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# Status Report: Black Hole Complementarity Controversy

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**Abstract**

Black hole complementarity was a consensus among string theorists for the interpretation of the information loss problem. However, recently some authors find inconsistency of black hole complementarity: large $N$ rescaling and Almheiri, Marolf, Polchinski and Sully (AMPS) argument. According to AMPS, the horizon should be a firewall so that one cannot penetrate there for consistency. There are some controversial discussions on the firewall. Apart from these papers, the authors suggest an assertion using a semi-regular black hole model and we conclude that the firewall, if it exists, should affect to asymptotic observer. In addition, if any opinion does not consider the duplication experiment and the large $N$ rescaling, then the argument is difficult to accept.

*Keywords:* Black Hole Information Loss Problem, Black Hole Complementarity, Regular Black Hole

## 1. Introduction

Black hole complementarity [1] is an interpretation to understand the information loss problem in black hole physics [2]. This is motivated from our beliefs on the natural laws. First, we hope to believe the *unitarity* of quantum mechanics; for any observer, the sum of all possible probabilities should be unity and it should not be smaller or larger than one. This implies that information should be conserved and the nature does not allow to observe the loss or copy of information. Second, we hope to believe the *semi-classical description* of a black hole by using the local quantum field theory for an observer outside the event horizon. The semi-classical calculations (Hawking temperature, evaporation of black holes, etc.) should be a good description unless we consider the singularity. Third, we hope to believe that *general relativity* should be a good description for an ingoing observer inside the event horizon.

Now the question is whether these three assumptions are consistent or not. In this context, Page [3] shows an interesting discussion on the black hole information issue. For a given closed system $U$, we can divide this to two subsystems: $A$ and $B$. Here, $A$ is interpreted as a black hole and $B$ is interpreted as the background. The number of states of $A$ is $n$ and the number of states of $B$ is $m$. The entire system is closed so that $n \times m$ is a constant, while $n$ and $m$ can vary. Initially, $m = 1$ and, as the black hole evaporates, $n$ decreases and eventually approaches to 1 when the evaporation ends. Now, the *mutual information* between $A$ and $B$ is defined as follows:

$$I(B : A) = S(B) - S(B \mid A), \tag{1}$$

where $S(B) = \log m$ is called by the *coarse-grained entropy* and $S(B \mid A)$ is called by the *fine-grained entropy*, or the entanglement entropy. From the estimation of Page, for a given pure and random state, all the mutual information should be transferred from $A$ to $B$ and $A$ begins to send a bit of information to $B$ when the black hole entropy (coarse-grained entropy) decreased its half value (Figure 1).

If we further assume that the black hole area is proportional to the logarithm of the number of states, then

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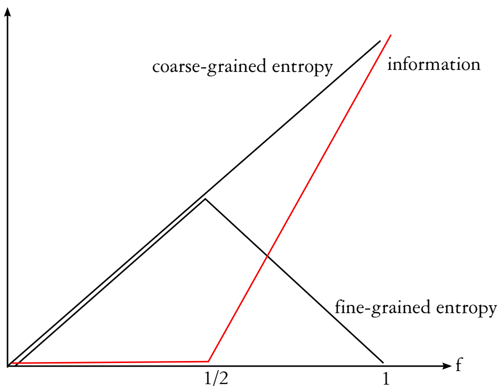


Figure 1: Information emission from a black hole.

the information should be emitted after the black hole area decreased to the half value. This time scale is on the order of the lifetime $\sim M^3$ of the black hole and this time is called the *information retention time*. One note is that the black hole can be still semi-classical even after the information retention time. Therefore, the only way to take out a bit of information is to rely on Hawking radiation: hence, *Hawking radiation should have information*.

Then, are these assumptions/results self-consistent? In literature, we can list three important historical stages on this issue. First, Susskind and Thorlacius [4] considered the consistency of black hole complementarity by considering the duplication experiment. In addition, even though we generalize black hole complementarity to the *scrambling time* [5], this principle seemed to be viable. Second, some authors discussed that semi-classical black holes allow the duplication experiment when we assume a large number of scalar fields. Dvali [6] considered this problem, but the considered examples were not semi-classical. Yeom and Zoe [7] considered rather semi-classical black holes with large $N$ rescaling and could confirm that a large number of scalar fields can allow the duplication experiment [8]. Third, recently, Almheiri, Marolf, Polchinski and Sully [9] discussed that black hole complementarity in itself is not consistent from a field theoretical argument. After the paper of AMPS, this issue is beginning to be focused by literature [10, 11, 12, 13, 14].

In this paper, we summarize these controversy and show perspectives for future studies. In Section 2, we summarize the duplication experiment and the consistency check for black hole complementarity. In Section 3, we show that the large $N$ rescaling can be used to allow the duplication experiment for any dimensions $D \geq 3$. In Section 4, we comment on the recent suggestion by AMPS on the firewall and the firewall controversy. Finally, in Section 5, we summarize and illustrate future perspectives.

## 2. Duplication Experiment

If the assumptions of black hole complementarity are true at the same time, then it seems contradictory because there are two copies of information: one is inside the horizon and the other is outside the horizon by Hawking radiation. However, if there is no observer who can see the both of the copied information at the same time, then black hole complementarity can be still safe; this can be similar with the case of particle-wave complementarity.

Let us define the *duplication experiment* and check whether it is allowed or not in principle (Figure 2). We illustrate this experiment more technically. Step 1: Create an entangled spin pare $a$ and $b$. Step 2: An observer Alice falls into the black hole with the spin $a$. However, $b$ is still outside. Step 3: Alice sends a signal on $a$ along the out-going direction before she touches the singularity. Step 4: There is an observer Bob who is outside the event horizon. Bob first measures the state of $b$ and he knows what it is. Second, Bob waits and measures Hawking radiation outside the event horizon and fortunately measures the information of $a$ that is attached by Hawking radiation after the information retention time. In principle, Bob can know that a Hawking particle contains the information of $a$ by comparing with the state of $b$. We call this information $h$. Step 5: Bob falls into the black hole and fortunately sees the signal of Alice. Step 6: Then Bob knows that he has two copied quantum states and copied quantum information that is definitely violates the unitarity principle.

We can carefully illustrate the assumptions that we used for this experiment. First of all, we used three assumptions of black hole complementarity as we commented in Introduction. Second, we assumed the *area-entropy relation*: then the information retention time is $\sim M^3$ and Hawking radiation should contain information. Finally, to justify Step 4 and Step 5, we implicitly assume that *there is an observer who can read a bit of information from Hawking radiation*. If one of these assumptions is not satisfied, then the duplication experiment cannot success. On the other hand, if we assume these assumptions, then the duplication experiment is well-defined in principle.

Now let us check whether this is indeed possible or not. A black hole has the spatial size $r_0 \sim M$ and Bob falls into the black hole after the time $\tau \sim M^3$. It is