationally invariant way. This is much like the way quantum theory defines spin ½ particles in terms of a 2x2 SU(2) matrix. The SU(2) matrix gives a representation of rotational symmetry on the surface of a sphere, but its two eigenvalues also define spin up and spin down states. These two spin states give a representation of information in a binary code, like a switch that is either on or off. The spin up and spin down states are like vectors that point up or down, but when these spin states are entangled, the vector can point in any direction, and so rotational symmetry is preserved. With the holographic principle, the n qubits of information encoded on a spherically symmetric holographic screen can be defined by the n eigenvalues of an nxn SU(2) matrix.

The laws of thermodynamics relate a change in total energy to temperature and a change in entropy as $\Delta E=T\Delta S$. In terms of the holographic principle, the fundamental reason for this relation between energy and entropy is each qubit of information encoded on the observer's holographic screen inherently carries an amount of thermal energy $E=kT$ given in terms of the Unruh temperature. At thermal equilibrium, each qubit carries an equal amount of thermal energy. Each qubit of information is a fundamental dynamical degree of freedom for the observer's holographic world. The equal partition of energy tells us that each dynamical degree of freedom, which is a qubit of information, carries an equal amount of energy $E=kT$ at thermal equilibrium, which defines temperature. As more qubits of information are encoded on the observer's holographic screen, more energy is inherent in that holographic world.

What about the laws of physics? Where do the laws of physics come from? The holographic principle gives a straightforward and perfectly good answer, which both Ted Jacobson and Tom

Banks have explicitly delineated. The space-time geometry of the observer's world appears to obey computational rules inherent in Einstein's field equations for the space-time metric. The matter particles that constitute the nature of all matter in that world and the force particles that transmit the electromagnetic and nuclear forces between matter particles obey computational rules inherent in the quantum field theory formulation of the standard model of particle physics. The holographic appearance of that world in terms of both the space-time geometry of that world and the particle physics of that world is constructed out of qubits of information encoded on a holographic screen. That holographic construction process obeys computational rules, like the rules that govern the operation of a computer, but the computational rules that govern the holographic appearance of the 3+1 dimensional space-time geometry and the particle physics of the observer's world aren't even exact. The rules arise as thermodynamic equations of state that only give an approximate thermal average description of the observer's world with a limited range of validity in the sense of thermodynamics.

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} \quad = \quad 8\pi G T_{\mu\nu} - \Lambda g_{\mu\nu}$$

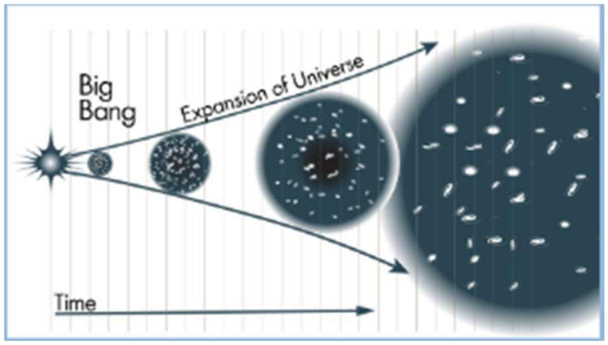
Einstein's Field Equations for the Space-time Metric

To begin with, we can deduce Einstein's field equations for the space-time metric, which is the nature of gravity, from the holographic principle. Einstein's field equations are thermodynamic equations of state that arise from the laws of thermodynamics that relate energy to entropy and temperature, $\Delta E = T\Delta S$. Ted Jacobson has shown how this derivation goes forward in terms of the area law for the entropy of the observer's event horizon and the Unruh temperature of that event horizon as observed by the accelerating observer in its accelerated frame of reference. As heat flows across a bounding surface of space, the total energy of that bounded region of space must change, which implies a thermodynamic change in the entropy of that bounded region of space. The holographic principle then tells us the area of the bounding surface must change, which implies a change in the geometry of the bounded region. Jacobson showed this change in the geometry of the bounded region is described by Einstein's field equations for the space-time metric. Einstein's field equations only have the validity of a thermodynamic equation of state. Once we have Einstein's field equations, all quantum fields of the standard model of particle physics can then be deduced as extra components of the space-time metric with the usual unification mechanisms of extra compactified dimensions of space and super-symmetry. The whole quantum field theory formulation of particle physics and the relativistic space-time geometry formulation of gravity can therefore be deduced from the holographic principle.

