TOPIC X

ALTERNATIVE PROPOSALS TO RESOLVE THE INFORMATION PARADOX

Lecture notes 1

Wormholes

1.1 The fabric of spacetime

What is spacetime made of?

One might answer: spacetime is made of points. But points by themselves are separate entities, with no relation to each other. So what organizes these points into a smooth four dimensional manifold? More precisely, what tells one point that it should be close to another point?

In this section we will discuss an intriguing suggestion by Maldacena and Susskind, which says that proximity of points in spacetime is determined by *entanglement*. This proposal was intended to supply an alternative resolution of the information paradox. In this proposal, the quantum state around the horizon remains the vacuum. But there exist very nonlocal effects in spacetime, encoded by wormholes connecting the inside of the hole to points at infinity. Because of these effects, the degrees of freedom at infinity are not distinct from the degrees of freedom inside the hole. With this fundamental change in the nature of the black hole spacetime, it is hoped that the information puzzle can be resolved without altering the physics at the horizon.

We will see that this proposal has some difficulties. But it is very useful to analyze the arguments for and against the proposal, because they give important constraints on the properties of quantum black holes.

1.1.1 Entanglement and wormholes

Lets return to our question: what knits together the points of spacetime into a smooth manifold?

To start, consider a crystal. The crystal is made of atoms, which are like our 'points'. These atoms arrange themselves in a regular 3-dimensional array, and this arrangement defines the crystal. The situation is simpler than our original question because we start with a background spacetime in which we can place our atoms. There are interactions between the atoms, and the emergent lattice structure is the one which minimizes the energy.

There is one important consequence of the interaction between the atoms. Suppose the system is an Ising model, so that each atom has two spin states $|\uparrow\rangle$ and $|\downarrow\rangle$. The energy between two neighboring spins is lower if they are in the same spin state and higher if they are in opposite spin states. If we had a system with just two spins, then the lowest energy state would have the form

$$\frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1|\uparrow\rangle_2+|\downarrow\rangle_1|\downarrow\rangle_2\right) \tag{1.1}$$

Thus the two spins would be entangled, just like the particles emitted in Hawking radiation. In the lattice the entanglement between two spins is not as complete as in (1.1); each spin has to entangle not with just one other spin but with all its neighbors, and to a lesser extent also with its next nearest neighbors, etc. But the essential fact remains: the states of two spins which are close to each other are entangled to some degree, and the strength of this entanglement is related to the proximity of the spins.

Now consider our case of interest, the spacetime manifold itself. We do not have a background space on which we can place the points of this spacetime, since we are hoping to make space emerge somehow from these very points. But one thing we have learnt in section **??** is that over spacetime live a set of quantum fields. Consider a scalar field ϕ. At each point (x, y, z, t), we are allowed a set of values for ϕ, just like the atoms were allowed a choice of values for the spin in the crystal. The energy of the field configuration has gradient terms, which have the schematic form

$$E \sim \frac{1}{2}(\nabla\phi)^2 \approx \frac{1}{2}\frac{(\phi(x_2)-\phi(x_1))^2}{(x_2-x_1)^2} \tag{1.2}$$

In the vacuum state we seek to minimize energy, and this will tend to make $\phi(x_2)$ have a value close to $\phi(x_1)$ if $|x_2 - x_1|$ is small. This makes the state of ϕ at nearby points be entangled, just like in the case of the Ising spins above.

We can now state the proposal of Maldacena and Susskind. Defining the structure of spacetime requires us to say which points are close to which points. Let us say that two points are close if the quantum states of the fields living on those points are entangled with each other. The more the entanglement of the fields, the closer, in some sense, should be the geometrical connection between these points. Thus once we define a quantum wavefunction over the our points, then the fabric of a manifold emerges automatically.

1.1.2 Applying the idea to black holes

Let us see how the above idea can impact the information paradox.

First, consider the vacuum state $|0\rangle$ of spacetime. In this state the quantum fields living on spacetime are described by some wavefunction, and in this wavefunction the field values at neighboring points are entangled, as noted above.

