A Brief History of the Holographic Principle

The holographic principle was discovered as theoretical physicists began to investigate the thermodynamic properties of black holes. The history of the holographic principle goes back to the early 1970's when John Wheeler and Jacob Bekenstein were trying to understand what happens to the information encoded for an object when that object falls into a black hole. All objects carry information, just as all objects carry thermal energy, which is the nature of temperature, and so as an object falls into a black hole, that information and thermal energy must become incorporated into the black hole.

A black hole is a region of space where the force of gravity is so strong that even light cannot escape. That region of space is defined by a bounding surface of space called an event horizon. At the surface of the event horizon, the velocity of escape from the black hole, called escape velocity, is equal to the speed of light. Since nothing can travel faster than the speed of light in relativity theory, nothing can escape from a black hole, not even light. Like everything else in the universe, black holes have the thermodynamic properties of information or entropy and temperature. The holographic principle was discovered when these thermodynamic properties were investigated.

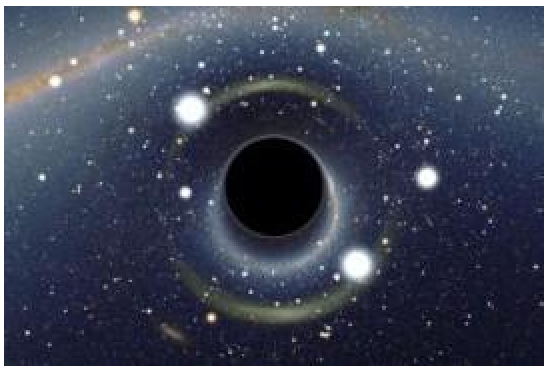
Black holes are solutions to Einstein's field equations for the space-time metric. This kind of solution is called the Schwarzschild metric, which describes the nature of a curved space-time geometry outside a massive object, like a gravitationally collapsed star that has burned through all of its nuclear fuel. In relativity theory, that curved space-time geometry is the nature of the gravitational field, which is mathematically represented by the space-time metric that measures the curvature of that space-time geometry. The Schwarzschild metric has a special radius from the center of the massive object called the Schwarzschild radius. If all the mass is inside the Schwarzschild radius, then the Schwarzschild metric is describing the gravitational field of a black hole.

$$R = \frac{2GM}{c^2}$$

Schwarzschild Radius of the Event Horizon of a Black Hole

The easiest way to calculate the Schwarzschild radius is with the escape velocity from the surface of the massive object. If we have a smaller mass m that is moving away from the larger mass M with a velocity v at a radial distance of r from the center of the more massive object, then the total energy of that motion in the gravitational field of the more massive object is $E=KE+PE=\frac{1}{2}mv^2-GMm/r$. The minus sign indicates that gravity is an attractive force. With escape velocity, the smaller mass has just enough kinetic energy of motion to overcome the potential energy of gravitational attraction, which means that E=0 for escape velocity. When the smaller mass reaches infinity, its motion comes to an end, but so too does the force of gravity. This tells us that escape velocity is given by $v^2=2GM/r$. At the surface of the event horizon of a black hole, where r=R, escape velocity is the speed of light, v=c, and so the radius of the event horizon of the black hole is given in terms of the mass of the black hole as $R=2GM/c^2$.

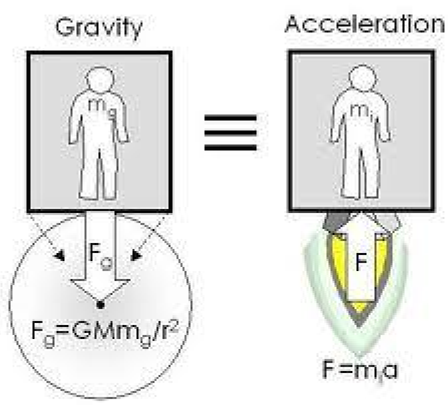
The event horizon of a black hole is a special spherical surface where the velocity of escape from that surface is the speed of light. Einstein's theory of gravity determines the Schwarzschild radius of the event horizon in terms of the mass of the black hole.



We normally think that the event horizon of a black hole is created by the force of gravity that arises from the mass of the black hole, but that's not quite correct. The event horizon of a black hole is an observer-dependent observation. The effects of the event horizon of a black hole only appear to an accelerating observer when the observer is in an accelerated frame of reference. It is only an accelerating observer in its accelerated frame of reference that observes the effects of the event horizon of the black hole. An observer in a freely falling frame of reference observes no effects of the event horizon. As far as the freely falling observer is concerned, there is no event horizon. Only the accelerating observer observes the effects of the event horizon.

In terms of the event horizon of a black hole, the effects of the event horizon are only observed by an accelerating observer that remains in a stationary position outside the event horizon of the black hole. An observer that hovers in a stationary position just outside the event horizon of a black hole must accelerate away from the black hole with an equal but opposite acceleration as that caused by the force of gravity that pulls the observer toward the black hole. The observer must accelerate away from the black hole to maintain its stationary position, like an observer in an accelerating rocket-ship, which defines the observer's accelerated frame of reference. Only the accelerating observer observes the effects of the event horizon of the black hole. A freely falling observer that falls into the black hole observes no effects of an event horizon.

In relativity theory, this distinction between the different effects that different observers observe in different frames of reference is called the principle of equivalence. This principle says there is no way to distinguish the effects of a force from the effects of an acceleration. The exertion of a force is always equivalent to an acceleration. Any force, like the force of gravity, is equivalent to an observer's acceleration, like an observer in a rocket-ship that accelerates through space. This equivalence specifically applies to the effects observed by an accelerating observer. An accelerating observer observes the same effects as those caused by the exertion of a force. In no significant way can the force of gravity be distinguished from an observer's own acceleration. An accelerating observer observes the same effects of gravity as caused by the exertion of a force.



Principle of Equivalence

The event horizon of a black hole is always defined in an observer's accelerated frame of reference, which is a coordinate system with an observer at the origin or central point of view of that coordinate system. An observer always measures its own space-time geometry in that coordinate system. The observer measures distances in space and intervals in time between events that take place in its own frame of reference or coordinate system that defines its own space-time geometry. The space-time metric is a way of mathematically representing those measurements of distances in space and intervals in time. At the event horizon of a black hole, those measurements break down.

Nothing can be measured by the observer beyond the event horizon of the black hole. The observer's own space-time geometry breaks down at the event horizon of the black hole. The observer can measure nothing beyond the event horizon, which is to say the event horizon is a bounding surface of space that limits the observer's observations of things in space. That limitation arises from a finite speed of light, which gives the maximal rate of information transfer in three dimensional space, and because the speed of light is the same for all observers, independent of their relative states of motion.

The effects of the event horizon of a black hole are solely observer-dependent effects that arise in the observer's accelerated frame of reference. Only the accelerating observer observes them. This is odd, since at the event horizon of the black hole, the observer's space-time geometry appears to break down. For example, the effect of time dilation appears to become infinite at the event horizon as observed by the accelerating observer. From the accelerating observer's own point of view, as things appear to fall into the black hole, it appears to take an infinite amount of time for those things to approach the event horizon, and they never really cross the horizon. From the accelerating observer's own point of view, nothing ever actually crosses the event horizon as things appear to fall into the black hole. As observed by the accelerating observer, everything that falls into the black hole seems to get stuck at the event horizon since it takes an infinite amount of time for things to approach the event horizon. For the freely falling observer, there is no effect of time dilation since there is no event horizon. The things that fall into the black hole with the freely falling observer just fall into the black hole unimpeded by an event horizon.

This breakdown of an accelerating observer's space-time geometry at the event horizon of a black hole has profound consequences when we try to quantize the gravitational field the same way we quantize any other quantum field theory. Just as the effect of time dilation at the event horizon tells us that time intervals between events become infinite at the event horizon as observed by the accelerating observer, the problem has to do with the measurement of distances. The bottom line is that there is a smallest possible distance scale that can be measured. This smallest possible distance scale is called the Planck length. The basic problem is that in quantum theory, the way we measure any distance scale is by scattering a quantum particle, like a photon of light, off of whatever object we are trying to measure. If we want to accurately measure the size of that object, we have to use an appropriate amount of energy inherent in the photon of light. The energy of the photon is given in terms of its frequency as $E=hf$. This relation between energy and frequency is what defines the photon as a quantum particle, which is a quantized excitation of the electromagnetic field. The photon's frequency is related to its wavelength in terms of the speed of light as $f=c/\lambda$, and so the photon's energy is given in terms of its wavelength as $E=hc/\lambda$.

