A brief history of black holes (and Information)

1916
Black holes emerge from general relativity: nothing, not even light, escapes event horizon

1974
Black holes emit Hawking radiation thanks to quantum mechanics

2004
Hawking accepts that information escapes from black holes

2012
Escaping information ignites firewall, which can't be reconciled with general relativity

2014
Event horizon replaced by apparent horizon that allows some light through - and kills firewall
outline

- Black holes ABC’s
- Information Loss Paradox
- Complementarity
- Firewall
- ?
Once upon a time ...

- Alice and Bob are engaged (entangled) couple. Alice went on adventure to the center of galaxy (supermassive black hole), while Bob decided to stay on Earth.
Bob saw an event horizon at $r=2GM$ instead the singularity at center of black hole (weak cosmic censorship hypothesis)

$$ds^2 = -(1 - \frac{2GM}{r})dt^2 + (1 - \frac{2GM}{r})^{-1}dr^2 + r^2 d\Omega^2$$

Infinite redshift at the horizon traps all lights behind it. Alice was stretched a bit approaching horizon and time seemed to pause there ...
Bob was not sure about what Alice felt ever since time seemed frozen for her at the horizon and there were several rumors (hypotheses) about what really happened to her ...
In the GR version, Alice felt *no drama* as she went *pass* the horizon (*Equivalence Principle*), except the increasing strong *tidal force*.

\[ t_s = t + f(r) \]

\[ ds^2 = -(1 - \frac{2GM}{r})t_s^2 + \frac{4GM}{r}dt_sdr + dr^2 + r^2d\Omega^2 \]

The story had a sad ending: she was *spaghettized* and torn apart at the singularity.
In the QM version, black hole is hot (Hawking radiation) due to pair production outside the event horizon. The pairwise entanglement is created but eventually lost when the black hole completely evaporates. (Information Loss Paradox)

The engaged bond between Alice and Bob is also gone with the black hole?
In other words, consider sending a wave packet of pure state from infinite past, then only a mixed state is received at the infinite future due to the Hawking radiation is thermal. The unitarity of quantum mechanics is lost.
But wait! Leonard Susskind et al (9310006) and \`tHooft (9306069) came to rescue by saying that quantum information could be both absorbed (carried by Alice) and reflected at the horizon. The reflected information would probably be scrambled at the stretched horizon, which locates at Planck distance from event horizon, and then radiate out as an unitary process (received by Bob). The black hole is claimed to be the fastest scrambler such that radiation looks (approximately) thermal. The entanglement between remaining black hole and earlier radiation first increases then decreases after about half lifetime (Don Page time). After then, it is possible (practical?) to use some kind of super duper computer to reconstruct those information once fallen into the black hole.

Susskind-Thorlacius-Uglum, 1993
Imagine someone throws in a picture of someone’s face into the black hole. At early stage of radiation, those pixels you retrieved from radiation look random like thermal spectrum.
About half of radiation, you start to figure out part of the picture since those pixels start to gather closer to reveal more information. Can you guess who is in this picture?
In Susskind et al’s proposal, the black hole behaves like a *quantum xerox machine* which *clones* the information. This *is allowed* if Alice or Bob were impossible to share his/her own copy with each other across the horizon. Each specific observer appreciates one’s own copy of information and tells one’s own version of story of the black hole. Two descriptions are *complementary*. (Black hole *complementarity*)

**No-Clothing Theorem**

\[ U|\psi\rangle_A|e\rangle_B = |\psi\rangle_A|\psi\rangle_B \]
\[ \langle e|_B\langle \phi|_A|\psi\rangle_A|e\rangle_B = \langle e|_B\langle \phi|_A U^\dagger U|\psi\rangle_A|e\rangle_B = \langle \phi|_B\langle \phi|_A|\psi\rangle_A|\psi\rangle_B, \]
\[ \langle \phi|\psi\rangle = \langle \phi|\psi\rangle^2. \]
There are more and more theorists favoring quantum unitarity than information loss. In particular the *Holographic Principle* in String Theory has connected degrees of freedom in certain black holes to those of some CFT’s. At last (for a moment), Stephen Hawking was conceding the bet in 2004 by giving John Preskill a copy of “Total Baseball, The Ultimate Baseball Encyclopedia” for the 1997 bet among Kip Thorne and themselves.

An earlier bet on whether Cygnus X-1 is a black hole has made Hawking pay Kip a one year subscription to Penthouse.
An alternative resolution to paradox of information loss is to assume the existence of remnant at the very last stage of evaporation. The Generalized Uncertainty Principle (GUP) provides such a scenario: an early work by Ronald Adler, Pisin Chen and David Santiago [Gen. Rel. and Grav., 2001, Vol.33, Iss.12], for example, showed the black hole ends with a Planck size remnant at very high but finite temperature. Some think this resolution still needs to explain how the remnant stores huge amount of accumulated entanglement entropy within such tiny space. Besides, can one talk more than just a principle?

![Graphs showing temperature (T) and entropy (S) vs mass (M)]
In the year 2012, Alice’s fate was changed by the AMPS(S) version of story [Almheiri-Marolf-Polchinski-Sully-(Standford), 1207.3123,1304.6483], which points out an apparent inconsistency in the black hole complementarity and makes a drama at the horizon. No need to wait for spaghetti at the singularity, poor Alice may have been long incinerated by a firewall right passing the horizon of an old black hole. The AMPS lists those assumptions underlying complementarity and they argued they cannot be all true:

(i) Hawking radiation is in a pure state, (unitarity)
(ii) the information carried by the radiation is emitted from the region near the horizon, with low energy effective field theory valid beyond some microscopic distance from the horizon, (field theory description)
(iii) the infalling observer encounters nothing unusual at the horizon. (no drama)
1. Production of maximum entangled pair B and C near horizon
2. (after Page time) radiation B is also maximum entangled with earlier radiation A
3. Quantum entanglement is monogamous, which means B cannot be at same time maximum entangled with both A and C
4. It costs energy to break the bond between B and C in order to entangle B with A. This high energy wall of flame is what burns Alice when she passed across horizon.
Raphael Bousso immediately responded with “Observer complementarity *upholds* the equivalence principle” but then converted to “Complementarity is *not enough*” three months later (1207.5192). Basically, he thinks in-falling Alice can still turn back before falling into the black hole and communicate with Bob.
This year, Hawking did a *weather forecasting* for a black hole *without* event horizon (but apparent horizon) and claimed it can remove the firewall. But it is unclear how exactly he can do that. However this was not a statement of no black hole as advertised by some news. A black hole without sharp horizon was not a news, there exists construction of fuzzyball or grey hole (Mathur). Valeri Frolov’s recent construction (1402.5446) using modified Vaidya metric might answer Hawking’s call.

Some would try to explore possibility of disentanglement between B and C (pair production at horizon) (Verlinde\(^2\), 1306.0515, Hossenfelder, 1401.0288).

Following Bousso’s (and Mathur) argument, some proposed only wave packet of high frequency will interact with firewall, while that of low frequency freely passes. As a result, complementarity is only approximate.
Let’s pray for Alice to find a better ending..

Thank you for your listening