Now imagine that some matter collapses to make a black hole. This process deforms the spacetime manifold to a different shape. The deformation is smooth everywhere away from the singularity, so the state of quantum fields on this manifold has not changed much. This accords with the fact that the proximity relations between points have not changed either: points which were close together before the black hole formed remain close after the metric deforms to the black hole metric.

But now the process of pair creation starts around the horizon region. The members of a pair b, c are in an entangled state that has the schematic form $\frac{1}{\sqrt{2}}(00+11)$. The quantum c falls into the hole while b escapes to a point far outside the hole. This creates a situation where the state at a point inside the hole (the location of c) is entangled with the state at a point far outside the hole (the location of b). If we are to take our postulate about proximity seriously, we should say that in some sense this point inside the hole is now close to a point far outside the hole. How should we visualize this change?

From the earliest days of general relativity, physicists have been fascinated by the possibility of *wormholes*. A wormhole is a tube of spacetime that connects points that are otherwise distant from each other. Thus it provides a shortcut in spacetime, giving points a proximity that they did not have without the wormhole.

The suggestion of Maldacena and Susskind is that when the quanta b, c separate from each other in spacetime, they nevertheless stay connected to each other by a thin wormhole. The wormhole in 'thin' because the entanglement of the bits at its ends is only $S_{ent} = \ln 2$; if the states at its two ends had a larger entanglement S_{ent} with each other, then the wormhole would be correspondingly 'thicker'.

As the hole radiates more quanta, we get a larger and larger number of these thin wormholes connecting the interior of the hole to points at infinity. This is pictured in fig.**??**. The ends of the wormholes inside the hole merge with each other, and create a structure which should be the new quantum gravitational interior of the hole.

How would such a picture of spacetime resolve the information puzzle? The picture of wormholes is qualitative, so we do not have a concrete understanding of the emergent spacetime around the horizon, where the pair creation effects were localized. But the immediate goal of the Maldacena-Susskind proposal was to find a a loophole in the standard derivation of the information paradox. Let us discuss the loophole that they propose.

Consider the two situations depicted in figs.**??**(a),(b).

(i) In fig.**??**(a) we denote a burning piece of paper. There are degrees of freedom in the paper. There are also degrees of freedom near infinity. When a photon leaves the paper and reaches near infinity, there is one less degree of freedom in the region where the paper is, and one more degree of freedom near infinity. The degrees of freedom in the vicinity of the paper and at infinity are *distinct*; we can move a bit from the paper to infinity, but we cannot say that a bit which is in the paper is also simultaneously at infinity. In the fuzzball proposal the black hole behaves exactly like this piece of paper: the hole radiates quanta to infinity, but the degrees of freedom in the fuzzball are distinct from degrees of freedom in quanta at infinity.

(ii) In fig.(b) we denote the new proposal of Maldacena and Susskind. The interior of the hole is linked to a point near infinity by a wormhole. The degrees of freedom at the two ends of this wormhole are assumed to be identified;

thus the bits making up the hole are not distinct from bits available at infinity. We have in effect changed the traditional assumption of locality. Normally we assume that different regions of spacetime contain different degrees of freedom, but when wormholes can provide alternative paths between regions, this assumption can become invalid.

The information puzzle arises because of a progressively growing entanglement between the degrees of freedom in the hole and the degrees of freedom at infinity. If these degrees of freedom are not distinct from each other, then the entire puzzle would need to be re-thought. There is no clear understanding of how the Maldacena-Susskind proposal may resolve the information paradox. But their postulate suggests a new path to explore, where the key would be a kind if extreme nonlocality: we can no longer assume that information resides at a given place, since it may be secretly connected by a wormhole to quite a different place.

1.1.3 The origin of the wormhole idea

At first the wormhole proposal may look rather unmotivated. Why would we wish to change the structure of our spacetime manifold in such a drastic way? The reason was a deep desire to preserve the classical intuition that the horizon should be a vacuum region. If the standard horizon leads to a violation of quantum mechanics, then we can either change the horizon (as fuzzballs do) or change how quantum mechanical entanglement works in our theory. By identifying bits in the hole with bits at infinity, we have changed the notion of what is entangled with what, and the hope is that this would somehow allow us to keep a vacuum horizon and yet avoid the growing entanglement between the hole and its radiation.