The way we measure the size of an object is by matching the photon's wavelength to the object's distance scale. This means we have to use higher energy photons to measure smaller objects. For example, we can visualize a biological cell with an ordinary light microscope, but if we want to visualize a virus, we have to use an electron microscope. The wavelength of light generated by an electron microscope is in the range of x-rays, which is much smaller than the wavelength of visible light. Correspondingly, an x-ray photon carries much more energy than a visible light photon.

The smaller the object we want to measure, the higher the energy and the smaller the wavelength of the photon we need to use to make that measurement.

The problem is that when we combine quantum theory with gravity, we discover that there is a smallest possible distance scale that we can measure. Since energy is equivalent to mass as $E=Mc^2$, if we concentrate enough energy into a small enough distance scale or region of space, we create a black hole. Einstein's theory of relativity tells us that this distance scale is defined by the radius of an event horizon given in terms of the mass of the black hole as $R=2GM/c^2$. If this distance scale is set equal to the wavelength of a photon of energy $E=hc/\lambda$, and E is given in terms of the mass M of a black hole as $E=Mc^2$, then $R=2GM/c^2=2GE/c^4=2hG/\lambda c^3$. If we set these distance scales approximately equal as $R=\ell=\lambda$, then the distance scale ℓ at which a black hole must form is approximately given as $\ell=2hG/\ell c^3$. The Planck length is defined by $\ell^2=\hbar G/c^3$.

$$\ell_p = \sqrt{\frac{\hbar G}{c^3}} \sim 1.6 \times 10^{-35}\text{m}$$

Planck Length

The Planck length is the smallest possible distance scale that can be measured. If we try to measure smaller distance scales, we concentrate so much energy into such a small region of space that we create a black hole. If we concentrate even more energy into an even smaller region of space, we only make the black hole bigger. A bigger, more massive black hole has a larger event horizon. The event horizon of a black hole is a limitation on our ability to measure things in space since nothing is observable beyond the limits of an event horizon as observed by an accelerating observer outside the event horizon. In effect, just like infinite time dilation at the event horizon, the event horizon is a breakdown in the accelerating observer's ability to measure distances in its own space-time geometry. This breakdown in the accelerating observer's ability to measure its own space-time geometry beyond the limits of the event horizon is reflected in a smallest possible measurable distance scale. The Planck length as the smallest possible distance scale that can be measured by an accelerating observer signifies this breakdown in the observer's measurement of its own space-time geometry.

We measure distances by focusing energy into a region of space. We focus energy into a region of space with light waves to measure distances, and the energy of the light wave is given in terms of its wavelength as $E=hc/\lambda$. To measure smaller distances we have to use smaller wavelengths, which means higher energies. At some point, we focus so much energy into such a small region of space that we create a black hole. If we focus even more energy into an even smaller region of space, we only make the black hole bigger with a larger event horizon. The distance scale at which the black hole forms is the Planck length, and so the smallest distance we can measure is the Planck scale. A Planck-size black hole is the smallest event horizon that can be created. We only make the black hole bigger when we focus more energy into it. Combining gravity with quantum theory tells us there is a fundamental limitation in our ability to measure distances smaller than the Planck scale since it's impossible to create an event horizon smaller than the Planck scale. This limitation in our ability to measure distances smaller than the Planck scale is how Jakob Bekenstein discovered holographic entropy. All information must ultimately be encoded on an event horizon. This encoding of entropic information on an event horizon is the essence of the holographic principle.

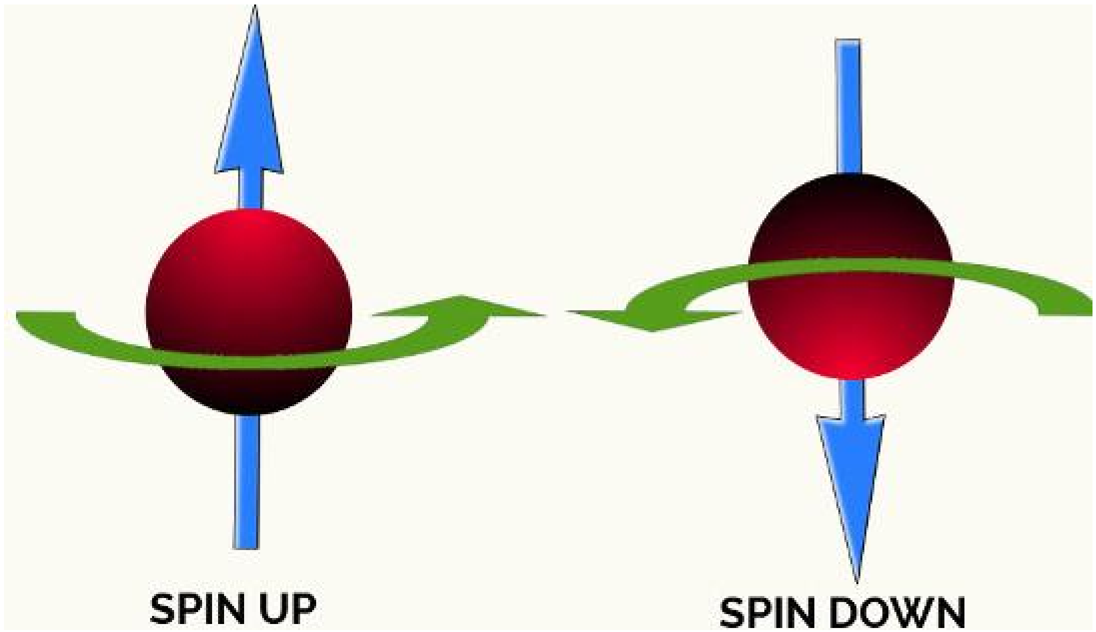
This incompatibility of quantum theory with gravity also tells us that we can never quantize Einstein's field equations for the space-time metric in terms of a quantum field theory. The reason is actually quite simple. The problem boils down to the very nature of space-time geometry. Quantum field theories are not consistent with gravity because they're not consistent with the dynamical curvature of space-time geometry. Quantum field theories can only be defined in gravity-free flat Minkowski space. All quantum field theories imply the existence of point particles as the quantized excitations of the fields. Those point particles have to occupy position coordinates in space and move through space over the course of time. That is only possible if we define a fixed background space-time geometry, like flat gravity-free Minkowski space, within which particles can occupy position coordinates in space and move through space. On the other hand, the force of gravity, understood as the dynamical curvature of a space-time geometry, is not consistent with quantum field theory. Gravity can never be understood as due to a point particle called the graviton that occupies a position coordinate in space and moves through space over the course of time. The very idea of gravity as the dynamical curvature of a space-time geometry is not consistent with the idea of a fixed background space-time geometry within which the graviton as a point particle would have to occupy a position in space and move through space. It's just not possible to understand the gravitational field as a quantum field theory. This means all attempts to unify gravity with other fundamental forces understood as quantum field theories are doomed to failure.

This state of affairs was an impasse that theoretical physics were unable to move past until John Wheeler and Jacob Bekenstein tried a new approach to solve the problem of unification. The new approach was to think of gravity in terms of thermodynamics. The bottom line was to think of the law of gravity not as a fundamental thing, but more like a thermodynamic equation of state, like the ideal gas law or equation for sound waves. In other words, there was something more fundamental than the law of gravity that underlies the law of gravity. In the thermodynamics of ordinary things, the more fundamental things are taken to be point particles, but Wheeler and Bekenstein had the idea that the most fundamental thing was a quantized bit of information.

The big question they had was about where or how the quantized bits of information that underlie the effects of gravity are encoded. The big clue they had was to consider the role played by the event horizon of a black hole. They imagined a photon of light falling into a black hole. They wanted to consider the simplest possible photon that was characterized by a single quantized bit of information. That quantized bit of information can be understood as the polarization state of the photon, which can only be observed to be circularly polarized in either a clockwise or a counter-clockwise direction relative to the direction of motion of the photon. The circular polarization of the photon in either a right-handed or left-handed state represents the spin state of the photon, similar to a spin ½ particle that can only be observed to spin in either a spin up or spin down state. This spin state represents a single quantized bit of information.