All we really need to explain the quantum field theory formulation of particle physics and the relativistic space-time geometry formulation of gravity is an observer in an accelerated frame of reference, which gives rise to an event horizon. Apply non-commutative geometry to that event horizon as a way to quantize position coordinates on the horizon, and we have an explanation for how to generate all the qubits of information that describe everything in a holographic world. Each quantized position coordinate defined by a non-commuting variable on the observer's event horizon is smeared out into an area element like a pixel that encodes a qubit of information. This encoding process not only includes information for all the elementary particles of that world that underlie the electromagnetic and nuclear forces, but also the space-time geometry of that world that underlies the effect of gravity. The only thing that seems to be fundamental to the explanation is the observer itself. The holographic principle is telling us that only the observer has its own independent existence, which fundamentally is the existence of consciousness.

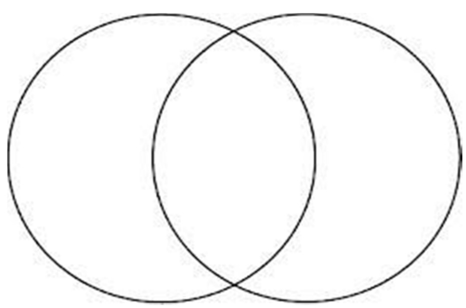
It should be noted that any thermodynamic equation of state that describes a physical system implies thermal equilibrium, which means the dynamical degrees of freedom of that system are thermalized or randomized in terms of their thermal energy. A thermodynamic equation of state is not valid when the system is not at thermal equilibrium. Since Einstein's field equations for the space-time metric, which is the nature of gravity, and the quantum field theories of the standard model of particle physics, which is the nature of physical matter and the electromagnetic and nuclear physical forces, are only thermodynamic equations of state for the physical universe, these equations do not apply when the physical universe is not at thermal equilibrium. As Roger Penrose has often pointed out, the physical universe is definitely not at thermal equilibrium, as is demonstrated by the normal flow of energy through the physical universe. If we are to have any hope of understanding the nature of the physical universe, we have to go beyond the simple understanding of the universe in terms of what we call the laws of physics inherent in Einstein's field theory for gravity and the quantum field theories of the standard model of particle physics. We have to start understanding the physical universe in terms of the holographic principle. We have to start understanding the perceivable physical world in terms of the observer of that world.

The physical universe is not at thermal equilibrium because space is expanding in the physical universe. The accelerated nature of the expansion of space, which is called dark energy, is the primordial energy that puts the *bang* in the big bang event. The idea of creation of the universe in a big bang is based on the idea of the expansion of space. As is well known, the expansion of space implies a cosmic horizon that limits the observations of the observer at the central point of view of that bounding surface of space. The holographic principle tells us the observer's cosmic horizon defines its own world whenever space expands since that is where all the fundamental qubits of information for that world are encoded. Inherent in the idea of the big bang is the idea the observer's observable world increases in size as space expands. This implies the observer's cosmic horizon increases in radius as the observer's world increases in size. As the observer's cosmic horizon increases in radius, its Unruh temperature cools, which explains the normal flow of heat in the observer's world as heat flows from hotter to colder objects. This also explains the second law of thermodynamics which says entropy tends to increase as heat flows in a thermal gradient. As the observer's cosmic horizon increases in radius, its Unruh temperature cools, but its surface area increases, which implies the entropy of the observer's world increases even as its world cools, since more qubits of information are encoded on the observer's cosmic horizon.




The Expansion of Space

This is wonderfully explained in detail in Amanda Gefter's recent book "Trespassing on Einstein's Lawn", where she interviewed many of the best theoretical physicists in the world that work in the area of quantum gravity and tried to make sense of the recent developments that led to the discovery of the holographic principle. At the end of her book she finally brings the holographic principle together with Carlo Rovelli's relational interpretation of quantum theory and comes to the conclusion that every observer must observe its own holographic world defined by its own event horizon that acts as a holographic screen. The observer's holographic screen is where all the qubits of information are encoded for the observer's own holographic world. The observer's holographic screen can only arise as an event horizon in the observer's own accelerated frame of reference, and so that holographic screen is inherently observer-dependent. The idea of a consensual reality shared among different observers can only arise in the sense of a Venn diagram of information sharing among different but overlapping holographic screens. This problem of information sharing among overlapping holographic screens is the essence of the entanglement problem of quantum gravity, as Tom Banks has repeatedly pointed out.