But there should be some basic reason why we expect wormholes to arise when bits are entangled. This reason comes from an earlier proposal of Maldacena involving the eternal black hole. We will see that this proposal itself has difficulties. But examining this proposal and its difficulties will yield an important constraint on the behavior of black holes. Let us therefore turn to the history which led to the wormhole proposal.

1.1.4 The eternal hole

The eternal hole is an object. We started from a spacetime with one 'infinity'; i.e., the region $r \to \infty$. But if we go into the hole, we find that spacetime continues to another region outside the hole, which is another 'asymptotic infinity' – the left wedge. What is the significance of this left wedge?

Israel made an interesting conjecture of the role of the left wedge. In statistical mechanics, the expectation value of an observable O is given by an average over an ensemble of all possible states. This ensemble is encoded in the density matrix

$$\hat{\rho} = C \sum_k e^{-\beta E_k} |E_k\rangle\langle E_k| \tag{1.3}$$

where the constant

$$C = \left(\sum_k e^{-\beta E_k} \right)^{-1} \tag{1.4}$$

serves the provide the required normalization $Tr[\hat{\rho}] = 1$.

There are two principal methods of performing computations with this density matrix. One is to rotate time to a Euclidean signature $t \to -i\tau$. Thus makes the operator $\hat{\rho}$ look like a time evolution in time by $\Delta\tau = \beta$, and then the computations are handled by the standard rules for a theory with Hamiltonian evolution. But in this approach it is difficult to recover time evolution in the original real time t. The other method is the 'real time formulation' of thermal field theory. In this method one imagines a second, virtual copy of the actual dynamical system. The combined system is assumed to be in a definite state

$$|\Psi\rangle = C \sum_k e^{-\frac{\beta}{2} E_k} |E_k\rangle_1 |E_k\rangle_2 \tag{1.5}$$

where the subscript 1 corresponds to states in the actual system and 2 to the virtual copy. Now suppose we want to find the expectation value of an operator $\hat{O}_1$ in our actual system; thus the structure of $\hat{O}_1$ involves only the states $|E_k\rangle_1$. Then we find

Thus we have obtained the expectation values (**??**) for our thermal system, using a pure state (1.5) in place of a density matrix. Since time remains Lorentzian, it is now possible to directly compute time evolution in the thermal system.

The idea of Israel was to think of the left wedge of the black hole as the second copy introduced in the real time formalism. It was already known that black holes had interesting thermodynamic properties, so it is natural to seek an ensemble of states defining a canonical ensemble. Moreover, it was known that rotating time to Euclidean signature gives a spacetime that covers only in the right wedge. Keeping time Lorentzian gives a semiclassical spacetime which has both right and left wedges. With all these similarities to the real time formalism of thermal field theories, the postulate of Israel looks very natural.

But what does it mean? We have already seen that the thermodynamics of black holes is puzzling because in the standard semiclassical picture of the black hole, we do not see any of the states that would account for the entropy of the hole. The relation (**??**) has the same problem; it involves black hole states, but the semiclassical picture of the eternal hole shows none of these states. If we use string theory and the fuzzball nature of black hole states, then we can see the states that account for the entropy of the hole. But as we will see, in that case the whole picture of the eternal hole may need a complete revision. Thus for the moment let us stay with the standard semiclassical picture of the eternal hole, and see where it leads us.

We cannot see the states in the eternal hole, but let us see if we can use AdS/CFT duality and say something using the description of the dual CFT. The above eternal hole was in asymptotically flat space, but we can also consider an eternal hole in AdS space, as was done in [**?**]. The eternal hole is AdS has the same structure of 4 wedges: (1) a right wedge R that has goes to AdS space at large distances from the hole (2) a future wedge F which contains a singularity (3) a left wedge L which again goes to AdS space at large distances and (4) a past wedge P which again contains a singularity.