In order to make the photon as simple as possible and to carry no other information other than its spin state, the wavelength of the photon was assumed to be the same size as the radius of an event horizon of a black hole. As this photon fell into the black hole, only a single quantized bit of information was added to the black hole. The question they wanted to answer was about the black hole's entropy, which is the total number of quantized bits of information that characterize the black hole. They also wanted to know how or where those quantized bits of information were encoded.

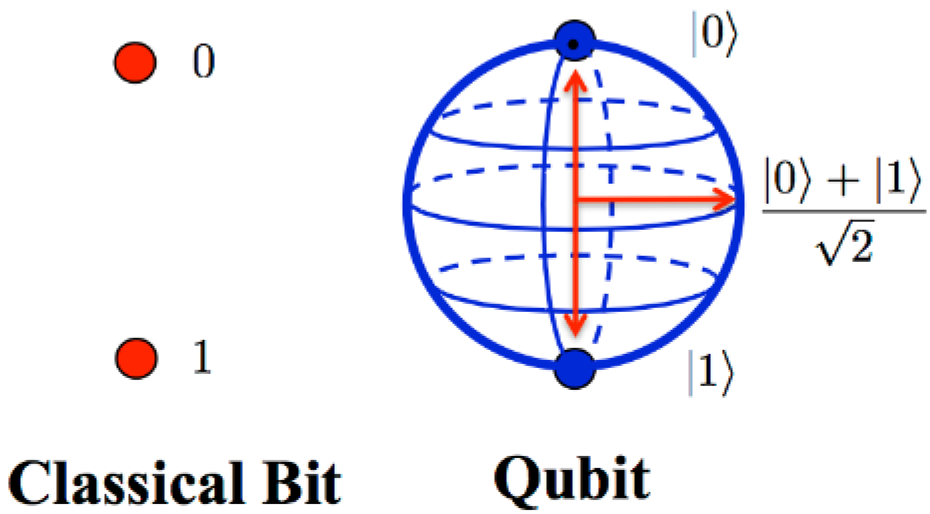
Wheeler and Bekenstein were interested in the information content of objects thrown into a black hole. What happens to that information? The first thing to be clear about is that all objects are characterized by their information content. To use the analogy of the images projected from a computer screen, the information content of the images arises from the way bits of information are encoded on the computer screen. The computer screen is composed of pixels, and each pixel encodes a single bit of information in a binary code of 1's and 0's, which is physically encoded in terms of electronic switches that are either on or off. This kind of binary encoding of quantized bits of information is also the case for elementary particles, like a photon or an electron. In quantum theory, an elementary particle is characterized by certain quantities, like its mass, electric charge and energy, which is quantized in terms of the frequency of vibration of its wavefunction as $E=hf$. The elementary particle is also characterized by its spin angular momentum, which is also quantized. For the spin ½ electron, its value of spin is quantized as either spin up or spin down, like a spinning top that spins in the clockwise or counter-clockwise direction. For the massless spin 1 photon that must travel at the speed of light, its value of spin is also quantized in terms of its polarization state as either a right-handed or left-handed spin state relative to its direction of motion.



Quantized Spin States

Both the photon and the electron carry a single quantized bit of information given in terms of its spin state, which is encoded in a binary code just like a computer switch that is either on or off. This quantized bit of information is called a qubit, which in quantum theory can be understood in terms of the mathematical formulation of matrices. A 2x2 SU(2) matrix encodes information in a binary code in terms of its two eigenvalues, which specify that a spin ½ particle can only spin up or spin down or that a massless spin 1 particle can only spin in a right-handed or a left-handed polarization state. In terms of quantum theory, the two eigenvalues of the matrix are entangled, and that entanglement preserves their rotational symmetry on the surface of a sphere. This is due to the SU(2) matrix giving a mathematical representation of rotational symmetry on the surface of a sphere. Quantum entanglement reflects that rotational invariance.

Bekenstein asked what happens to a single quantized bit of information when it's thrown into a black hole. Bekenstein imagined adding a single qubit of information to a black hole, and asked what happens to the event horizon. What he discovered surprised him. It is as though the event horizon of the black hole encodes bits of information on pixels, like a computer screen. Each pixel on the screen encodes a single quantized bit of information. When a single quantized bit of information is thrown into the black hole, the event horizon of the black hole increases in size by a single pixel. A qubit of information is a quantized bit of information, like the information carried by a spin ½ particle that can only be observed to spin up or down, like a computer switch that is either on or off, and so carries a single bit of information encoded in a binary code of 1's and 0's. Unlike a classical computer switch, this quantized information is entangled.



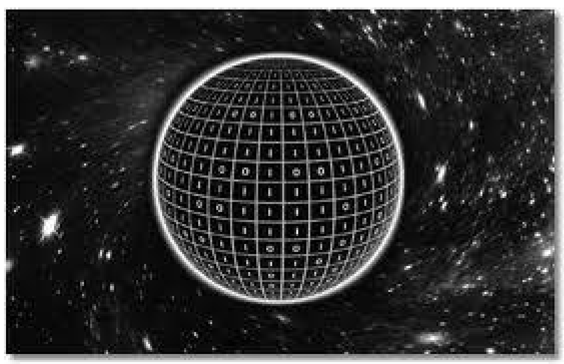
Qubit as the Quantized Information Encoded on the Surface of a Sphere

Quantum entanglement reflects that a quantized bit of information is being encoded on the surface of a sphere. A qubit is defined by an SU(2) matrix, like a Pauli spin matrix, which encodes information in a binary code, like a switch that is either on or off, in terms of the eigenvalues of the SU(2) matrix, which define observable spin states in terms of spin up and spin down states. This information is entangled because the SU(2) matrix also gives a mathematical representation of rotational symmetry on the surface of a 2-sphere. At the level of qubits, quantum entanglement mathematically represents this rotational invariance, which is fundamentally defined on the surface of a 2-sphere.

Bekenstein imagined that a single qubit of information is added to a black hole when a photon falls into the black hole. That qubit of information is carried by a photon that we know nothing about except for its polarization state. The photon is polarized in either a right-handed or left-handed polarization state, which is the same as a spin variable that is either spin up or spin down, and so carries a single qubit of information. When that qubit of information is added to the black hole, the event horizon of the black hole increases in size by about a single Planck area, and so it is as though each Planck area on the event horizon encodes a single qubit of information, like pixels on a computer screen. Bekenstein was able to do a simple approximate calculation to demonstrate this effect using basic concepts from both quantum theory and gravity.

A photon carries an amount of energy given in terms of its wavelength as $E=hc/\lambda$. If we know nothing about the photon except for its polarization state, then when the photon falls into the black hole, its wavelength must be approximately equal to the size of the black hole, as $\lambda=R$, where the Schwarzschild radius of the black hole is given in terms of its mass as $R=2GM/c^2$. The black hole has a total energy of $E=Mc^2$. The addition of the photon's energy to the black hole increases its energy by an amount $\Delta E=hc/\lambda=hc/R$, and so the mass of the black hole increases by an amount $\Delta M=h/Rc$. This addition of the photon's energy to the black hole's mass also increases its Schwarzschild radius by an amount $\Delta R=2G\Delta M/c^2=2hG/Rc^3$. The surface area of the event horizon is given by $A=4\pi R^2$. When the photon's energy is added to the black hole, its surface area changes as $\Delta A=8\pi R\Delta R=16\pi hG/c^3$. The Planck area is defined as $\ell^2=\hbar G/c^3$, and so when the photon's energy is added to the black hole's mass, the surface area of its event horizon increases by about a single Planck area. Since the photon carries a single qubit of information encoded in terms of its polarization state, it is as though each Planck area on the surface of the black hole's event horizon encodes a single qubit of information.