Overlapping Bounding Surfaces of Space Create the Appearance of a Consensual Reality

This way of understanding observation in terms of every observer observing its own holographic world leads to a more natural solution of the measurement problem, since it eliminates paradoxes like the Wigner friend paradox. Multiple observers simply cannot exist inside the same observable world without creating logically inconsistent paradoxes. Every observer observes its own observable holographic world. Different observers can only share a consensual reality due to information sharing among different but overlapping holographic worlds. As Gefter struggled to understand in her book, this raises fundamental questions about the true nature of the observer. These are fundamental questions about the true nature of observing consciousness.

Quantum theory in the context of the holographic principle is telling us that the observable physical world can only appear to come into existence in relation to the observations of the observer that observes that holographic world. Every observer must observe its own holographic world for that world to appear to come into existence. If the observer does not observe its own holographic world, that world remains in an unobserved state of potentiality. That unobserved state of potentiality is the nature of the quantum state. For the unobserved quantum state of potentiality of the world to come into an observed state of actuality, the observer must make an observation of that world. The unitary time evolution of the world, represented by the process U, only applies to the unobserved quantum state of potentiality of the world. Measurement or observation of the world, represented by the quantum state reduction process R, only applies to the observer's observation of its own holographic world, which reduces the state of potentiality of the observer's world to an observed state of actuality of that world. It cannot be stressed strongly enough that the observer's world only appears to come into an actual state of existence when the observer observes that world. Without the observer's observation of its own world, that world remains in an unobserved state of potentiality. Simply put, an observable world cannot appear to actually exist unless an observer observes it, but this raises fundamental questions about the true nature of the observer. What is the true nature of the observer's own existence?

This fundamental relation of an observer observing its own observable world essentially defines a subject-object relation. The true nature of the subject is the observer. The holographic principle tells us that the objective nature of all things the observer can observe in its own observable world are forms of information that can always be reduced to qubits of information encoded on the observer's own holographic screen, which can only arise as an event horizon in the observer's own accelerated frame of reference. The holographic principle is telling us that in some sense the objective nature of all things the observer observes is a holographic illusion, since all observable things can be reduced to qubits of information encoded on the observer's holographic screen. The observable things include the nature of all elementary particles that appear in space, including all the matter particles and all the force particles that transmit the electromagnetic and nuclear forces. The observable things also include the dynamical nature of space-time geometry, which is understood in relativity theory to be the nature of gravity. With the holographic principle, all of this observable stuff can be reduced to qubits of information encoded on the observer's holographic screen, but that's not the end of it.

Everything observable in the observer's holographic world, including the observer's own body and brain, can be reduced to qubits of information encoded on the observer's own holographic screen. The true subjective nature of the observer cannot be its body or brain, since these are only forms of information that appear in the observer's own holographic world. At most, the observer's own body and brain can only transmit or process information about the nature of that holographic world. A form of information is something observable, and cannot observe itself without creating a logically inconsistent paradox of self-reference. As quantum theory tells us, an observable object, which is a form of information, can only arise in a subject-object relation as the observer observes that observable thing. If the observer's own body and brain is not the true nature of the observer observing its own observable world, then what is the true subjective nature of the observer? This is fundamentally a question about the true subjective nature of observing consciousness, which by simple deductive logical reasoning, cannot itself be reduced to an observable thing. A body and brain that appears inside an observable holographic world cannot be the true subjective nature of the observer of that holographic world.

Until we confront the true subjective nature of the observer, we will never be able to make any real progress in terms of understanding the objective nature of the physical reality that we observe. The problem with modern physics and the lack of an adequate resolution of the measurement problem of quantum theory is that we are not confronting the true subjective nature of the observer. Is there something that we don't want to know? What exactly is it that we don't want to know? These are fundamental questions like: Who is the observer? Who is the knower? What is the true subjective nature of observing consciousness? Who am I?

The holographic principle is fundamentally an observer-centric description of observable reality. The observable reality of the world we perceive is not only perceived in an observer-centric way, but also in an observer-dependent way. The holographic principle is telling us that the observer is a presence of perceiving consciousness at the center of its own holographic world.

The measurement problem is the most important and pressing problem in modern physics.

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