Now let us recall the AdS/CFT correspondence. This conjecture suggests that *the entire dynamics of string theory in a region which is asymptotically AdS space is described by a CFT placed at the boundary of this AdS space.* In the eternal hole we have *two* asymptotically AdS boundaries: one in the right wedge R and one in the left wedge L. This suggests the the entire physics in the presence of the eternal hole should be captured by a set of *two* CFTs, one living at the boundary of the right wedge R and one at the boundary of the left wedge L.

Note that these the two boundaries of AdS are disconnected from each other. Thus the two CFTs cannot interact with each other. This means that the CFT Hamiltonian has the form

$$H^{CFT} = H^{CFT}_R + H^{CFT}_L \tag{1.6}$$

where the two terms correspond to the R and L wedges. Thus there is no interaction between the two CFTs. But the state of the CFT can still be entangled between the two copies. In fact there is a natural expectation for this entangled state. We do not know (in this semiclassical picture) where the states of the hole are, but we have called $|E_k\rangle_R$ as the states of the hole on the right side and $|E_k\rangle_L$ as the states of the left side. The AdS/CFT map then suggests that the gravity states $|E_k\rangle_R$ should map to states $|E_k\rangle^{CFT}_R$, and the gravity states $|E_k\rangle_L$ should map to states $|E_k\rangle^{CFT}_L$:

$$|E_k\rangle_R \;\leftrightarrow\; |E_k\rangle^{CFT}_R, \qquad |E_k\rangle_L \;\leftrightarrow\; |E_k\rangle^{CFT}_l \tag{1.7}$$

Then (1.5) says that the state of the CFT should be

$$|\Psi\rangle^{CFT} = C\sum_k e^{-\frac{\beta}{2}E_k}\,|E_k\rangle^{CFT}_R\;|E_k\rangle^{CFT}_L \tag{1.8}$$

Now we observe something interesting:

(i) In the CFT description, we have two disconnected spaces, corresponding to the left and right CFTs. The overall state of these two spaces is an entangled one.

(ii) In the dual gravity description, the eternal hole is a connected manifold.

Thus we conclude: *Entangling the states of two disconnected CFTs generates a physical connection in the gravity dual.*

To see the nature of this physical connection, look at the metric of the eternal hole on the slice $\mathcal{S}$ of fig.**??**. As we move inwards from infinity in the R wedge, the angular sphere shrinks in size, reaching its smallest value at the point where the R and L wedges join. This point is on the horizon, so the radius of the sphere is just r_h, the radius of the horizon. The radius then increases again all the way towards infinity in the L wedge. Thus the shape of the spacelike slice $\mathcal{S}$ is the shape of a *wormhole* connecting the R and L sides (fig.**??**).

We can now begin to see where the wormhole idea emerges from: entanglement in the CFT has led to the appearance of a wormhole in the dual gravity description. But we have one more step to go, before we reach the ideas that Maldacena and Susskind used for the information paradox.

1.1.5 Entangling gravity states

Van Raamsdonk [**?**] took Maldacena's proposal for the eternal hole one step further, as follows:

(i) Consider a state $|E_k\rangle_R^{CFT}$ of the right CFT. AdS/CFT duality suggests that there should be corresponding state $|E_k\rangle_R^{grav}$ in the dual gravity description. (We have added the superscript *grav* to these gravity states to avoid confusion with the CFT states.) The problem is that in the semiclassical description we do not see the black hole states on the gravity side, so we are missing the duals of a large number of the states $|E_k\rangle_R^{CFT}$. But let us assume for a moment that we found a description where we did see such states, for example the fuzzball description of states in string theory. Then there is a map

$$|E_k\rangle_R^{CFT} \;\leftrightarrow\; |E_k\rangle_R^{grav} \tag{1.9}$$

for all k.

(ii) There is a similar map for the left side

$$|E_k\rangle_L^{CFT} \;\leftrightarrow\; |E_k\rangle_L^{grav} \tag{1.10}$$

(iii) The entangled state (1.8) in the CFT then maps to a dual state where *gravity* states are entangled

$$C\sum_k e^{-\frac{\beta}{2}E_k}\,|E_k\rangle_R^{CFT}\,|E_k\rangle_L^{CFT} \;\leftrightarrow\; C\sum_k e^{-\frac{\beta}{2}E_k}\,|E_k\rangle_R^{grav}\,|E_k\rangle_L^{grav} \tag{1.11}$$

This is depicted pictorially in fig.**??**.