This is how Bekenstein discovered the holographic entropy of a black hole. Each Planck area defined on the surface of the black hole's event horizon encodes a single qubit of information. It is as though the surface of the event horizon is covered with Planck-size pixels and each pixel encodes a single qubit of information.



$$S_{\mathrm{BH}} = \frac{kA}{4\ell_{\mathrm{P}}^2}$$

Black Hole Holographic Entropy

This tells us that a Planck-size event horizon is the smallest event horizon that can ever be created since it encodes a single qubit of information, which is the smallest amount of information that can ever be measured. A single qubit of information can only be encoded on a Planck-size event horizon. Larger event horizons encode more qubits of information, but always in terms of an integral number of Planck areas. A qubit is the smallest amount of information can ever be measured, and so the Planck length is the smallest distance scale can ever be measured. The Planck length is the smallest possible distance scale that can ever be measured since a Planck-size event horizon, which encodes a single qubit of information, is the smallest possible event horizon.

Although Bekenstein did not do so, in addition to calculating the holographic entropy of a black hole's event horizon, he could also have calculated the temperature of the black hole's event horizon. The laws of thermodynamics tell us that a change in energy is related to a change in entropy and temperature as $\Delta E=T\Delta S$. Bekenstein calculated that the holographic entropy of the black hole's event horizon is given in terms of the number of qubits of information encoded on the surface area of the black hole's event horizon. This number n is proportional to the surface area A. The exact result was calculated by Stephen Hawking in terms of the Planck area, $\ell^2=\hbar G/c^3$, as $n=A/4\ell^2$. The holographic entropy of the black hole's event horizon is defined in terms of this number as $S=kn$.

The concepts of entropy and temperature only apply at thermal equilibrium. The reason we can assign a holographic entropy to the black hole's event horizon is because the black hole is at thermal equilibrium. That's also the reason we can assign a temperature to the event horizon, which is called the Unruh temperature of the event horizon.

At thermal equilibrium, all the dynamical degrees of freedom for the system of interest carry the same amount of thermal energy, which is called the equal partition of energy. This is a consequence of the thermal randomization of energy. At thermal equilibrium, each dynamical degree of freedom that characterizes the system of interest carries the same amount of randomized thermal energy. The temperature of the system of interest is defined in terms of this randomized thermal energy as $E=kT$. When we write the laws of thermodynamics as $\Delta E=T\Delta S$, and characterize entropy in terms of the number of dynamical degrees of freedom as $S=kn$, we're only saying that a change in energy represents a change in the number of dynamical degrees of freedom as $\Delta E=kT\Delta n$, where the energy carried by each dynamical degree of freedom is given as $E=kT$.

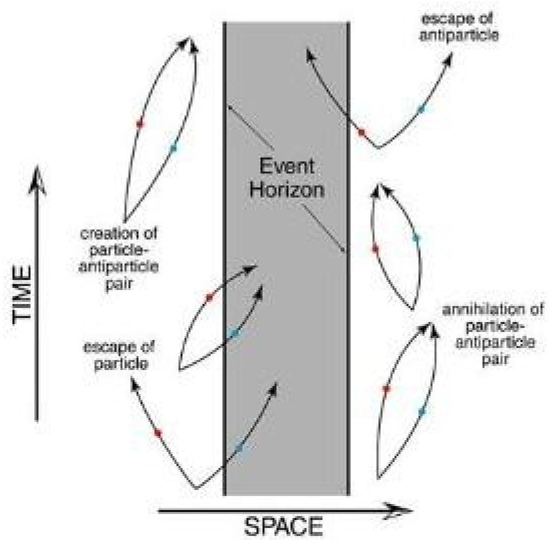
For a black hole, the dynamical degrees of freedom that characterize the black hole are qubits of information encoded on the surface of the black hole's event horizon. At thermal equilibrium, each qubit of information carries the same amount of randomized thermal energy, $E=kT$, where T is the temperature of the event horizon. If we imagine that each qubit of information encodes information for a photon of thermal radiation that is radiated away from the event horizon, then we can calculate the temperature of the event horizon. The energy of that photon of thermal radiation is given in terms of its wavelength as $E=hc/\lambda$. Since the black hole is at thermal equilibrium, the wavelength of that photon can only be given in terms of the Schwarzschild radius of the black hole. If we approximate the wavelength of that photon in terms of the maximal circumference of the event horizon as $\lambda=2\pi R$, this tells us that the thermal energy of the photon is given in terms of the Schwarzschild radius of the event horizon as $kT=hc/2\pi R$.

This result actually makes sense since a photon can only escape away from the black hole if the photon is not gravitationally bound to the black hole, which means it has to have a wavelength that is larger than the Schwarzschild radius. That's the only way the event horizon can radiate away thermal radiation. This thermal radiation from the event horizon of a black hole is called Hawking radiation, which the event horizon radiates away into space because the event horizon has a temperature. This temperature of the event horizon is called the Unruh temperature. The Unruh temperature can be rewritten in terms of the acceleration due to gravity at the event horizon, $a=GM/R^2$, and the Schwarzschild radius of the black hole, $R=2GM/c^2$, which gives the acceleration due to gravity at the event horizon as $a=c^2/2R$. At the level of the approximation used in this calculation, this gives the Unruh temperature of the event horizon as $kT=hc/2\pi R=ha/\pi c$.

The calculation performed by Bekenstein was only an approximation based on very general principles. Stephen Hawking was able to perform a more exact calculation, and found essentially the same thing. The number of quantized bits of information that characterize a black hole is given in terms of the surface area A of the event horizon of the black hole as $n=A/4\ell^2$, where $\ell^2=\hbar G/c^3$ is called the Planck area. It is as though every four Planck areas on the surface of the event horizon acts like a pixel that encodes a single quantized bit of information. In terms of the idea of matrices encoding this information, the n qubits of information encoded on a spherically symmetric event horizon are given in terms of the n eigenvalues of an nxn SU(2) matrix. The surface area of the event horizon is equivalent to the number of pixels or qubits encoded on the horizon. In a very real sense, space-time geometry is being created from information.

Hawking was able to perform a more exact calculation than the approximate calculation performed by Bekenstein. Hawking was able to perform this exact calculation because he was able to give an exact calculation for the Unruh temperature of the event horizon of a black hole, which is given in terms of the acceleration due to gravity at the event horizon as $kT=\hbar a/2\pi c$. Hawking was able to perform this calculation by using quantum field theory in the vicinity of the black hole's event horizon. Although quantum field theory only has the validity of a thermodynamic equation of state, and is only valid for small quantum fluctuations around thermal equilibrium, this is a valid approximation because the black hole is at thermal equilibrium and the thermal radiation radiated away from the event horizon of the black hole is a form of black-body radiation that is emitted from a black-body that is at thermal equilibrium. The nature of this thermal radiation is the separation of virtual particle-antiparticle pairs at the event horizon of the black hole. The virtual particle-antiparticle pairs are the small quantum fluctuations around thermal equilibrium, which are becoming separated at the event horizon of the black hole.

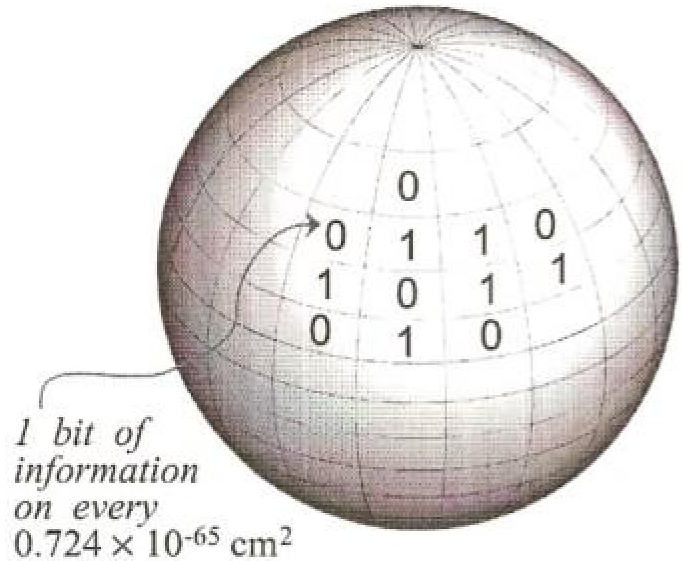
The temperature of the black hole's event horizon at thermal equilibrium is called the Unruh temperature. Stephen Hawking gave the best explanation for the nature of the Unruh temperature in terms of the apparent separation of virtual particle-antiparticle pairs at the event horizon. As observed by an external observer in an accelerated frame of reference, virtual particle-antiparticle pairs appear to separate at the event horizon. The virtual antiparticle can appear to fall across the event horizon and become unobservable while the virtual particle can appear to become observable as it radiates away from the event horizon towards the external observer. This particle of radiation is radiated away from the event horizon toward the external observer and appears to become a particle of thermal radiation called Hawking radiation, which carries heat. The observer observes heat energy being radiated away from the event horizon as though the event horizon has a temperature. Where does this thermal energy come from? The answer is that thermal energy comes from the observer's own accelerated motion, which gives rise to the appearance of its event horizon in the observer's own accelerated frame of reference. If the observer accelerates with an acceleration, a, the observed temperature of the black hole's event horizon is given in terms of that acceleration as $kT=\hbar a/2\pi c$, which is how the Unruh temperature is defined.