(iv) But the CFT state (1.8) was supposed to have as its gravity dual the eternal black hole. This suggests that *if we take disconnected but entangled states in gravity, then we generate a physical connection between them in the nature of a wormhole.* This is depicted in fig.**??**.

We can now see the origin of the Maldacena-Susskind wormhole picture. Consider the black hole. We are now in the gravity theory, and not considering any CFT dual. The creation of particle pairs creates entanglement, in this gravity theory, between the interior of the hole and the region near infinity. By Van Raamsdonk's conjecture, one would argue that this entanglement generates a physical connection between the interior of the hole and infinity, in the form of a wormhole. An accumulation of wormhole mouths in the interior of the hole changes the structure of the region around the horizon, and may offer a new approach to resolving the information paradox.

At first, this argument looks very appealing. But a closer inspection reveals several difficulties, which we now consider.

1.1.6 The F and P wedges

Let us start by asking: what does the relation in fig.**??** mean? There are two possibilities:

(i) The left side is just an entangled sum of gravity states. Suppose the right side was an *equivalent* but alternative description. Then we would have the choice of using only the left side description; i..e, we would gave entangled states but no new connections between them. In that case we learn nothing new about the information problem, as we have already explored the consequences of having entangled states on the usual black hole geometry.

(ii) The left side is an entangled sum, but this entanglement may generate new physical effects, which go beyond what one would get if one just considered the separate terms in the sum and then superposed the corresponding quantum amplitudes. In that one must use the wormhole picture to understand what the black hole spacetime looks like, and new effects can emerge.

Clearly, (ii) is what we should consider if we are looking for a novel resolution to the information puzzle. But what could be the 'extra' thing that we get by entangling two spacetimes? To see this, consider the diagram of the eternal hole. In the fuzzball picture, the states $|E_k\rangle_R^{grav}, |E_k\rangle_L^{grav}$ involve gravity wavefunctionals that live only in the R and L wedges respectively. Thus there are no F and P wedges in the terms on the left side sum in (**??**). But the eternal hole on the right does have these F,P wedges. Thus the nontrivial content of the Van Raamsdonk conjecture is that entangling gravity states generates new regions; these new regions are continuations of the R,L wedges across smooth horizons.

This picture may look very reasonable, since it seems to closely resemble the Rindler decomposition of Minkowski spacetime. Consider 1+1 dimensional Minkowski space, depicted in fig.**??**. Take the slice $T = 0$, and consider a scalar field ϕ on it. To be concrete, let us discretize this slice so that the field is defined only on the spacetime points denoted by the dots. The dots in the right wedge are denote by $i = 1, 2, \dots$, while those in the left wedge are denoted by $i = -1, -1, \dots$. The wavefunction describing ϕ on this slice has the form

$$\Psi\Big[\dots\phi[-2], \phi[-1], \phi[1], \phi[2], \dots\Big] \tag{1.12}$$

While this wavefunction does not factorzie between the R and L sides of the spacelike slice, we can always write it as a sum of factorzied terms; i..e, as an entangled state between the R and L sides

$$\Psi = \sum_j \psi_{R,j}\Big[\dots\phi[-2],\phi[-1]\Big]\ \psi_{L,j}\Big[\phi[1],\phi[2],\dots\Big] \tag{1.13}$$

At first the situation looks similar to the relation (**??**) of Van Raamsdonk, as follows:

(i) The states $\psi_{R,j}\Big[\dots\phi[-2],\phi[-1]\Big]$ are defined in the right wedge. Thus they can be evolved by the Rindler Hamiltonian H_R in the right wedge. Under this evolution, the points where the state was defined would evolve to points that remain in the right wedge.

(ii) The states $\psi_{L,j}\Big[\dots\phi[-2],\phi[-1]\Big]$ are defined in the left wedge. Thus they can be evolved by the Rindler Hamiltonian H_L in the left wedge. Under this evolution, the points where the state was defined would evolve to points that remain in the left wedge.

(iii) Using the usual time evolution of the Minkowski Hamiltonian, however, we can evolve the state to the later slice $\mathcal{S}'$ shown in fig.**??**. Thus the initial state (1.13) was defined as an entangled state between the R and L wedges, but its evolution carries it into the F wedge.

Based on the above Minkowski spacetime example, we might think that a similar situation holds for the gravity states considered by Van Raamsdonk. The states $\psi_{R,j}\Big[\dots\phi[-2],\phi[-1]\Big]$ are like the gravity states $|E_k\rangle_R^{grav}$ in fig.**??**. The Rindler Hamiltonian of the right wedge in the Minkowski spacetime example evolves the right wedge to the right wedge; thus it is analogous to the CFT Hamiltonian H_R^{CFT} which describes only states dual to the gravity in the right wedge, and evolves these states into themselves. Similarly, the states $\psi_{L,j}\Big[\dots\phi[-2],\phi[-1]\Big]$ are like the gravity states $|E_k\rangle_L^{grav}$, and the left Rindler Hamiltonian is analogous to H_L^{CFT}. Since the F wedge appeared naturally in the Minkowski example under the full evolution of the initial entangled state, we might expect that the F wedge appears somehow in the black hole spacetime as well, when we start with the initial entangled state fig.**??**(a). This would make the effect of entanglement very nontrivial in gravity, since a new spacetime regions F,P would result from entangling states which by themselves had no such regions.

But there is a problem with the analogy between MInkowski space and the eternal black hole. On the slice $\mathcal{S}$ in Minkowski space, we have considered the state Ψ as defined on the points $i=-\infty,\infty$. But to know how this state evolves, we need to know which points i are coupled to each other. The standard

Hamiltonian for a scalar field has interactions terms that couple any point to its neighbour with the schematic form

$$H_{int} \sim \frac{1}{2}(\nabla\phi)^2 \approx \frac{1}{2}\frac{(\phi(x_{i+1})-\phi(x_i))^2}{(x_{i+1}-x_i)^2} \quad (1.14)$$

But which sites are coupled this way? There are two possibilities:

(i) Each side in the right wedge $i = 1, 2, \dots$ is coupled to the next site. Each site in the left wedge $i = -1, -2, \dots$ is also coupled to the next site. But the last site site $i = 1$ in the right wedge is *not* coupled to the point $i = -1$ of the left wedge. Thus the overall Hamiltonian has the form

$$H = H_L + H_R \quad (1.15)$$

(ii) We have the couplings between sites in the right and left wedges as above, but *also* have a coupling between $i = 1$ and $i = -1$. Thus the overall Hamiltonian is of the form

$$H = H_L + H_R + H_{int} \quad (1.16)$$

where H_{int} is the interaction between $i = 1$ and $i = -1$.

The Minkowski case is like (ii), since all sites on the slice $\mathcal{S}$ are linked to their neighbour. It is the coupling H_{int} between $i = 1$ and $i = -1$ which allows the state to evolve into the F wedge. But now consider the eternal hole. In the CFT description, we had seen the Hamiltonan (1.6) was of the form (1.15), with no term H_{int} coupling the R and L sides. Thus the CFT Hamiltonian at least is like case (i). Thus we cannot use the Minkowski analogy directly to argue that an F wedge must emerge from entangling gravity states.

What then does the relation fig.**??** mean? The eternal hole in fig.**??**(b) certainly has an F wedge, and states on the slice $\mathcal{S}$ do evolve into this wedge. Thus the Van Raamsdonk conjecture implies that a disconnected Hamiltonian (1.6) has a gravity dual of type (1.16), which *does* have an interaction term between the R and L sides. Thus we must conjecture that entangling gravity states generates the interaction term H_{int} between the states, even though no such term exists in the CFT Hamiltonian.

We will now see that this difference between the CFT and gravity Hamiltonians leads to a conflict.

1.1.7 A difficulty with the wormhole conjecture

At first sight there appears to be an immediate difficulty with the conjecture that the eternal hole is dual to two disconnected CFTs. one at each boundary. We will see that the conjecture neatly sidesteps this difficulty. But a second iteration of the difficulty is more problematic, and has no clear resolution.