Hawking Radiation

Once Hawking had this result for the Unruh temperature of the black hole's event horizon, he was able to calculate the holographic entropy of the event horizon in terms of its surface area using the laws of thermodynamics, $\Delta E=T\Delta S$. It's a straightforward exercise to show that this equation implies that the holographic entropy of the black hole's event horizon is given in terms of its surface area as $S=kn=kA/4\ell^2$, where the total energy of the black hole is given by $E=Mc^2$, the Schwarzschild radius of the black hole is given by $R=2GM/c^2$, the surface area of the event horizon is given by $A=4\pi R^2$, the acceleration due to gravity at the event horizon is given by $a=GM/R^2$, and the Unruh temperature of the event horizon is given in terms of that acceleration by $kT=\hbar a/2\pi c$.

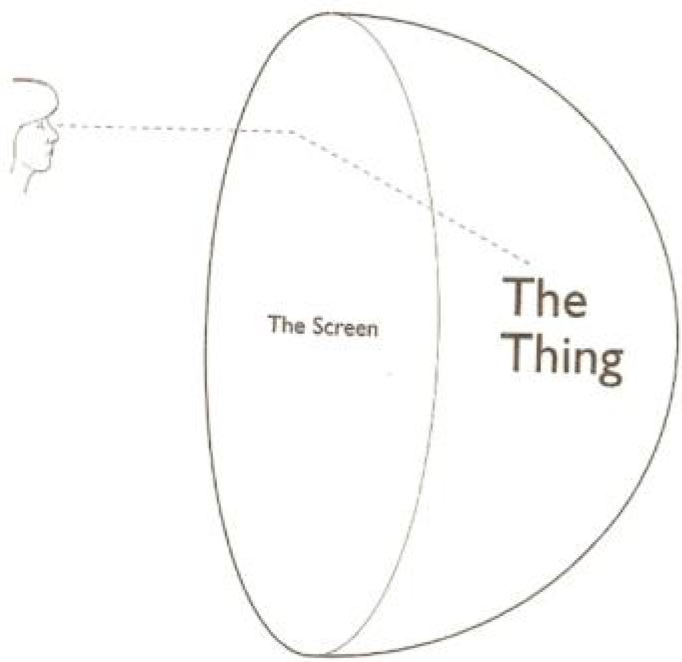
The Hawking calculation was confusing. Unlike Wheeler and Bekenstein, Hawking was not willing to characterize the event horizon of a black hole in terms of pixels. This confusion persisted for about 20 years until Leonard Susskind and Gerard 't Hooft again reconsidered characterizing the event horizon of a black hole in terms of pixels, with each Planck-size pixel defined on the event horizon encoding a single quantized bit of information. They called this idea the holographic principle.



Holographic Principle

A peculiar aspect of black holes is that they can evaporate away. If the temperature of the surrounding space is colder than the temperature of the black hole's event horizon, the horizon will radiate thermal radiation into space. The nature of that thermal radiation is Hawking radiation that arises at the black hole's event horizon due to the separation of virtual particle-antiparticle pairs that appear to separate at the event horizon. The virtual particle is radiated away from the event horizon toward an external observer and appears to become a particle of thermal radiation that carries positive heat energy, while the virtual antiparticle falls into the black hole and carries negative energy that reduces the mass of the black hole as the black hole appears to evaporate away. Eventually, if the surrounding space is cold enough, the black hole can appear to evaporate away to nothing as the radius of its event horizon and its mass both approach zero.

What happens to the information encoded on the black hole's event horizon when the black hole appears to evaporate away to nothing? This puzzle is called the information loss paradox, which literally drove a large number of theoretical physicists crazy as they attempted to reconcile the conflict between quantum theory and gravity. The solution to this puzzle was suggested by Leonard Susskind and Gerard 't Hooft, which solves the puzzle in terms of the holographic principle. It's just not correct to consider the black hole in isolation. We can't just consider what's happening to information at a black hole event horizon. We also have to consider what's happening to information out at a cosmic event horizon. The cosmic horizon is like a holographic screen that projects all the images of whatever is observed to happen in an observer's holographic world to the observer's own central point of view. Whatever appears to happen in the observer's holographic world includes whatever appears to happen to the black hole. The observer is at the central point of view of its own holographic world, which is ultimately defined in terms of the information encoded on its own cosmic event horizon. All the information that characterizes a black hole and its particles of Hawking radiation in that holographic world is ultimately encoded on the observer's cosmic horizon. Everything perceivable in a holographic world, including all the point particles of that world, can be reduced to entangled qubits of information encoded on an observer's own cosmic horizon. Even the space-time geometry of the observer's own holographic world is reducible to information encoded on its own cosmic event horizon. The essential lesson of the holographic principle is that the observation of a particle at a position in space and a moment of time is never a local phenomena, but rather a holistic phenomena that arises from the way entangled qubits of information are encoded on an observer's holographic screen.



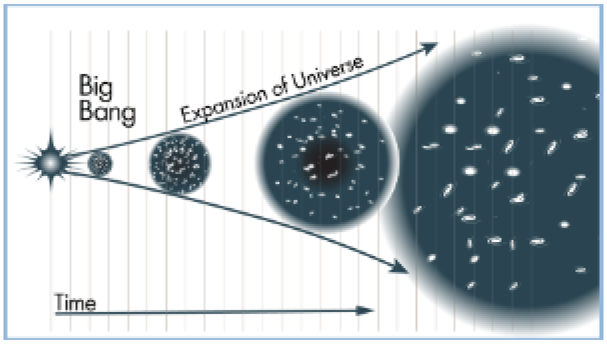
The Observer, the Observer's Holographic Screen, and its Object of Perception

Shortly after Leonard Susskind and Gerard 't Hooft suggested this explanation, the AdS/CFT correspondence was discovered, which solves the information loss paradox in anti de Sitter space in terms of the boundary of anti de Sitter space, which behaves like an observer's holographic screen in that everything observable in anti de Sitter space is reducible to qubits of information encoded on the boundary of anti de Sitter space. This encoding of information is specified in terms of a conformal field theory that is defined on the boundary. Even when a black hole appears to evaporate away in anti de Sitter space, there never really is any information loss because that information is always encoded on the boundary of anti de Sitter space. Unfortunately, the AdS/CFT correspondence is a special case that only applies to anti de Sitter space.

The holographic principle was a speculative idea, but based on very general and widely accepted principles of modern physics. This speculative idea gained credibility when the exact mathematics of string theory confirmed it in a concrete example. This example is the AdS/CFT correspondence, which proves it is possible to mathematically construct a holographic world. The boundary of that holographic world is the conformal boundary of anti de Sitter space. This boundary arises with a negative cosmological constant, which in the sense of relativity theory gives rise to the accelerated contraction of space. The boundary of anti de Sitter space is a bounding surface of anti de Sitter space. Within that bounded space, the force of gravity is active, and is described by Einstein's field equations for the space-time metric. On the boundary of that space, there is no force of gravity, only a quantum field theory. This quantum field theory is a supersymmetric version of an SU(N) Yang-Mills field theory, similar to the field theories of the strong and weak nuclear forces, but has the special properties of being a conformal field theory.

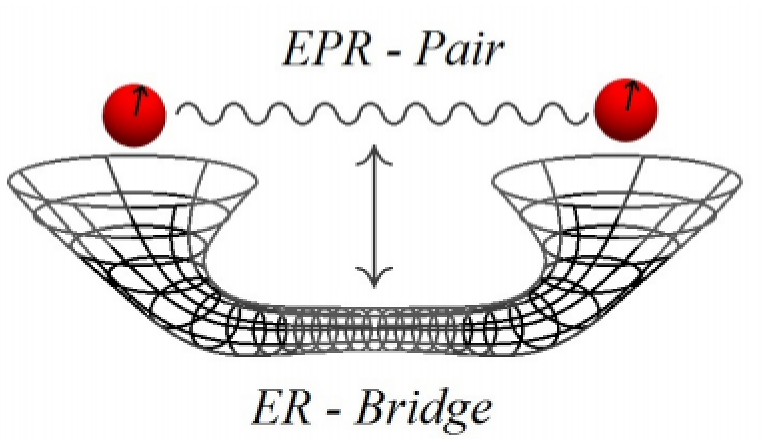
In the language of quantum theory, the boundary of AdS encodes a conformal field theory that is characterized by qubits of information. There is no force of gravity on the boundary. The interior of AdS is characterized by the force of gravity as described by Einstein's field equations for the space-time metric. This is an explicit demonstration of a holographic world. All the qubits of information characterizing that world are encoded on the conformal boundary of that world. The interior of that world is characterized by the force of gravity, but there is no gravity on the boundary. The boundary of AdS is only characterized by a conformal field theory, which is reducible to qubits of information encoded on the boundary, while the interior of AdS is characterized by gravity as formulated by 11-dimensional super-gravity, which is a low energy limit of M-theory.

At this point, many people will object that our world is not AdS, but this objection is simply wrong. Our world is characterized by de Sitter space. Around the same time that Susskind and 't Hooft proposed the holographic principle in the mid 1990's, astronomers were trying to get a handle on the expansion of the universe. The idea of the big bang assumes that the universe is expanding from the moment of its creation, which is like an outward explosion from a single point. If that expansion is opposed by the attractive force of gravity, that expansion should be slowing down. That's what astronomers expected to find. Instead, what they discovered is the expansion is speeding up. The expansion is accelerating. In relativity theory, this expansion is understood in terms of a positive cosmological constant, which gives rise to the accelerated expansion of space. The astronomers were actually measuring a positive cosmological constant. The accelerated expansion of the universe from the big bang event only occurs due to the accelerated expansion of space. In the sense of inflationary cosmology, this expansion in the size of the universe occurs because the cosmological constant is transitioning to a lower value. That's the only reason why the observable universe expands in size.

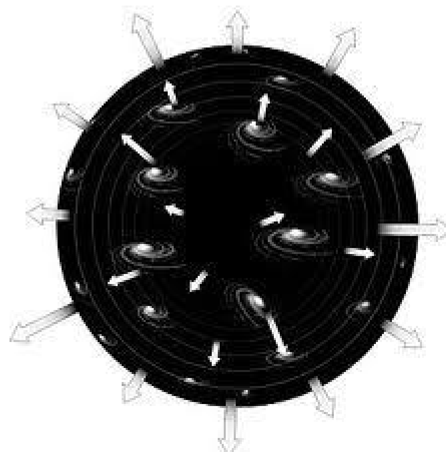


Accelerated Expansion of the Universe

There recently has been a great deal of interest in how the AdS/CFT correspondence solves the information loss paradox in terms of entangled black holes that are connected by wormholes. This is called ER=EPR. The wormhole is an Einstein-Rosen bridge that connects a pair of black holes, which are entangled like an EPR pair of spin variables. When we don't consider the black hole in isolation, but consider how the information the black hole encodes on its event horizon is entangled through wormholes with the information other black holes encode, there is no loss of information as Hawking radiation appears to be radiated away from the black hole and the black hole appears to evaporate away. The quantum entanglement of black holes through their connection by wormholes preserves all the information at the level of an entangled quantum state. The ultimate solution for the information loss paradox in anti de Sitter space is the way entangled qubits of information are encoded on the conformal boundary of anti de Sitter space, which defines that holographic world.



Unfortunately, we don't live in anti de Sitter space, and so things aren't this simple. We live in de Sitter space. We live in an expanding universe characterized by dark energy and the accelerated expansion of space. The accelerated expansion of space is what gives rise to each observer's own de Sitter cosmic event horizon. Every observer has its own unique central point of view from which space appears to expand and every observer observes its own unique de Sitter cosmic horizon. With the expression of dark energy, space appears to be expanding away from the observer's central point of view in an accelerated way, faster the farther out the observer looks out into space. At the observer's de Sitter cosmic horizon, space appears to be expanding away from the observer's central point of view at the speed of light, and so nothing is observable to the observer beyond the limits of its own cosmic horizon. The observer's de Sitter cosmic horizon becomes its holographic screen when the horizon encodes qubits of information for everything the observer can observe in its own holographic world.



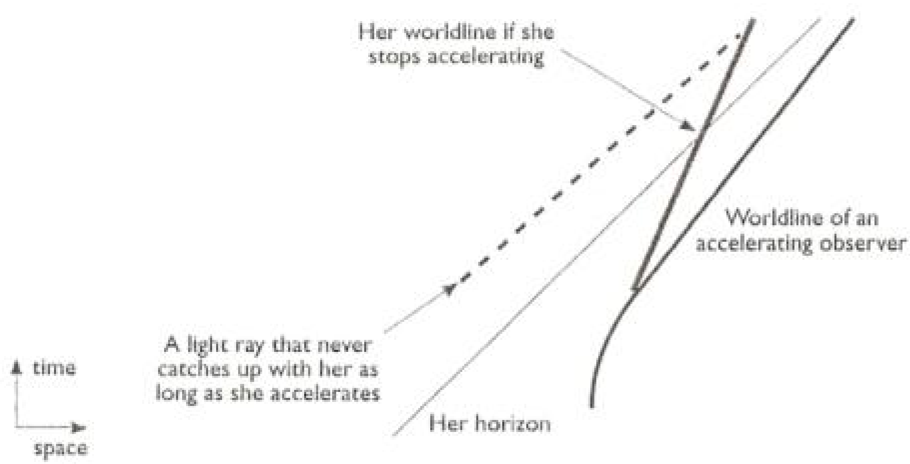
Accelerated Expansion of Space

The holographic principle tells us that we can't just consider what's appearing to happen to something in the universe, like a black hole, in isolation. We also have to consider how information is encoded on an observer's cosmic horizon. Whatever is being observed in a holographic world, like a black hole, that information is ultimately encoded on the observer's cosmic horizon. The information for everything perceivable in a holographic world can ultimately be reduced to information encoded on the observer's cosmic horizon. This was the motivation for the discovery of the holographic principle in the first place. We can't consider the black hole and its Hawking radiation in isolation. The information for the Hawking radiation and the information encoded on the black hole's event horizon are both ultimately encoded on an observer's cosmic horizon.

The reason the accelerated expansion of space is important is because that expansion gives rise to the boundary of the observable universe. From the point of view of an observer at the center of its own observable universe, that boundary is a cosmic event horizon. From the point of view of the observer at the central point of view, space expands away from the observer at the speed of light at the boundary of that cosmic horizon, and so nothing is observable beyond the observer's cosmic horizon. The strange thing about relativity theory and the accelerated expansion of space that arises with a positive cosmological constant is that every observer is at the center of its own observable world, which is bounded by the observer's own cosmic horizon.

In relativity theory, the observer is nothing more than the central point of view of that observable world. Just like the event horizon of a black hole that encodes qubits of information, or the boundary of AdS that is characterized by the qubits of information encoded by a conformal field theory, the boundary of that observable world encodes qubits of information for everything the observer can observe in that observable world. The observer's cosmic horizon encodes all the qubits of information for that world.