In the CFT description, the R and L copies of the CFT are disconnected. This means that we cannot send information from the right CFT to the left CFT. The states of the two CFTs are entangled with each other, but it is known that we cannot actually use entanglement to send information.

In the gravity description we have the eternal hole, where the right and left boundaries are connected by the wormhole. If we could use this connection to send information from the right boundary to the left boundary, then we would have a contradiction: the CFT description would behave differently from its dual gravity description, and AdS/CFT would be violated.

But the structure of the eternal hole actually forbids information transfer from one boundary to the other, at least if we use classical physics. A light ray coming from the right boundary falls into the singularity, instead of reaching the left boundary. Nothing can emerge, classically, from the horizon, and this fact prevents any timelike or null path from connecting the two boundaries of the eternal hole.

This looks promising: the wormhole connecting the two boundaries may be somehow encoding the entanglement between the CFTs boundaries, without allowing any information transfer between the boundaries. This would accord well with the behavior of the dual CFT, and the whole picture looks promising.

But if we look beyond the classical limit, and consider quantum physics, then particles *do* emerge from the horizon. In fact the horizon emits Hawing radiation, and with this fact we now have to reconsider the duality between the eternal hole and two disconnected CFTs.

The name 'eternal black hole' suggests that this black hole somehow lasts for ever. Does this hole Hawking radiate? The answer is that it does. We have seen how the stretching of slices at a black hole horizon leads to the creation of pairs. The eternal hole has a horizon on both its left and right sides, and we will get Hawking radiation at each of these horizons. To keep the hole 'eternal' we have to imagine that we feed energy back into the hole at the same rate that it radiates. In particular, this can be done if we imagine the hole is in equilibrium with a thermal bath at the Hawking temperature T. Then the hole emits quanta by Hawking radiation. but also absorbs quanta that fall in from the bath, and so the overall metric remains that of a hole with the same mass M.

What we will do now is consider the two sided black hole in AdS, but we will *not* feed energy back into the hole. Thus we will start with a hole that has the structure of R,L F,P wedges, but we will let the hole emit Hawking radiation, and decrease in mass. When a quantum emitted from the right horizon reaches the right boundary of AdS, we imagine that we apply an operator at this boundary to extract the particle; we do not reflect it back in. We do the same for the left boundary.

Now we argue in the following steps:

(i) We can create an excitation in the right CFT which corresponds to a particle p being thrown in from the right boundary of AdS. Let this particle carry one bit of information, say a spin $\pm$.

(ii) In the gravity picture, this particle falls through the right horizon. We assume that information escapes in Hawking radiation, but we are not restricting to any particular mechanism for this to happen. The question we ask is: does the information of p emerge on the right boundary, on the left boundary, or on a combination of both?

(iii) In the CFT description the answer is clear. The particle p is an excitation in the right CFT, and its information must always stay in the right CFT; there is no transfer of information possible to the left CFT since there is no interaction between the two CFTs.

(iv) The problem now is that it is hard to see how this requirement (iii) will be realized in the gravity picture. The particle p falls into the right horizon, so at first one may imagine that the information of p starts coming out on the right. But over a relatively small time, p crosses the vertical line drawn through the center of the hole; the required time order the crossing time, which is order the radius of the hole $\sim r_h$. The Hawking evaporation time t_H, over which the radiation comes out, is much longer than r_h, and it over times $\sim t_H$ that the full information of p is expected to emerge. So how should we ensure that this information gets encoded only in the radiation escaping to the right boundary of AdS?

One may try a model where particles moving leftwards like p somehow emit radiation that only goes to the right. But consider the situation in fig.**??**; the particle p collides with another particle p' sent in from the *left* boundary, and the collision generates three particles. The data of p and p' is now scrambled among these three particles, and it looks unlikely that we can find a mechanism of Hawking evaporation that will send the data originally contained in p out to the right boundary alone.