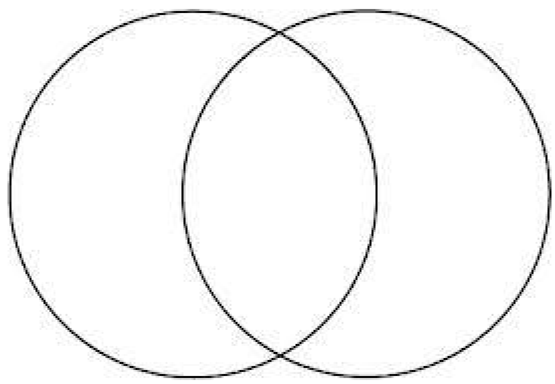
Even without the accelerated expansion of space, any observer in an accelerated frame of reference that follows an accelerating world-line through its space-time geometry has an event horizon that limits the observer's observations of things in space. In the general case of an accelerating observer, this event horizon is called a Rindler horizon. By the very fact of the observer's accelerated motion, nothing is observable beyond the limits of the observer's event horizon since a light ray that originates on the other side of the horizon can never cross the horizon and reach the observer's point of view.



Accelerating Observer's Event Horizon

If the holographic principle is applied to the observer's event horizon, then all the qubits of information that characterize all the observable things the observer can observe in the space-time geometry of its own holographic world are encoded on the observer's event horizon. Even the space-time geometry of that holographic world is reducible to qubits of information encoded on the observer's own event horizon. That's the nature of the holographic principle, which tells us that the observer's observable world is very much like a computer-generated virtual reality displayed on a computer screen. All the qubits of information that characterize all the observable things the observer can observe in its own observable world are encoded on the observer's own event horizon that acts as a holographic screen. In effect, the observer itself is creating the quantum computer that gives rise to the appearance of its own holographic computer-generated virtual reality with its own accelerated motion that gives rise to its event horizon that becomes its holographic screen when qubits of information are encoded on the screen.

How do we explain the related observations of multiple observers, each present at the central point of view of its own holographic world? The answer is information sharing. Each observer's own holographic world is defined on its own cosmic event horizon that becomes its holographic screen when the horizon encodes information. Those cosmic event horizons can overlap like a Venn diagram and share information, and so multiple observers can share similar observations in a consensual reality.



Information Sharing Among Overlapping Holographic Screens

It's worth discussing the nature of event horizons in greater detail. Every accelerating observer has an event horizon, which is a two dimensional bounding surface of space that limits the observer's observations of things in three dimensional space. Nothing is observable to an accelerating observer beyond the limits of its event horizon because a light ray that originates on the other side of the event horizon can never reach the observer's point of view as long as the observer continues to undergo its acceleration.

An event horizon is a direct result of the constancy of the speed of light for all observers, independent of their relative states of motion. The speed of light is not about light per se, but is about the maximal rate of information transfer in three dimensional space, similar to how information is transferred within a computer network. Since the holographic principle in effect gives a way to construct the network of a quantum computer, the rate of information transfer plays an important role in that construction. An event horizon acts as a holographic screen when it encodes qubits of information, like a computer screen, which is the output device of a computer. Information is being outputted to an observer. That construction process begins with the observer's own accelerated motion that gives rise to its event horizon.

There are several kinds of event horizons. A Rindler horizon is an event horizon that arises when an observer follows an accelerating world-line through its space-time geometry. A de Sitter cosmic horizon arises due to the accelerated expansion of space that expands relative to the central point of view of an observer. At the observer's cosmic horizon, space is moving away from the observer at the speed of light, and since nothing can travel faster than the speed of light, nothing is observable beyond the limits of the cosmic horizon. Observations of our own universe demonstrate that we live in an expanding universe that is characterized by dark energy and the accelerated expansion of space, which is the nature of de Sitter space. A black hole event horizon arises due to the force of gravity at the horizon, which is so strong that even light cannot escape. Escape velocity at the black hole event horizon is the speed of light. An important point is that all the effects of the black hole event horizon, like Hawking radiation, are observer-dependent, and are only observed by an accelerating observer that maintains a stationary position outside the event horizon. A freely falling observer experiences no acceleration and no effects of an event horizon. For the freely falling observer, there is no event horizon and no Hawking radiation. The situation with a Rindler horizon and a de Sitter cosmic horizon is similar. Only an accelerating observer observes the effects of an event horizon, like the thermal radiation of the Unruh effect.

In all cases, a light ray that originates on the other side of the observer's event horizon can never reach the observer as long as the observer continues to accelerate, and so nothing is observable to the observer beyond the limits of its event horizon. This is a consequence of the nature of accelerated motion and the constancy of the speed of light. The holographic principle is built on the nature of event horizons, which act as holographic screens when they encode qubits of information. The event horizon always arises in an observer's accelerated frame of reference and it is the observer itself that is observing the effects of the event horizon, like the thermal radiation of the Unruh effect.

Once we understand the nature of holographic entropy in terms of qubits of information encoded on an observer's event horizon, and understand the nature of the Unruh effect that gives the event horizon a temperature, then the laws of thermodynamics explain the nature of gravity, as formulated in terms of Einstein's field equations for the space-time metric, as thermodynamic equations of state that are only valid near thermal equilibrium. Instead of quantizing Einstein's field equations like a quantum field theory, the holographic principle turns the very idea of quantum gravity completely around, and gives us Einstein's field equations as an effective field theory that is only valid near thermal equilibrium. The holographic principle is not really a theory of quantum gravity, but a way to completely avoid the problem of field theories. There is a very good reason to avoid field theories all together if we're trying to formulate physics in a fundamental way. All quantum field theories are built upon the invalid premise of unitary time evolution. Field theories can never be fundamental because time is not fundamental.

Instead of trying to quantize Einstein's field equations as a quantum field theory, the holographic principle assumes that information is encoded on event horizons in terms of qubits. A qubit is mathematically represented by a two dimensional array of numbers called a matrix that must be encoded on a two dimensional surface of space. That surface of space arises as an event horizon in an observer's accelerated frame of reference. Every observer observes events in its own holographic world as defined by the way qubits of information are encoded on its own event horizon that acts as its holographic screen. The observer's holographic world is characterized by a dynamically curved space-time geometry that can be reduced to the way qubits of information are encoded on its own event horizon. Every observer carries with itself its own sense of proper-time that arises from its own accelerated motion that can be understood as a world-line that it follows through that curved space-time geometry. The observer itself can only be understood to be a point of view that arises at the center of its own holographic world. Fundamentally speaking, the whole thing has to begin with the observer and its own accelerated motion in an accelerated frame of reference.

There are still a few points we need to clear up to have a complete explanation. How do we understand the energy inherent in the observer's acceleration? Where do the laws of physics come from? Why does the observer's holographic computer-generated virtual reality world seem to obey computational rules?

Where does the flow of energy through the observer's holographic world come from? The answer is that energy comes from the observer's own acceleration. The observer's acceleration gives rise to the observer's event horizon that acts as its own holographic screen when its event horizon encodes qubits of information, but that acceleration also gives rise to the flow of energy through the observer's own holographic world.

The secret behind the flow of energy through the observer's own holographic world is the Unruh temperature of the observer's event horizon as observed by an accelerating observer. The Unruh temperature of the observer's event horizon arises as the energy of thermal radiation the accelerating observer observes emitted from its own event horizon. This is the thermal energy that flows through the observer's own holographic world as observed by an accelerating observer. This energy is given in terms of the Unruh temperature of the observer's event horizon as $E=kT$, which is proportional to the observer's acceleration as $kT=\hbar a/2\pi c$. In effect, the observer's acceleration is defining a frequency in the sense that $E=hf$, which is the defining relation between energy and frequency in quantum theory. The Unruh temperature arises as the temperature of thermal radiation the accelerating observer observes emitted from its event horizon. In terms of Hawking radiation, this thermal radiation arises from the separation of virtual particle-antiparticle pairs at the event horizon as observed by the accelerating observer.

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 accelerating observer, something weird appears to happen. The accelerating 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 quantized bits of information for all the point particles that can appear in the observer's own holographic world, but the separation of virtual particle-antiparticle pairs at the event horizon gives the event horizon an apparent temperature proportional to the observer's acceleration.