Thus we see that we are in a trap after all. The CFT picture requires no communication between the left and righty sides, but in the gravity dual it is hard to see how the quantum process of the black hole evaporation can avoid such a communication. There are many related problems that we can raise using Hawking evaporation in the 2-sided hole; see [**?**] for a discussion.

One may wish to take one step back and argue that the eternal black hole is dual to two entangled CFTs only in some classical approximation; in that case the quantum process of Hawking evaporation cannot be used to seek a contradiction. This is in fact a reasonable possibility, and some simple effects in the CFT have been matched to gravity computations using the eternal hole [**?**]. But if the duality of the eternal hole to two entangled CFTs is not an exact one, then we cannot use the wormhole picture at the level of full quantum gravity. In particular, the wormhole picture of Maldacena and Susskind has argued that a wormhole should connect an entangled pair of particles b, c created during Hawking emission. This is certainly a very quantum process; with just one pair of quanta involved, there is no classical limit. It is therefore not clear why the eternal black hole in AdS can be used to argue for a resolution of the information paradox based on the picture of wormholes.

With this conclusion, we have gotten ourselves into a trap. There does appear to be a way out, which is very interesting.

1.1.8 Breaking up into fuzzballs

Let us return to our original question: what is the dual of the eternal black hole in AdS? We have seen the following:

(i) The eternal black hole in AdS has two asymptotically AdS boundaries. The AdS/CFT duality conjecture says that the gravitational theory in any region which is asymptotically AdS has a dual description in terms of a CFT living at the boundary of AdS. Thus the dual of the eternal hole should be two CFTs which cannot interact with each other; the states of the CFTs are however entangled with each other.

(ii) We have seen this leads to a conflict: in the CFT we should not be able to send information from the right CFT to the left CFT, but this seem shard to avoid in the gravity picture, once we take into account the process of Hawking radiation.

So what is the logical way out? In [**?**] it was suggested that the way out is to say that the eternal hole spacetime does not exist.

But how can this be? The metric on the central slice $\mathcal{S}$ is smooth everywhere, and has a vanishing time derivative. This seems to be a good set of initial condition for the classical Einstein equations. This in turn would imply that the semiclassical description of the eternal hole spacetime should be a valid one, at least until we reach the singularity in the future.

But we have seen in section **??** that the semiclassical approximation can break down due to tunneling into fuzzballs. The large number of possible fuzzball states gives a measure in the path integral that competes with the classical action. This competition is triggered whenever we try to fit a mass M in a region smaller than the horizon radius r_h for a black hole of mass M.

With this intuition, let us look again at the central slice $\mathcal{S}$ of the eternal hole. Consider the angular sphere on this slice, at any given value of r. The mass enclosed within this sphere is M, the mass of the eternal hole, regardless of the value of r. The value of r itself decreases as we move in from infinity, reaching its minimum value at the center of $\mathcal{S}$. At this point we have $r = r_h$, the horizon radius corresponding to the mass M. Thus we are in the situation where we cannot trust the semiclassical approximation any more. In fact if we look at a later slice $\mathcal{S}'$, then the radius of the narrowest point is $r < r_h$, so the instability to tunneling into fuzzballs will be vary string indeed.

We can now see what we need to get out of our trap. We need the tunneling to fuzzballs to be so rapid that the eternal black hole geometry cannot be trusted even over one crossing time. In that situation we cannot follow the motion of an infalling particle like p to a point where it falls through the horizon, crosses the central line and emits a few quanta of Hawking radiation. But our discussion of the fuzzball complementarity suggests that this tunneling is so rapid that the interior of the hole never forms; the fuzzball surface nucleates before a collapsing shell can reach $r < r_h$. This would be in accord with the tunneling we need to argue that the eternal hole spacetime does not exist.

With this situation, the picture of AdS CFT duality would be the one in fig.**??**(a); an entangled set of CFT states is dual to an entangled set of gravity solution; no bridge forms as a consequence of this entanglement, and so no future wedge F develops. The only way to get a region interior to a horizon is as an effective approximate description of the dynamics of fuzzball surfaces, and this approximation is not accurate enough to track information in Hawking quanta. This picture resolves the paradox arising from AdS/CFT duality applied to the eternal hole.

Bibliography