Hawking radiation is weird. The key thing to realize is that although it appears virtual particle-antiparticle pairs separate at the event horizon as observed by the accelerating observer and that thermal particles of Hawking radiation are radiated towards the observer, the fundamental quantized bits of information that define all these particles of Hawking radiation are encoded on the event horizon, which is acting as the observer's holographic screen. The observation of a particle at a position in space and a moment of time is never a local phenomena, but a holistic phenomena that arises from the way entangled qubits of information are encoded on an observer's holographic screen.

The holographic principle is telling us that each Planck area defined on the observer's event horizon acts like a pixel that encodes a quantized bit of information. The particles of Hawking radiation the accelerating observer perceives to be radiated away from its event horizon are reducible to quantized bits of information encoded on its horizon, which is the observer's holographic screen. The essential lesson of the holographic principle is that particles that appear to exist in three dimensional space and to move through three dimensional space can always be reduced to quantized bits of information encoded on the two dimensional bounding surface of space of an observer's event horizon that bounds that three dimensional region of space and acts as its holographic screen. The accelerating observer is observing events in its own holographic world as displayed on its holographic screen. Those perceivable events can always be reduced to qubits of information encoded on the observer's holographic screen, which gives rise to the form of things and the flow of energy that animates those forms. This flow of energy can be understood in terms of the Unruh temperature of the observer's event horizon as the thermal energy that arises from the observer's own accelerated motion.

The laws of thermodynamics relate a change in total energy to temperature and a change in entropy as $\Delta E=T\Delta S$. The laws of thermodynamics are not really laws of physics, but rather very general statistical relations that specify how thermal energy flows from hotter to colder objects in terms of the dynamical degrees of freedom of those objects. This specifies how objects carry thermal energy, which is understood as the random kinetic energy of those objects. In terms of the holographic principle, the fundamental nature of the dynamical degrees of freedom of all objects are qubits of information encoded on an observer's holographic screen, which is the nature of the entropic information that characterizes those objects. Thermodynamic entropy is the same as entropic information when things are at thermal equilibrium. The holographic principle gives entropy in terms of the number of qubits encoded on the observer's holographic screen, which depends on the surface area A of its event horizon, as $S=kn=kA/4\ell^2$. The fundamental reason for this thermodynamic relation between energy and entropy is each qubit of information encoded on the observer's holographic screen carries an equal amount of thermal energy, $E=kT=\hbar a/2\pi c$, at thermal equilibrium, given in terms of the Unruh temperature, which depends on the observer's acceleration. The laws of thermodynamics assume thermal equilibrium. Each qubit of information encoded on the observer's holographic screen 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. This simply specifies that $\Delta E=kT\Delta n$ at thermal equilibrium. As more qubits of information are encoded on the observer's holographic screen, more energy is inherent in that holographic world.

Where do the laws of physics come from? The holographic principle gives a perfectly good answer, as Ted Jacobson has demonstrated. It turns out that the holographic principle not only can be deduced from the laws of physics, but the laws of physics can also be deduced from the holographic principle. It works both ways. The space-time geometry of the observer's holographic world, which is the nature of the force of gravity in the sense of the dynamical curvature of that space-time geometry, 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 all matter particles, also 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 and the particle physics of that world is constructed out of qubits of information encoded on the observer's 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.

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

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, as $\Delta E = T \Delta S$. Ted Jacobson has shown how this derivation goes forward in terms of the area law for the holographic 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 surface area of that bounding surface must change, which implies a change in the geometry of that bounded region of space. Jacobson showed how this change in the geometry of that bounded region of space is described by Einstein's field equations for the space-time metric. Einstein's field equations for gravity 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 final result of unification looks like 11-dimensional super-gravity, which is understood as a low energy limit of M-theory. All quantum particles, like the photon and electron, are understood as quantum excitations of an underlying quantum field. Maxwell's equations for the electromagnetic field and Dirac's equation for the electron field naturally arise as extra components of the space-time metric with extra compactified dimensions of space. Even particle charges, like electric charge, can be understood in terms of momentum quantized in extra compactified dimensions of space. All particle spin, like the spin ½ electron and spin 1 photon, can be understood in terms of the super-symmetry of space, with both commuting and anti-commuting dimensions of space. It therefore turns out that the whole quantum field theory formulation of the standard model of particle physics and the relativistic space-time geometry formulation of gravity can be deduced from the holographic principle in a natural way.

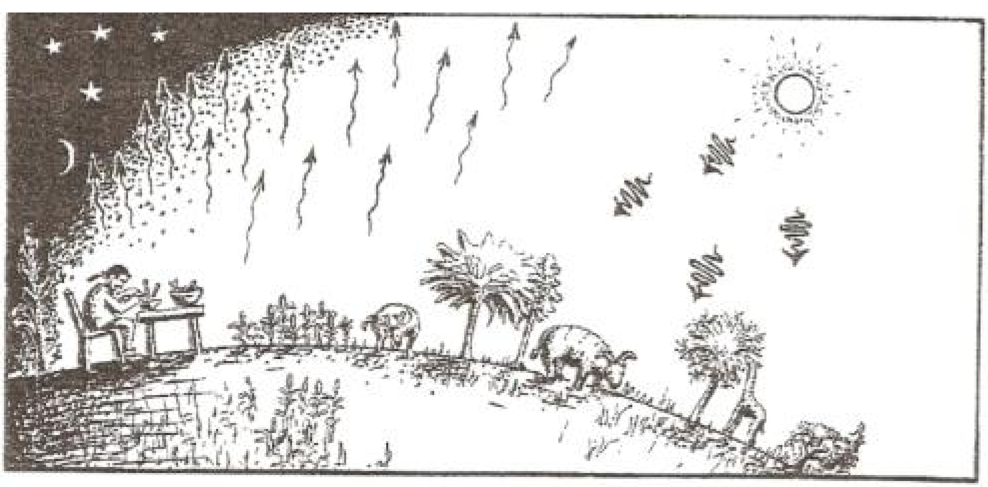
All we really need to explain the quantum field theory formulation of particle physics and the relativistic space-time geometry formulation of gravity is an accelerating observer, which gives rise to the observer's event horizon. Apply the holographic principle to that event horizon as a way to encode quantize bits of information on the horizon, along with the usual unification mechanisms of super-symmetry and extra compactified dimensions of space, and we have an explanation for how to create the observer's own holographic world. The form of everything in that world is reducible to qubits of information encoded on the observer's holographic screen. Even the flow of energy that animates everything in that world can be understood in terms of the observer's accelerated motion and the Unruh temperature of its event horizon. Each Planck-size pixel defined on the surface of the observer's event horizon encodes a qubit of information. This encoding process not only includes information for all the point particles of that world that underlie the electromagnetic and nuclear forces, but also the space-time geometry of that world that underlies the force of gravity. The only thing that is really fundamental to the explanation is the observer itself. The holographic principle tells us that only the observer itself has its own independent existence, which fundamentally is the existence of consciousness.

Any thermodynamic equation of state describing 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 most definitely not at thermal equilibrium, as is demonstrated by the normal flow of thermal energy through the physical universe. It makes no sense to try to understand the nature of the physical universe in terms of equations that are not fundamental and only give an approximate thermal average description of 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 nature of the accelerated 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.

The accelerated expansion of space that arises from the expression of dark energy 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 that the observer's cosmic horizon defines its own holographic 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 event is the idea that 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 holographic world as heat flows from hotter to colder objects. In the sense of inflationary cosmology, this naturally happens as the cosmological constant transitions to a lower value and the observer's cosmic horizon increases in radius.

This also explains the second law of thermodynamics, which says entropy increases 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, and so the entropy of the observer's world increases as it cools, since more qubits of information are encoded on the observer's cosmic horizon. This naturally happens as the cosmological constant transitions to a lower value. The normal flow of heat in a thermal gradient is created as the observer's world increases in size with the expansion of space. This also explains the direction of *time's arrow* and the normal flow of energy through the observer's holographic world. The direction of *time's arrow* is literally directed in the direction of the expansion of space that gives rise to the creation of the observable universe as heat flows from hotter to colder objects and as qubits of information are encoded for those objects on the observer's holographic screen. Ultimately, when the cosmological constant transitions to its final value of zero, the observable universe expands in size to infinity and it cools to absolute zero, which is called the heat death of the universe.



Normal Flow of Thermal Energy through the Observer's Holographic World